COST 716

Exploitation of Ground-Based GPS for Operational Numerical Weather Prediction and Climate Applications

Final Report

Edited by

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"COST Action 716:
Exploitation of ground-based GPS
for climate and numerical
weather prediction applications"

COST
European Cooperation in the field of
Scientific and Technical Research

Contents

Executive Summary

Background

The COST Action 716 "Exploitation of Ground-based GPS for Operational Numerical Weather Prediction and Climate Applications" was prepared during 1997 and 1998 when a Memorandum of Understanding (MoU) was written and approved. The necessary signatures, from different countries, were obtained during the autumn of 1998 and its kick-off meeting was held in January 1999.

Around that time many European countries had installed, or had plans for, continuously operating ground-based GPS networks to be used as geodetic references, support surveying and navigation, and deliver data for basic research studying the dynamics of the earth. It has by then also been realized that information about the atmospheric water vapour content above each receiving antenna was obtained from the accurate geodetic GPS data analysis. Water vapour is difficult to measure, but is of great importance for accurate modelling of the dynamics of the atmosphere, both for weather prediction and for climate applications. The possibility to have continuous time series of the water vapour content was therefore identified as a potential new important data source. It was time for a collaboration, and coordination at the European level, and geodesists and meteorologists were invited to work together within the COST Action 716.

Accomplishments

The demonstration experiment, originally in the MoU planned to be three months, developed into a three year long operational experiment. Although these data are of a varying quality, there has been continuous improvements, and we have demonstrated that the operational requirements in terms of latency of delivered data and accuracy can be met. It is also worth to mention that in the MoU there was an estimate of a ground-based GPS networks of some 85 sites, now, at the end of the action more than 400 sites are delivering data to the central hub at the UK Met Office.

The action has developed a GPS data message type in the BUFR format which has been approved an agreed upon by the WMO.

We have studied the user requirements for climate monitoring and found that there are large uncertainties in these specifications. WMO's requirements do not to apply to all the different applications in the area. We recommend that these requirements are revisited and possibly modified.

The application of nowcasting was added during the work of the action. In the MoU only NWP and climate were identified as possible applications.

Conclusion and Outlook

The overall conclusion from the work in the COST Action 716 is that it was capable of making useful products for the meteorological community in terms of timeliness and accuracy. The work did indeed increase collaboration in the area significantly. Of course there was a collaboration between countries but also between the scientists in the meteorological and the geodetic communities.

Our estimate of the total amount of work is 480 man months together with additional investments of the order of 1.8 Meuro. These funds were mainly from national funding agencies, but were to a large extent motivated by the work within the COST action.

We see a mixed picture with regards the impact of GPS data on NWP forecasts. Many of the forecast impact experiments run thus far used a sparser station network than is currently available (March 2004), and in addition assimilation schemes have yet to be tuned to use GPS data in an optimal fashion. Furthermore, since the time series of the water vapour content from GPS data have a temporal resolution of many minutes, 4D-Var impacts may be significantly greater in magnitude than those seen for 3D-Var.

We have not come to a definite conclusion regarding the cost benefit of including GPS data in weather forecasting—given the limited time for acquiring statistics. The results obtained so far indicate small impact due to GPS data when averaged over all weather conditions. During disturbed weather conditions the impact of including GPS data can be significant. These results are in agreement with those obtained in the US (Gutman et al., 2004).

Concerning climate monitoring applications the required stability in the observables are met since it is a “time-of-arrival” measurement. In addition we formulate the requirement that water vapour time series from GPS data must be consistently processed and adequate models for other effects influencing the observables, such as the electromagnetic environment at each GPS antenna, must be used.

The status of the field now in 2004 when the COST action is ending is described by the following ongoing activities:

- A EUMETNET proposal has been submitted by Denmark, the Netherlands, and the UK, aiming at a four year long transition project to transfer the very successful demonstration experiment into a useful and highly reliable observing network, contributing both to weather forecasting as well as to the Global Climate Observing System (GCOS).
- A Task Group is formed in the geodetic community in order to be a discussion partner to the EUMETNET project scientists. This task group will also interact will the established International GPS Service (IGS) and the European reference frame commission (EUREF).
- The research project TOUGH (Towards Operational Use of GPS Humidity Measurements in Meteorology), supported by the 5th EC Framework Programme, used ground-based GPS data for additional impact studies and the developing and improving algorithms and models within the GPS data analysis and the subsequent assimilation into the NWP models.
- The European Centre for Medium range Weather Forecasting (ECMWF) is starting to assess the impact of the ground-based GPS data.
- The most important need for climate monitoring applications is to keep efficient archiving of the raw (RINEX format) GPS data. We believe that this is actually taken care of but would like to stress the importance of keeping a precise documentation also of the sites and their possibly changing electromagnetic environments.

We that have been active in the COST Action 716 are pleased to see that our work has resulted in follow-on activities which are in line with our conclusions and wish success to these activities.

Foreword

COST is a programme operated by the European Community (EC) in order to stimulate co-operation in the field of scientific and technical research. The funding for the actual research is obtained from other bodies, national as well as international, and the COST activity funds the co-ordination. This mainly means travel costs for meetings, contributions to workshops/conferences, contributions to publications, and short term scientific missions (STSM) of researchers to visit other partners and institutions stimulating valuable co-operation within the action.

COST is built up by "actions". Actions are grouped into different research areas, e.g., meteorology, telecommunications, and transport. The individual actions are defined by a Memorandum of Understanding (MoU) signed by the governments of the COST states wishing to participate in the action. An action typically runs for 5 years. In our case the work lasted for 5 years and 6 months due to a prolongation motivated by a reorganization of the COST administration in Brussels meaning that no meetings could be arranged for approximately half a year. Other reasons for the prolongation were that the number of continuously operating GPS stations producing data in near real time were growing rapidly towards the end of the action and we wanted to create a good overlap with the TOUGH research project to keep the momentum going. More detailed information about COST can be obtained from the official web site: `http://cost.cordis.lu/src/home.cfm`.

Acknowledgement

In addition to the work carried out within COST Action 716 we would like to thank Mr. David Pick who took the lead in order to initiate the action and produce the Memorandum of Understanding during 1998–1999.

The work has also benefitted from the support from the COST Secretariat in Brussels, where Mr. Andrej Hocevar helped us to start up the action and Mr. Zoltan Dunkel and Mr. Pavol Nejedlik served us during the 1999–2001 period and the 2002–2004 period, respectively.

Since the support from the COST Secretariat is focused on networking such as travel to meetings and workshops, there are also European and national research projects whose support have been fundamental and shall be recognized.

The work was of course made possible with the support from the participating institutes (see Appendecies A and B). Furthermore, we would like to thank all the anonymous station managers who supply hourly GPS data, as well as the IGS and EUREF data and analysis centres.

The following EC projects have been valuable for our work:

- The EC project WAVEFRONT (GPS WAter Vapour Experiment For Regional Operational Network Trials) was supported by the Environment and Climate Work Programme

(1996–1999, see `http://www.nottingham.ac.uk/iessg/research/research_project/isgres30/isgres30.html`).

- The Research DG of the European Commission for Environment and Climate RTD (contract ENV4-CT98-0745) for its co-funding of the MAGIC project (1998–2001, see `http://www.acri.fr/magic/`).
- The Research DG of the European Commission with the RTD activities of the Environment and Sustainable Development sub-programme (5'th Framework programme, contract EVG1-CT-2002-00080) for its co-funding of the TOUGH project (2003–2006, see `http://dmiweb.dmi.dk/pub/tough/`).

In addition to the support from our home institutions we like to mention the following funding agencies at the national level :

- The GOP contribution is supported by the Ministry of Education, Youth and Sports of the Czech Republic (OC 716.001, LN00A005).
- The Danish Research Council supported the GODANS project.
- The GFZ contribution to COST Action 716 was carried out under BMBF grant 01SF9922/2 in the framework of GASP project.
- The national support for GPS meteorology in Sweden came from the Swedish National Space Board starting already in the mid nineties and focused on near-real time applications during 2001–2004. General support for basic research on space geodetic techniques was obtained from the Swedish Research Council.
- The Swiss Federal Office of Education and Science supported major parts of the work at the University of Berne under Grant No. C99.0046.

Special thanks also goes to those that have been involved in arranging our meetings and workshops. Especially we are grateful to GeoForschungsZentrum Potsdam for running our 2nd workshop, although no COST support was available at that time. We also like to thank the sponsors of the international workshop on GPS meteorology, held in Tsukuba, Japan, in January 2003, which included many participants from our COST action.

The Editors

September 2004

Acronyms and Abbreviations

3D-Var	Three-Dimensional Variational Data Assimilation System
4D-Var	Four-Dimensional Variational Data Assimilation System
AC	Analysis Centre (of GPS data)
ACRI	ACRI-Sciences de la Terre (ACRI-ST, Sophia Antipolis, FR)
aLMo	Alpine Local Model (the Swiss NWP model)
ARP	Antenna Reference Point
ASI	Agenzia Spaziale Italiana (Matera, IT)
AT	Austria (country participating in this COST action)
BE	Belgium (country participating in this COST action)
BKG	Bundesamt für Kartographie und Geodäsie (Frankfurt am Main, DE)
BSW	Berniese SoftWare (for analysis of GPS data)
BUFR	Binary Universal Format for the Representation of data (WMO)
CALTECH	California Institute of Technology
CEDR	Centre of Earth Dynamics Research (CZ)
CEOS	Committee for Earth Observation Satellites
CESAR	Cabauw Experimental Site for Atmospheric Remote Sensing
CGPS	Continuous GPS (meaning continuously operating/receiving data)
CH	Switzerland (country participating in this COST action)
CHMI	Czech Hydrometeorological Institute
CLARA	Clouds and Radiation (project in NL)
CLIMAP	Climate and Environment Monitoring with GPS-based Atmospheric Profiling (EU)
CNRM	Centre National de Recherches Météorologiques
CNRS	Centre National de la Recherche Scientifique (France)
CODE	Center for Orbit Determination in Europe (AC within the IGS)
COSMC	Czech Offices for Surveying, Mapping and Cadastre
COSMO	COnsortium for Small-Scale MOdelling
COST 716	Co-operation in Science and Technology Action 716 (EU)
CSH	Column Specific Humidity
CTU	Czech Technical University in Prague
CZ	Czech Republic (country participating in this COST action)
DE	Germany (country participating in this COST action)
DGPS	Differential GPS (navigation supported by nearby reference site(s))
DK	Denmark (country participating in this COST action)
DORIS	Doppler Ranging System (FR)
DWD	NMS of Germany (in Offenbach)

Acronyms and Abbreviations (continued)

E-AMDAR	EUMETNET - Aircraft Meteorological Data Relay
EC	European Community
ECMWF	European Centre for Medium Range Weather Forecasting
EPN	EUREF Permanent GPS Network
EPOS	GPS analysis software package from GFZ
ERA40	ECMWF 40 year reanalysis data set
ERP	Earth Rotation Parameters
ES	Spain (country participating in this COST action)
ESA	European Space Agency
ESEAS	European Sea Level Service
ESF	European Science Foundation
ETRS	Eurasian Terrestrial Reference System
EU	European Union
EUCOS	EUMETNET Composite Observing System
EUMETNET	European Meteorological Network, the cooperation between European NMSs
EUREF	IAG reference frame sub-commission for Europe
FGAT	First Guess at Appropriate Time
FI	Finland (country participating in this COST action)
FM94	WMO Form no. 94 (i.e. BUFR)
FM-DARC	Frequency Modulated DAta Radio Channel
FM-RDS	Frequency Modulated Radio Data System
FMI	Finnish Meteorological Institute
FR	France (country participating in this COST action)
FTP	File Transfer Protocol (under TCP/IP)
Galileo	European GNSS (EU/ESA)
GAMIT	GPS analysis software package from MIT and SIO
GASP	GPS Atmosphere Sounding Project
GB-GPS	Ground-Based GPS (in this context for the observation of atmospheric water vapour)
GCM	General Circulation Model
GCOS	Global Climate Observing System
GeoDAF	Geodetic Data Archiving Facilities (ASI)
GFZ	GeoForschungsZentrum Potsdam (Potsdam, DE)
GI	Geodetic Institute (NMA, NO)
GLONASS	GLObalnaya NAvigatsionnaya Sputnikovaya Sistema (Russia)
GNSS	Global Navigation Satellite System (generic for GPS/GLONASS/Galileo)
GOP	Geodetic Observatory Pecny (CZ)
GOS	Global Observing System
GPS	Global Positioning System (USA)
GTS	Global Telecommunications System (WMO)
HGF	Helmholtz Association of German Research Centers
HIRLAM	High Resolution Limited Area Model
hNmf	hydrostatic Niell mapping function
HPUX	Unix operating system for Hewlett Packard workstations
HU	HUngary (country participating in this COST action)

Acronyms and Abbreviations (continued)

HPUX	Unix operating system for Hewlett Packard workstations
HU	HUngary (country participating in this COST action)
IAC	Instituto de Astrofísica de Canarias (Spain)
IAG	International Association of Geodesy
IAP	Institute of Applied Physics (University of Bern, CH)
ICC	Institut Cartogràfic de Catalunya (Spain)
IEEC	Institut d’Estudis Espacials de Catalunya (Barcelona, ES)
IESSG	Institute for Engineering Surveying and Space Geodesy (Nottingham University, UK)
IGN	Instituto Geográfico Nacional (Spain)
IGN	Institut Geographique National (France)
IGS	International GPS Service
IGU	IGS Ultra rapid orbits
IPCC	Intergovernmental Panel on Climate Change
IPWV	Integrated Precipitable Water Vapour (measured in mm)
IT	Italy (country participating in this COST action)
ITRF	International Terrestrial Reference Frame
IWV	Integrated Water Vapour (measured in kg/m^2)
JMA	Japan Meteorological Agency
KNMI	Koninklijk Nederlands Meteorologisch Insituut (De Bilt, NL)
LAC	Local Analysis Centres
LM	Lokal Modell (limited-area NWP model of the DWD)
LMS	Least Median of Squares
LPT or L+T	Bundesamt für Landestopographie (Swiss Federal Office of Topography) (Wabern, CH)
MC	Management Committee (in our case consisting of the national delegates)
MAGIC	Meteorological Applications of Global Positioning System Integrated Column Water Vapour Measurements in the Western Mediterranean (EU project)
MetDB	Meteorological Data Base (Met Office)
Met Office	NMS of the United Kingdom (in Exeter, UK)
MES	MESoscale model (Met Office)
MIT	Massachusetts Institute of Technology
MoU	Memorandum of Understanding
MSL	Mean Sea Level
NCEP	National Center for Environmental Prediction
NKG	Nordic Commission of Geodesy (in this report also the GPS analysis centre for NKG in Norway)
NKGS	GPS analysis centre for NKG in Sweden
NL	Netherlands (country participating in this COST action)
NLS	National Land Survey (of Sweden)
NMC	National Meteorological Centre
NMS	National Meteorological Service
NO	NOrway (country participating in this COST action)
NRT	Near-Real Time

Acronyms and Abbreviations (continued)

NRTS	Near Real Time System
NWP	Numerical Weather Prediction
OHMCV	Observatoire Hydrométéorologique Méditerranéen Cévennes Vivarais
OPERA	Operational Programme for the Exchange of weather RAdar information (EUMETNET)
OSE	Observing System Experiment
pc	piecewise constant (here used to describe the type of estimation of the ZTD)
PCV	Phase Centre Variation (here used for GPS antennas)
PPP	Precise Point Positioning (a technique to process GPS data)
PWV	Precipitable Water Vapour
RAOB	RAdiosonde OBservation
RIGTC	Research Institute of Geodesy, Topography and Cartography (CZ)
RINEX	Receiver independent exchange (format for GPS data)
RMDCN	Regional Meteorological Data Communications Network (Europe)
RMI	Royal Meteorological Institute (BE)
RMS	Root-Mean Square
ROA	Real Observatorio de la Armada (Spain)
ROB	Royal Observatory of Belgium
RTK	Real-Time Kinematic
rw	random walk (here used to describe the type of estimation of the ZTD)
SE	Sweden (country participating in this COST action)
SGN	Service de Geodesie et Nivellement (Toulouse, FR)
SIO	Scripps Institution of Oceanography
SLR	Satellite Laser Ranging
SMHI	Swedish Meteorological and Hydrological Institute
SRIF	Square Root Information Filter
STD	STandard Deviation
STD	Slant Total Delay
STSM	Short Term Scientific Mission (special travel support within a COST action)
TCP/IP	TeleCommunications Protocol / Internet Protocol
TOUGH	Targeting Optimal Use of GPS Humidity (project within the 5th framework programme of the EU)
TUD	Technical University of Delft
TZD	Total Zenith Delay
VAR	Variational (NWP data assimilation technique)
UCAR	University Consortium for Atmospheric Research (Boulder CO, US)
UK	United Kingdom (country participating in this COST action)
UMTS	Universal Mobile Telecommunications System (Third generation (3G) mobile technology)
UPS	Uninterruptible Power Supply
USA	United States of America
UTC	Universal Time Co-ordinated (in practice the same as the Greenwich Mean Time)

Acronyms and Abbreviations (continued)

UTH	Upper Troposphere Humidity
VLBI	Very-Long-Baseline Interferometry
WG	Working Group (in our case the group responsible for one of four projects)
WMO	World Meteorological Organization
WCRP	World Climate Research Programme
WINPROF	The EUMETNET WINd PROFiler programme
wNmf	wet Niell mapping function
WVR	Water Vapour Radiometer
WWW	World Weather Watch
ZHD	Zenith Hydrostatic Delay, a part of the zenith propagation delay accurately calculated from the total ground pressure
ZPD	Zenith Path Delay (normally the same as ZTD)
ZTD	Zenith Total Delay (sometimes referred to as “Total Zenith Delay” or TZD)
ZWD	Zenith Wet Delay (component of the ZTD leftover when the ZHD is removed from the ZTD)

Chapter 1

Introduction

Gunnar Elgered

1.1 Objectives of the COST Action 716

The objectives of the action were specified in the Memorandum of Understanding (MoU). The primary objective is:

- Assessment of the operational potential on an international scale of the exploitation of a ground-based GPS system to provide near real time observations for Numerical Weather Prediction (NWP) and climate applications.

Secondary objectives are:

- Development and demonstration of a prototype ground-based GPS system on an international scale;
- Validation and performance verification of the prototype system;
- Development and demonstration of a data exploitation scheme for NWP and analysis of data exploitation techniques needed for climatic applications;
- Requirements for an operational implementation of a ground-based GPS system on an international scale.

1.2 Overview of the activities within COST Action 716

The following fifteen countries participated in the COST Action 716: Austria (AT), Belgium (BE), Czech Republic (CZ), Denmark (DK), Finland (FI), France (FR), Germany (DE), Hungary (HU), Italy (IT), Netherlands (NL), Norway (NO), Spain (ES), Sweden (SE), Switzerland (CH), and United Kingdom (UK).

Ten Management Committee Meetings (MCMs) have been held (see Appendix A for details) and these have often been collocated with Working Group Meetings.

COST Action 716 consists of four working groups (WGs). The 1st WG reviewed the state of the art, the 2nd and 3rd concern the demonstration experiment and the applications of NWP and climate, respectively. Finally, WG 4 deals with the planning for implementation and operations. Table 1 summarize the tasks of the different working groups. There are only minor modifications compared to the original work plan presented in the MoU.

Working Group 1 produced the final report which reviewed the state of art in ground-based GPS technology and data analysis as it was in late 2000 to early 2001. It also summarizes the status in the participating countries and established a common foundation for the continued work between geodesists and meteorologists in Working Groups 2 and 3. This state-of-the-art report can also be seen as the input to the work of WG 4. It is available for download through the home page of the action.

Working Groups 2 and 3 were formed at the 2nd MC meeting in April 1999 and Working Group 4 had its kick-off meeting in Bracknell in late 2001. The specific WG meetings are listed in Appendix A. An overview of the time schedule, including the MC meetings and the workshops, is shown in Figure 1.1.

Two Short Term Scientific Missions (STSMs) have been carried out within the action. Guergana Guerova from Switzerland visited DWD in Offenbach in April 2001. The impact of using GPS data in NWP models was investigated in two case studies. Changes of the order of 20% in the integrated water vapour content was observed. The report is available on the web under WG 3 documents:
`http://www.oso.chalmers.se/geo/cost716.html/STSM_report_gg.pdf`

The second STSM was made by Oddgeir Kristiansen visiting the Onsala Space Observatory of Chalmers University of Technology in Sweden. The purpose of this visit was to coordinate the analysis of GPS data from Scandinavia for the demonstration experiment of WG 2. The report is also available via Internet. The link is found under working group 2 documents: `http://www.oso.chalmers.se/geo/cost716.html/cost-short-term-rep_ok.pdf`

The first workshop was held in Oslo during July 2000 and had the title “Towards Operational GPS Meteorology”. The information related to the workshop is available at `http://www.gdiv.statkart.no/cost716/`. The workshop was regarded as a success by many participants. The main part of all contributions were published in the proceedings of the workshop (see Appendix D2).

The second workshop of the action was held at GeoForschungsZentrum (GFZ) in Potsdam during January 28–29, 2002. It had the title: “Exploitation of Ground-Based GPS for Meteorology”. Due to budget problems only three external experts could be reimbursed, and all WG and MC meetings had to be canceled. Nevertheless, more than 60 scientists and researchers participated in the workshop. The proceedings were distributed in printed form to the participants at the workshop. They are also available to the public via Internet: `http://op.gfz-potsdam.de/D1/COST716`.

An international workshop on GPS meteorology was held in Tsukuba, Japan, in January 2003. Although not formally involving our COST action there were several groups invited by the Japanese hosts presenting results from the COST activities (see `http://dbx.cr.chiba-u.jp/Gps_Met/gpsmet/index.html` and the publication list in Appendix D2).

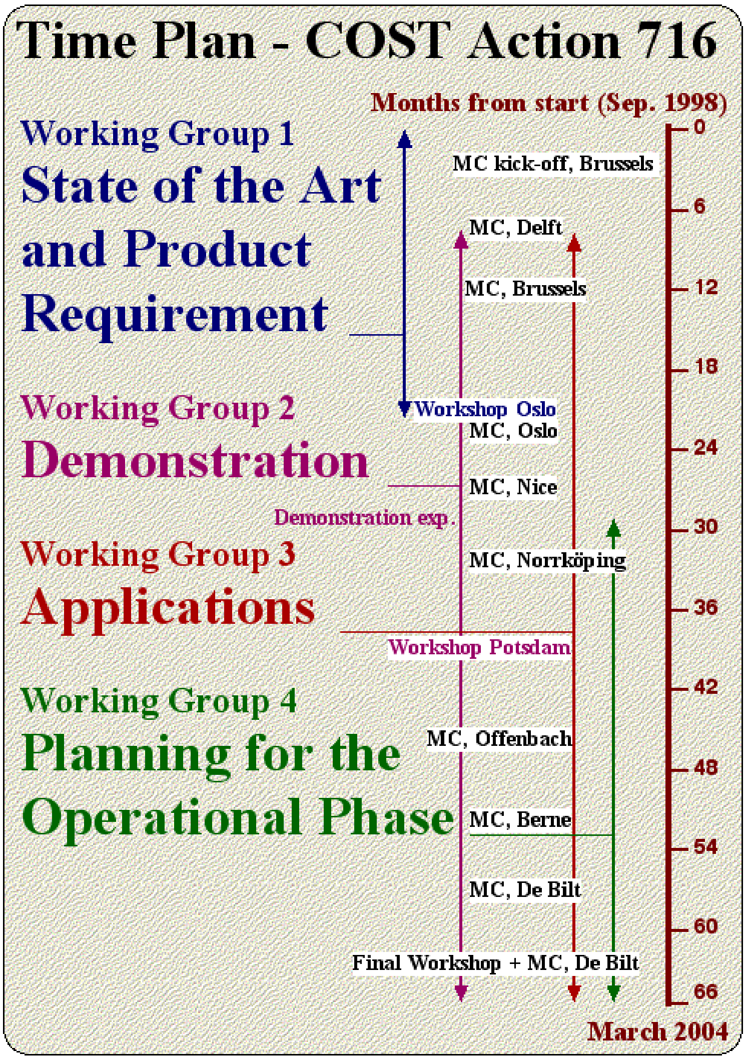


Figure 1.1: The actual schedule of the COST Action 716. The total length of the action was 66 months, including a 6 month prolongation.

A Symposium on Atmospheric Remote Sensing using Satellite Navigation Systems was arranged by URSI and ESA in Matera during October 13–15, 2003. Several presentations related to our COST action were presented here. Both from the demonstration experiment as well as from studies within the applications in NWP and climate (the page `http://www.estec.esa.nl/conferences/past_events.html` contains the link)

The final workshop of COST 716 was held in De Bilt, The Netherlands, in December 2003. Here the activities of COST 716 were summarized and the future of ground-based GPS meteorology was assessed by invited speakers and ourselves. (see `http://www.knmi.nl/samenw/cost716/final-workshop/`).

Table 1.1: The working plan of COST Action 716, divided into the different Working Groups.

Project 1 (WG 1) **State of the Art** **and Product Requirement**	**Project 2 (WG 2)** **Demonstration**
State of the art review and workshop - Theory (ground based) - Hardware - Software Error sources Additional data requirements Modifications needed to geodetic systems	Equipment field trials Operational reliability Code validation Sensitivity assessment to meteorological and site variables Consider possible quality control and validation measurements Near Real Time (NRT) network demonstration Met system Geodetic system and an international scale
Deliverables:	Deliverables:
Review report Equipment specification Critique of system Recommended software Specification of data exchange format	Trial report Demonstration system NRT data set on regional / continental scale

Project 3 (WG 3) **Applications**	**Project 4 (WG 4)** **Planning for the Operational Phase**
Development of assimilation & data utilization approach for: Numerical Weather Prediction Climate Impact and validation assessment Development of quality control and a performance monitoring scheme on-line scheme off-line trend and bias detection	Review of implementation options Logistics (include communications and coding standards) Assessment of optimal density Assessment of delta impact on current observing system Cost benefit analysis
Deliverables:	Deliverables:
Impact assessment Recommendations for - Data exploitation - Quality control and performance monitoring	Cost benefit / analysis for enhancing observing system with GPS observations. Recommendations for international operational network

1.3 Report structure

This Final Report of COST Action 716 is structured as follows. Chapter 2 first gives a general background to the method of ground-based GPS meteorology, the physical theory and the basics of the GPS data analysis together with some general references. WG 3 has had the main responsibilities for Chapter 3 which describes a review and an assessment of the user requirements for the three applications of nowcasting, Numerical Weather Prediction (NWP), and climate. The demonstration experiment carried out by WG 2 is presented in Chapter 4. It gives an introduction to the GPS analysis and describes the methods and assumptions used by the different analysis centres that have delivered data in near-real time to the project. The corresponding work on the GPS data flow, the data monitoring, and the data validation was a collaboration between WG 2 and WG 3 and is described in Chapter 5. Here also statistics of the number of stations and data delivery are summarized. The GPS applications in nowcasting, NWP, and climate research/monitoring were addressed by WG 3 and is summarized is Chapter 6. The work on the planning for the operational phase was carried out by WG 4 and is reported in Chapter 7. This includes recent descriptions of the status within the different participating countries. Finally, our conclusions and recommendations for continued work are found in Chapter 8.

Appendix A lists dates and places of meetings and workshops. Appendix B lists the persons that have been involved in the action. Appendix C is the submitted EUMETNET proposal for continued ground-based GPS meteorology in Europe. Finally, in addition to the bibliography of references cited in the report itself, Appendix D is a list of publications published (or submitted) by authors that have been active in the action. It can be useful to identify important contributions to this field of research during the time period of the action.

Chapter 2

Theoretical Physical Background

Gunnar Elgered and Hans van der Marel

2.1 Parameters describing the neutral atmosphere

The primary observable of Global Navigational Satellite System (GNSS) receivers is the time of arrival of signals transmitted from satellites. Alternatively, the observable is the difference in time of arrival of the satellite signals between pairs, or within networks, of antennas for the applications of relative positioning. These observables are obviously influenced by the atmosphere above the antennas. The excess propagation time for a signal transmitted from a satellite to a receiver on the ground can be written as

$$\Delta t = \int\limits_S \frac{1}{v}\, ds - \int\limits_G \frac{1}{c}\, dg \tag{2.1}$$

where S is the actual path through the atmosphere; G is the straight line distance that would have been the path without an atmosphere; v is the propagation velocity (group and phase velocities are equal in the neutral atmosphere since the dispersion can be ignored at the frequencies transmitted by the GNSS satellites); c is the speed of light in vacuum. The excess propagation time is often expressed as an equivalent excess propagation path length ℓ, compared to the path in vacuum conditions, which is obtained by multiplying the time delay Δt in (2.1) by the speed of light in vacuum

$$\ell = \int\limits_S \frac{c}{v}\, ds - \int\limits_G dg \tag{2.2}$$

We rewrite this expression as

$$\ell = \int\limits_S \frac{c}{v}\, ds - \int\limits_S ds + \int\limits_S ds - \int\limits_G dg \tag{2.3}$$

and obtain

$$\ell = \int\limits_S (n-1)\, ds + S - G \tag{2.4}$$

where n is the radio refractive index in the atmosphere. When the excess path length is expressed using this equation we see that the first term is caused by the fact that the signal velocity is reduced compared to the case of propagation in vacuum. The excess path is of the order of 2.3–2.7 m in the zenith direction from a site at sea level. The main part, approximately 2.3 m from the sea level, can be accurately modelled using observations of the total ground pressure whereas the water vapour contribution varies between almost zero for cold and dry conditions and 40 cm for a warm and humid atmosphere. The "$(S-G)$" term is the difference between the true propagation path and the straight line distance. This term can be ignored for large elevation angles but must be taken into account when low elevation angles are used in the observations. Typically the size of this term is about 3 cm at 10 degrees and increases rapidly for smaller angles. This term is often referred to as the "bending term" or the "geometric delay". We note that for a horizontally stratified atmosphere it is equal to zero in the zenith direction. When modelling the total excess path the second bending term is often included through a modified elevation dependence of the first term.

Since the radio refractive index is very close to one it is practical to introduce the refractivity N which is defined as

$$N = 10^6\,(n-1) \tag{2.5}$$

The refractivity is easy to calculate if the state of the atmosphere is known. The general form of the refractivity formula in the neutral atmosphere is (Crane, 1976).

$$N = k_1\,\frac{p_{(d-\mathrm{CO_2})}}{T} + k_2\,\frac{e}{T} + k_3\,\frac{e}{T^2} + k_4\,\frac{p_{\mathrm{CO_2}}}{T} \tag{2.6}$$

where $p_{(d-\mathrm{CO_2})}$ is the partial pressure of dry air without carbon dioxide (CO_2); e is the partial pressure of water vapour; $p_{\mathrm{CO_2}}$ is the partial pressure of carbon dioxide; T is the absolute temperature; and the coefficients k_1, k_2, k_3, and k_4 are empirically determined from laboratory experiments.

The refractivity equation is sometimes supplemented with so called compressibility factors (Thayer, 1974). These are included to model deviations from the ideal gas law for the respective constituent. Of course, they shall only be included if it is consistent with the laboratory experiments carried out to determine the empirical coefficients. Since this is not clear, e.g., for the work carried out by Boudouris (1963) which is often referred to and used, it has recently been recommended to ignore compressibility factors in the refractivity formula (Rueger, 1999).

Another simplification is to combine the two terms for the dry gases. Since the CO_2 content in the atmosphere is stable, except for a small seasonal variation (approximately 6 ppm) and the well known long term anthropological effect of +1.7 ppm/yr (Keeling et al., 1989), the CO_2-term can be taken into account by increasing the value of k_1 and thereby obtain one term for the dry gases. Thus we obtain the formula

$$N = k_1\,\frac{p_d}{T} + k_2\,\frac{e}{T} + k_3\,\frac{e}{T^2} \tag{2.7}$$

where p_d is the partial pressure of all the dry gases.

A commonly used value for k_1 is 77.691 K/hPa which is based on a CO_2 content of 300 ppm. The expected value in 2004 is 375 ppm which will imply a value of k_1 equal to 77.695 K/hPa (Rueger, 1999). The change in the zenith excess path caused by this updated value of the CO_2 content is only 0.1 mm.

The values for k_1, k_2, and k_3 originally measured by Boudouris (1963) were: 77.593±0.08 K/mbar, 72±10 K/mbar, and (3.754±0.03)$\cdot 10^5$ K^2/mbar, respectively.

When integrating the refractivity to determine the excess propagation path, according to the equations above, it is an advantage—in the analysis of space geodetic data—if the effect can be divided up into a so called hydrostatic term and a remaining term caused by water vapour. The reason is that the hydrostatic term can be determined with an uncertainty of less than 1 mm in the zenith direction if the total ground pressure is measured with an uncertainty of less than 0.3 hPa.

Following the presentations by Davis et al. (1985) and Elgered (1993)—but ignoring compressibility factors as discussed above—we arrive at the following equations tailored to describe the excess atmospheric propagation path.

The hydrostatic delay in the zenith direction is given by

$$\ell_h = 0.0022768 \, \frac{P_\circ}{f(\phi, H)} \quad [\mathrm{m}] \tag{2.8}$$

where P_0 is the total ground pressure in hPa; the function

$$f(\phi, H) = (1 - 0.00266 \cos 2\phi - 0.00028 \, H) \tag{2.9}$$

is used to model the variation of the acceleration due to gravity; ϕ is the latitude; and H is the height in km of the station above the ellipsoid. The remaining delay—which we refer to as the wet delay—is, when using the refractivity constants from Boudouris (1963), written

$$\ell_w = 24 \cdot 10^{-6} \int_S \frac{e}{T} \, ds + 0.3754 \int_S \frac{e}{T^2} \, ds \quad [\mathrm{m}] \tag{2.10}$$

where, as above, e and T are expressed in hPa and K, respectively. The mapping function describes the dependence of the radio path delay in different directions through the earth's atmosphere. Although there are mapping functions that model systematic effects in the horizontal direction (Davis et al., 1993), (MacMillan, 1995) we here focus on a function that is used to map a delay between different elevation angles ε without any dependency on the azimuth angle. We denote the total delay by ℓ_{tot} and define the mapping function for the total delay at the elevation angle ε as:

$$m_{tot}(\varepsilon) = \frac{\ell_{tot}(\varepsilon)}{\ell_{tot}(90^\circ)} \tag{2.11}$$

In almost all applications it is, however, practical to divide the integral of the total refractivity into the two components just defined: one hydrostatic and one wet term (Davis et al., 1985). It is worth noting that the hydrostatic term is the result of the integration of the total pressure in the atmosphere and hence this term includes also some of the delay caused by water vapour. Therefore we prefer to name it the hydrostatic term — rather than the dry term. A consequence of this is of course also that the whole influence of water vapour is not included in the term which we here call the wet delay. Therefore, it has been proposed that the delay in (2.10) can be called the "non-hydrostatic component" (Mendes, 1999).

With two different delays it is meaningful to define one mapping function for the hydrostatic delay m_h and one for the wet delay m_w:

$$\ell_{tot}(\varepsilon) = \ell_h(90^\circ) \cdot m_h(\varepsilon) + \ell_w(90^\circ) \cdot m_w(\varepsilon) \tag{2.12}$$

The use of two different mapping functions is further justified since the height profiles for the hydrostatic and the wet constituents are rather different. The typical scale height of the partial pressure of water vapour is 2 km whereas it is 8 km for the total pressure in the troposphere (where most of the refractivity is found). In the following we will use the term Zenith Total Delay (ZTD) for $\ell_{tot}(90^\circ)$ which is the sum of the Zenith Hydrostatic Delay (ZHD), $\ell_h(90^\circ)$, and the Zenith Wet Delay (ZWD) $\ell_w(90^\circ)$.

2.2 Accuracy of GPS meteorology

2.2.1 Ground based GPS data processing

The accuracy of the estimated atmospheric delay depends on many parameters. Most important are the uncertainties in the orbit parameters of the satellites, the model used for the receiver coordinates, and the minimum elevation angle used for the observations.

The output atmospheric parameter in high precision GPS data processing is normally the ZTD. The ZHD is determined through an a priori knowledge of the ground pressure at the GPS antenna height (Saastamoinen, 1972)—observed or modelled. Using the hydrostatic mapping function in order to calculate an a priori slant hydrostatic delay an additional ZWD is solved for using its elevation dependence specified by the wet mapping function. The mapping functions most commonly used for GPS are those derived by (Niell, 1996) by ray-tracing several years of radiosonde profiles. The Niell mapping functions use elevation angle, latitude, altitude, and day of year as input parameters.

However, during the GPS data processing stage usually no accurate ground-pressure measurements are available to compute the ZHD, and thus an approximated value is computed using a standard atmosphere. The effect on the ZTD, via the effect on the estimated ZWD, may be neglected if the true ZHD and the a priori ZHD are sufficiently close. For example, using a minimum elevation angle of 10°, an a priori error of -20 hPa implies an underestimate of the ZTD of 1.1 mm. If the minimum elevation angle is reduced to 5°, the ZTD error increases to -2.4 mm (Niell, 2004).

GPS processing centres generally have different ways to compute the a priori ZHD and sometimes use different mapping functions. Therefore, the ZTD, and not the estimated ZWD, is the preferred quantity to be exchanged. The ZTD itself can then be assimilated into a numerical weather prediction model, or the ZWD itself can be extracted from the ZTD by subtraction of a more accurately computed ZHD using accurate estimates or measurements of the surface pressure.

Also the way in which the ZWD is modelled, and therefore the ZTD, can be different for different GPS processing centres. The ZWD is modelled as a random walk process in some of the GPS analysis softwares, assuming a known a priori power spectral density. In these cases the ZWD can be estimated (updated) every data sampling epoch, but the model is further strengthened by assuming that the difference between two epochs has zero mean with a standard deviation related to the assumed power spectral density and the time interval between the two epochs. In other software packages the ZWD is modelled as a step function, e.g. estimating one ZWD parameter every 20 to 60 minutes, depending on the analysis centre. Also when the ZWD is modelled as a step function, relative constraints are sometimes applied between consecutive estimates of ZWD.

The uncertainties in the estimated orbit parameters are reduced by using a large tracking network. The IGS (Beutler et al., 1996) provides different products of different quality, where the most accurate orbit parameters are available many days after the time of the data acquisition. The ZTD errors caused by orbit uncertainties are correlated both temporally and spatially meaning that observed rapid changes and differences between nearby GPS sites have a high common mode rejection of orbit induced errors.

Uncertainties in the orbit parameters are the main difficulty encountered in the application for using the ZTD in weather forecasting where the requirement of data availability in near real time often means within 1–2 hours from data acquisition. The ZTD obtained from post processing, using the most accurate orbit parameters, have a value as an independent source of information for validation purposes.

2.2.2 Characteristics of GPS network systems

The ZTD is estimated along with several other geodetic parameters. The parameters that are estimated depend to a large extent on the domain of the GPS network. The network of the International GPS Service (IGS) is a world-wide network of 200–300 receivers. This network is used mainly to estimate precise satellite orbits and satellite clock parameters for the GPS satellites. Other parameters that are estimated are the daily station coordinates, the receiver clock errors, the ZTD and phase ambiguities, as well as Earth Rotation Parameters (ERP). Delays due to the ionosphere are estimated by using a linear combination of phase measurements on two frequencies, thereby eliminating the first order ionosphere delay. Other short periodic effects, such as solid earth tides, ocean loading, phase wind-up, antenna elevation dependent delays, etc., are taken care of by using a-priori models. There are three main types of IGS products:

- Ultra-rapid orbits, available twice daily and since May 2004 every 6 hours, which include a prediction for up to one day
- Rapid orbits, satellite clocks and ERP (available after two days)
- Final orbits, satellite clocks and ERP (available after two weeks)

The main objective of the IGS network is to define a global and long-term stable reference frame, based on ITRF, below the cm level accuracy level for the ground based stations and at the cm level for the satellite orbits.

The IGS products can be used in other ground-based networks for both geodetic and meteorological purposes. The final IGS satellite orbits and Earth Rotation Parameters (ERP) are used for instance in the EUREF Permanent GPS Network (EPN), a regional densification of the IGS network in Europe of about 200 receivers. The EPN provides daily coordinate time-series, and plays therefore a crucial role in the maintenance of the European part of the terrestrial reference frame. The EPN network is a very robust network that is well monitored, and every station is processed by at least 3 of in total 16 EPN analysis centres. The EPN also provides time-series of hourly estimates of ZTD, which is also a combined product of the individual analysis centres and is available with a delay of 2–3 weeks.

2.2.3 GPS network processing strategies

Two different strategies can be used for the processing of local and regional networks:

1. Network approach using zero or double difference
2. Precise Point Positioning (PPP) approach

In the network approach only IGS orbits and ERP parameters are used. The IGS satellite clock parameters are not used as the satellite clock parameters are estimated in the network along with the other parameters such as station coordinates, receiver clocks, ZTD, and phase ambiguities. Within the network approach broadly two different approaches exist: double and zero difference processing. In the double differencing approach the satellite and receiver clock parameters are eliminated on an epoch-by-epoch basis by forming differences of the observations. First, observations of two different receivers to the same satellite are subtracted, eliminating the satellite clock parameters, giving the so-called single difference. Next, two single differences are subtracted to eliminate the receiver clock parameter, giving the double difference. This greatly reduces the amount of parameters to be estimated in the batch least squares adjustment, leaving only the station coordinates, the phase ambiguities, and the ZTD as unknown parameters. In the zero-difference approach the satellite and receiver clock parameters are estimated along with the other parameters, usually based on a Kalman-filter type of approach. The zero difference and double difference approach give in theory identical results, although the implementation in software may result in small differences. The main advance of the double difference approach is that it results in normal equations, which later on can be combined to constrain the solution or combine different estimates. The main advantage of the zero difference approach is that it is slightly more flexible with respect to changes in the tracking configuration. The other advantage is that it usually uses a Kalman filter (although a Kalman filter is sometimes also used in single or double difference processing), and is therefore slightly more flexible in modelling the time behaviour of parameters such as the ZTD. The domain of the GPS network is important. In a local network only coordinate and ZTD differences between two stations can be estimated; this is because the satellite clock parameters have to be estimated as well. Absolute ZTDs can be estimated only when the network is covering a reasonable region, because then the same satellite is seen from different elevation angles at different stations, allowing estimation of both satellite clock parameters as well as absolute ZTD values.

In the Precise Point Positioning (PPP) approach both previously estimated satellite orbits and ERP are used, as well as satellite clock parameters (Zumberge et al., 1997). Therefore, for each station only station coordinates, epoch-wise receiver clock parameters, ZTD and phase ambiguities have to be estimated. One of the advantages of the PPP approach is that stations can be processed station by station, and that it is not necessary to process a regional network. The downside of the PPP approach that it is much more difficult to estimate integer phase ambiguities, as is often done in the network approach. In the PPP approach this is only possible when several stations are processed together. It is essential in the PPP approach that orbits, ERP, and satellite clock parameters come from the same source. In general the estimation errors of these parameters are highly correlated. This is a problem in particular for near-real-time applications, because the IGS ultra-rapid products cannot provide an accurate clock prediction. Therefore, for near-real time applications analysis centres that use a PPP approach either preceding their PPP processing by a global network adjustment in order to get good orbits and satellite clocks, or use one of the few near-real time orbit and satellite clock products that are available at present. It is expected that in future the number and quality of the near-real time orbit and clock products continue to improve.

The ZTD time series from GPS data have spatially and temporally correlated estimation errors. This is the case both for the network and the PPP approach. In the network approach errors in the satellite orbits and the satellite clock parameters that are estimated introduce correlations between the ZTD, which depend on the network size. In the PPP approach correlations between the ZTD are introduced because of common mode errors in the satellite orbits and clocks.

Furthermore, in the near-real time processing many of the GPS processing centres fix (i.e. do not estimate) the station coordinates onto weekly and monthly averages in order to get a more stable ZTD time series. This leads to an improvement (reduction) of the formal uncertainties of the ZTD. Although this use of average coordinates reduces the noise, it may cause small time varying biases. Models for short term variations in the coordinates, and especially in the vertical coordinate, such as those caused by earth tides and loading effects by the ocean and the atmosphere need to be included. This is also true when site coordinates are estimated if the update period is longer than a couple of hours.

Additionally, the ZTD estimation is very sensitive to elevation dependent effects. Errors in the calibration of satellite and receiver elevation dependent phase delays, which may include significant multipath effects, or errors in the mapping functions, may result in small systematic effects of a few mm in the estimated ZTD. However, using the wrong antenna type in the GPS processing, or fixing the coordinates to the wrong values (e.g. after an earthquake), may result in gross errors of occasionally up to 20 mm or more in the ZTD. In general, the error in the ZTD, and thus ZWD, is below 10 mm.

The total water vapour content (IWV), along the zenith path, can be derived from the ZWD by using a mean atmospheric temperature for the wet refractivity. An estimate of this mean temperature can be obtained from an empirical formula using the surface temperature as input data (Bevis et al., 1994). Used in this way, simultaneous measurements of surface pressure and temperature yield values of the IWV with an accuracy of the order of 1–2 kg/m^2 on a total content of order 10–40 kg/m^2 for temperate regions.

Let us conclude this background discussion by noting that the absolute accuracy of ZTDs estimated from ground-based GPS networks is poor but that a major part of the unknown bias type of error should be possible to keep constant over time scales of years. The strength of the method is the possibility to observe continuously with a good temporal resolution and the horizontal resolution is simply determined by the distance between the GPS sites in the network used.

Chapter 3

User Requirements

Sylvia Barlag, Dave Offiler, and Siebren de Haan

This chapter summarizes the user requirements of the European meteorological and climate user communities with regard to the meteorological data derived from GPS signals. The user requirements served to specify and communicate the user needs taking regard of the expected mode of operation of the GPS ground based networks taking part in the COST action, including operation of receiver equipment and network connections between the stations and the regional processing centres (also called analysis centres).

This expected operation mode of the network was characterized by the following:

- No satellite or ground network anomaly impacts on the on-ground processing,
- The intra-network data flow and data production operate at the planned capacity and efficiency,
- During the demonstration phases the data are expected to be sent from the processing centres to user centres via public networks.

The participating processing centres of the GPS meteorology network were requested to provide Zenith Total Delay (ZTD) values, together with supporting data for each of the stations in the network. These products are known as “Level 2” products. The supporting data include at least time, location, receiver altitude, pressure and temperature at the receiver location (measured, or estimated from, e.g., interpolated ground observation data or NWP) and quality information. In addition, the Level 2 product should also contain Integrated Water Vapour (IWV) if available. The user requirements given in the next sections pertain to these Level 2 products.

For the exchange and distribution of these data specific formats were developed, including a COST-716 ASCII format, a WMO binary (BUFR) format, and an ASCII format for the exchange of data from meteorological surface observation stations nearby GPS receiver stations. Within COST 716 a Near Real Time demonstration was set up specifically for operational meteorology. For this it was assumed that Level 2 products would be available in near-real time, i.e. within 1 hr 45 min of the observation time, in the COST 716 format. In conjunction with this, a real time data server and a monitoring web site were set up that served both the validation of product quality and the data flow and availability. Real time validation of IWV was performed by comparison with NWP models for combinations of all GPS sites and processing centres in Europe. Validation was also performed for GPS sites at a maximum distance of 60 km from a radiosonde launch site. The geographical and temporal coverage of the exchanged GPS meteorology products was limited only by the characteristics of the GPS network.

The approach to define the user requirements for Level 2 products follows the general WMO practice, and is reflected in the tables presented in each of the following sections. As a starting point, generic requirements for humidity observations, independent of the observing system used, were gathered from WMO documents summarizing the needs of several user communities for meteorological products (WMO (2001)). From these, requirements for humidity observations specific to the GPS observing system were derived. These user requirements were discussed and refined at several occasions with the help of COST 716 Working Groups 2 and 3 and the COST 716 Workshops. It shall be noted that WMO humidity requirements are specified as column specific humidity (CSH). We prefer IWV since the differences can be ignored for this purpose (COST-716 (2004)).

The COST 716 action has identified several classes of users, as noted in WMO (2001). For the purpose of the GPS meteorological network development, we present user requirements for three classes of use: qualitative meteorology (nowcasting), NWP, and climate. Several notes are helpful to better understand the tables.

1. User Requirements do not represent a hard cut-off value of “good/no good”; rather there is often a broad range of acceptability. Where two values are given, the first one is the target value whereas the second indicates a threshold beyond which data may have marginal use (impact). Data with quality better than the target values may be over-specified, as the additional ’quality’ cannot be exploited by the application.

2. For NWP, an implicit requirement exists that states that observation errors should be uncorrelated in time and space and the observations should be free of biases. Given the general introduction about GPS processing above, it is clear that the existing ways of solving for tropospheric parameters may introduce unknown correlations and unknown biases. In the sequel, we will only discuss correlation and bias free observational requirements.

3. Requirements are either presented for the IWV or for the path delay. IWV is usually expressed in kg/m^2 or alternatively as the equivalent height of the water column in mm (1 kg/m^2 = 1 mm). To avoid mixing up with path delay the first notation will be used for IWV.

4. Horizontal sampling means the average horizontal sampling separation distance.

5. Repetition Cycle is the effective sampling interval at the same location.

3.1 Requirements for meteorological nowcasting

Meteorological nowcasting, or very short-range weather prediction, is based on a quantitative assessment of weather parameters. The generic requirements of this user community for column integrated humidity have been extracted from the database of the World Meteorological Organisation (WMO) and are presented in Table 3.1. Here we stress again that these requirements are generic, and independent of any particular observing system. The presented ranges represent the threshold and target requirements.

From the above generic requirements for total column humidity data, it is clear that the primary goal of the GPS Meteorology network products is to provide geophysical (Level 2) products, which meet these. With respect to the general requirements for GPS products a requirement for integration time is added. The connected requirements for repetition cycle and integration time stem from a requirement that (time) samples should be uncorrelated. Note that the integration time is the period over which GPS signals are gathered and processed. Also note that relative accuracy is required for quantitative analysis rather than absolute accuracy. When comparing the previous table with Table 3.2 it becomes clear that the target is

Table 3.1: Generic User Requirements for Nowcasting.

	IWV
Horizontal Domain	Sub-regional
Horizontal Sampling	5–50 km
Repetition Cycle	0.25–1 hrs
Absolute Accuracy	1–5 kg/m^2
Timeliness	0.25–0.5 hr

Table 3.2: GPS Meteorology Network Requirements for Nowcasting.

	IWV
Horizontal Domain	Europe to national
Horizontal Sampling	10–100 km
Repetition Cycle	5 min–1 hr
Integration Time	MIN(5min, rep cycle)
Relative Accuracy	1–5 kg/m^2
Timeliness	5–30 min

to capture small scale and rapidly changing humidity structures for the purpose of forecasting rapid and severe weather developments. However, the threshold requirements show that also less frequently and densely sampled information can be useful.

3.2 Requirements for numerical weather prediction

Generic requirements for numerical weather prediction are gathered in the same way as for Nowcasting by extracting values from the WMO database. Table 3.3 explicitly includes users requiring data for regional and/or mesoscale NWP models. In general, the requirements for global and regional NWP are very similar except that horizontal sampling better than 50 km and timeliness better than 1 hour are preferred for regional NWP applications.

For use in nowcasting applications it was made clear that the primary goal of the GPS Meteorology Networks should be to provide humidity products. However, from several NWP assimilation trials (see Chapter 6) and from the processing practices highlighted in Chapter 4 it is clear that non-geophysical (Level 1b) products may be the preferred deliverable of the networks for many NWP users. Centres applying variational data assimilation methods may prefer the use of ZTD or Slant delay to the use of IWV. In case an NWP centre needs IWV that quantity can be derived from ZTD using the methods indicated in Chapter 2. NWP centres are naturally in a better position to overcome the problem of missing meteorological data than network operators having to use approximations for these. Given this, the main difference with the tables of Section 3.1 is the introduction of zenith total delay and slant delay in Table 3.4. Differences between Table 3.3 and Table 3.4 stem from a stricter interpretation of present day capabilities of NWP systems. Again, an integration time requirement is added to ensure uncorrelated samples. It should also be noted that the absolute accuracy range quoted here is rather general and should be better in wintertime with lower humidity budgets.

Table 3.3: Generic User Requirements for Numerical Weather Prediction.

	IWV	**IWV**
Horizontal Domain	Global	Regional
Horizontal Sampling	50–500 km	10–250 km
Repetition Cycle	1–12 hrs	0.5–12 hrs
Absolute Accuracy	1–5 kg/m^2	1–5 kg/m^2
Timeliness	1–4 hrs	0.5–2 hr

Table 3.4: GPS Meteorology Network Requirements for Numerical Weather Prediction.

	Zenith Total Delay or Slant delay	
Horizontal Domain	Global	Regional
Horizontal Sampling	50–300 km	30–100 km
Repetition Cycle	30 min–2 hrs	15 min – 1 hr
Integration Time	MIN(30 min, rep cycle)	MIN(15 min, rep cycle)
Absolute Accuracy	3–10 mm	3–10 mm
Timeliness	1–2 hrs	30 min–1.5 hrs

For example, the mean IWV value in January (2002–2004) observed in Ny-Ålesund (Svalbard, Norway) is around 2 to 3 kg/m^2; in July (2001-2003) this monthly mean value is around 11 to 12 kg/m^2. The spread for both the winter and the summer month is around 2 kg/m^2. In a more southerly located site, Noto (Sicily, Italy), January values of 11 to 12 kg/m^2 and July values of 25 to 27 kg/m^2 were observed. For this site the spread is 4 kg/m^2 in the winter and 6 kg/m^2 in the summer.

3.3 Requirements for climate

Table 3.5 illustrates in a similar way the user requirements for the climate community, in particular those for climate monitoring and prediction where trends in the past and future are analysed. The noteworthy requirement is for long-term system stability. For climate monitoring it is necessary that the data are homogeneous and do not drift by any insufficiency of the instruments, the surrounding measurement site, or changes in the processing. According to the climate monitoring principles fostered by the Global Climate Observing System (GCOS), the quality and homogeneity of data should be regularly assessed as a part of routine operations whereas the details of local conditions, instruments, operating procedures, data processing algorithms and other factors pertinent to interpreting data, i.e. the meta-data, should be documented and treated with the same care as the data themselves. Climate prediction models and studies performed with re-analysed meteorological data show that trends between 0.1–0.4 kg/m^2/decade in the global, yearly averaged atmospheric water vapour content can be expected (Bengtsson et al., 2004). For specific (dry) regions these numbers may even be smaller. This is far less than the measurement accuracies of the GPS system at present but also less than the variations seen in local biases. The significance of any trend detected is therefore extremely sensitive to long-term system stability. A value for the long-term stability near zero is theoretically right and is to be preferred but may be practically unrealistic. The requirement for this is therefore expressed as an acceptable drift of the bias on the order

Table 3.5: Generic User Requirements for Climate Monitoring and Prediction.

	IWV
Horizontal Domain	Regional–global
Horizontal Sampling	10–100 km
Time Domain	>> 10 years
Repetition Cycle	1 hr
Absolute Accuracy	0.25–2.5 kg/m^2
Long Term Stability	0.02 0.06 kg/m^2/decade
Timeliness	3–12 hrs

Table 3.6: GPS Meteorology Requirements for Climate Monitoring and Prediction.

	IWV
Horizontal Domain	All
Horizontal Sampling	10–250 km; individual stations
Time Domain	Weeks to many years
Repetition cycle	1 hr
Absolute Accuracy	1 kg/m^2
Long Term Stability	0.04–0.06 kg/m^2/decade
Timeliness	1–2 months

of 10–30% of the expected trend within any decade. Except for this requirement, if the requirements for operational meteorology are met, those for climate applications will be so too. The requirement for timeliness stems from the WMO/GCOS requirements as found in WMO documents (web-based database WMO/CEOS). It may be applicable to some applications, but it is felt that this requirement can in general be relaxed.

A climate user is probably not only the end user of a climatological product. Therefore a climate user will not only be interested in time- and space averaged values but preferably in the values in full resolution in time and space as specified in Table 3.5. Three dimensional (3D) analysis fields from an NWP assimilation may be one option for deriving gridded data but as long as the influence of the NWP model on the result is still a matter of discussion this should not be the only option. The climatologist will always be interested in the most independent data. Climate users may not make direct use of zenith (total or wet) delays; they are likely to either use temporally and spatially averaged water vapour columns, or use 3D analysed fields, which have assimilated GPS ground-based meteorology data via NWP systems. Table 3.6 reflects the average requirements for any realistic network of GPS ground receiver equipment.

Several notes apply to this table:

1. Ideally, data for global studies are sampled in regular 2.50° x 2.50° or 10° x 10° grids; ideally each grid box should have >40 independent observations per day. For local and regional studies (e.g. Baltex) stations are required every 100 to 200 km but not necessarily arranged in a grid. Sites chosen must reflect climate areas of interest. For special events (e.g. storms or extreme events) a higher network density, e.g. comparable to NWP network density, may be required over the region

of interest.

2. For climate monitoring the time domain should in principle be unlimited. However, for climate studies the time stretch for which data are required may be shortened to several (tens of) years. For special events (see note 1) weeks may be sufficient. For each of these studies climate accuracy is required, obtained through post-processing of the data using accurate orbit parameters.
3. Daily, monthly, yearly, mean diurnal cycle, mean daily means, mean seasonal cycle, mean yearly means over many (30 or more) years etc. are required. These are best based on an hourly repetition cycle.
4. W.r.t. Table 3.5 timeliness has increased to allow for acquisition of accurate orbit data. This has a positive impact on the absolute accuracy.

Although this does not pertain to the geophysical products (Level 2 products) a special remark should be made concerning the requirement for archiving of products. Archiving concerns the saving of processed products and its subsequent extraction. Especially climate users have an interest in extracting and reprocessing data or, alternatively, to have the archived data reprocessed. To produce useful and consistent time series, and to make any reprocessing feasible, each observation should be accompanied by all relevant meta-data, as also recognized by the monitoring principles of GCOS. These meta-data should at least include the type of meteorological station (or method of estimation) used to produce pressure and temperature data, the ZTD solution from the network processing and its error covariances, and an error estimate for the humidity product.

Chapter 4

Demonstration Experiment

Hans van der Marel

4.1 Introduction

The main task of WG 2 (Demonstration project) was to develop a near real-time (NRT) demonstration system, including all the steps from data acquisition up to assimilation into an NWP model, and to verify the operational reliability of the hardware and software codes. The near real-time demonstration system involves several analysis centres, each processing a GPS network and delivering estimates of ZTD to a gateway at the UK Met Office in the COST 716 format.

The specifications for the NRT demonstration system were defined by WG 3 (see Chapter 3). This includes the specifications from the operational meteorology, climate research and climatology communities. In order to be useful for NWP the estimates of ZTD must arrive within 1 hour and 45 minutes from the time of the first observation.

The algorithms, data flow, formats and assimilation into NWP models have first been tested on 15 days of GPS data which were processed off-line, but to near-real time quality, using a benchmark data set spanning the period of June 9–23, 2000. The benchmark data set was processed by 7 analysis centres.

The first observations for the NRT demonstration system were processed in February 2001. The near-real time demonstration started with two analysis centres, but soon included six out of seven analysis centres that participated in the benchmark data set. Later during the project four additional analysis centres became involved in the near real-time demonstration. The system consisted in March 2004 of about 420 stations processed by 10 analysis centres in near real-time.

In this chapter we will focus on the design of the near real-time network and the processing strategies used by each of the GPS analysis centres. Also we will present the results of the benchmark data set and inter-comparisons between the results from different GPS analysis centres, and some of the specific properties of the near real-time system. The data flow and monitoring of the near real-time system and its applications are discussed in Chapters 5 and 6, respectively.

4.2 Design of the near real-time network

One of the main goals of COST 716 is to demonstrate that it is possible to use data from ground based GPS for operational meteorology. For this reason a near real-time demonstration was organized using existing GPS infrastructure and analysis centres. The purpose of the near real-time demonstration is threefold:

1. Proof that GPS networks can provide properly validated ZTDs in near real-time
2. Create a data set that can be used to assess the impact on NWP applications
3. Establish data formats and procedures, and verify hardware and software codes in an operational manner

Because we wanted to use existing GPS infrastructure it was decided to organize the GPS processing around several near real-time networks, each handled by an analysis centre.

In order to be useful for meteorology and climate applications, the networks should cover at least Europe and as much as possible of the Northern Atlantic. Figure 4.1 and Figure 4.2 give an impression of the geographical distribution of the stations in March 2004 with their analysis centres. Please note that only analysis centres are indicated. The data providers, on which the analysis centres rely for the data, are not listed in Figure 4.1 and Figure 4.2. A list of data providers can be found at the end of this chapter. The density and size of the networks primarily depends on the number of stations, within each area, which can provide NRT data, and can be handled by each network. Because the ZTD will be assimilated directly into NWP models the stations do not necessarily have to be equipped with meteorological sensors.

The analysis centres that are taking part in the near real-time demonstration are:

ASI	Agenzia Spaziale Italiana, Matera, Italy
ACRI	ACRI-ST, Valbonne, France
BKG	Bundesamt für Kartographie und Geodäsie, Frankfurt, Germany
GFZ	GeoForschungsZentrum Potsdam, Potsdam, Germany
GOP	Geodetic Observatory, Pecný, Czech Republic
IEEC	Institut d'Estudis Espacials de Catalunya, Barcelona, Spain
LPT	Federal Office of Topography, Wabern, Swiss
NKG	Nordic Geodetic Commission, Norwegian Mapping Authority, Norway
NKGS	Nordic Geodetic Commission, Onsala Space Observatory, Sweden
SGN	Institut Geographique National, Paris, France

The near-real time demonstration started in February 2001 with two analysis centres, GeoForschungsZentrum Potsdam (GFZ), Germany and Geodetic Observatory Pecný (GOP), Czech Republic. GOP is processing a European network with stations from the UK, Belgium and the Netherlands (Douša, 2002b), while GFZ contributes stations from the German Atmospheric Sounding Project (GASP) network (Gendt et al., 2004), with some of the Dutch and French data. Institut d'Estudis Espacials de Catalunya (IEEC), Barcelona, Spain, Agenzia Spaziale Italiana (ASI), Matera, Italy and the Federal Office of Topography (LPT), Wabern, Switzerland joined the demonstration network in respectively May, June and December 2001. ASI and IEEC are contributing two networks centred on the Mediterranean from the MAGIC campaign (Flores et al., 2000; Haase et al., 2001; Pacione & Vespe, 2003). LPT is processing a very dense Alpine network centred on Switzerland, with some of the French stations (Brockmann et al., 2001). The Nordic Geodetic Commission is processing mainly two sub-networks

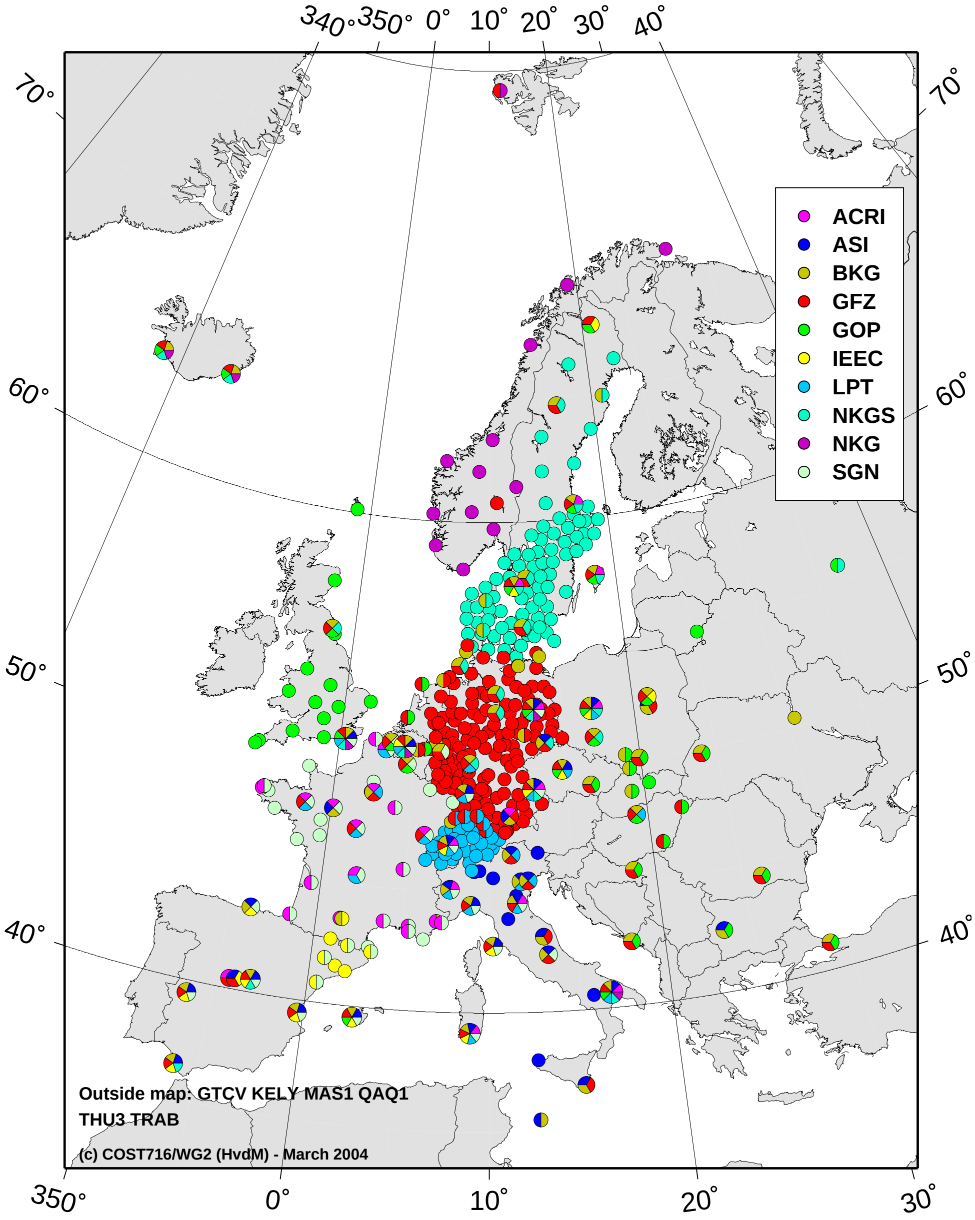


Figure 4.1: GPS stations in the near real-time network demonstration and analysis centres processing the data (March 2004).

of Scandinavian stations. The Norwegian stations are processed by the Norwegian Mapping Authority, Norway (NKG), together with a number of global stations for orbit determination. They started to contribute data in April 2002, after having participated for a short period in October 2001. Onsala Space Observatory, Sweden (NKGS), is providing a dense network for Sweden, and has in 2003 added a large set of Danish stations. In 2003 two more analysis centres came on-line, increasing the number of analysis centres to nine. They are ACRI-ST (ACRI), Sophia Antipolis, France, taking over one of the MAGIC networks that was originally processed by CNRS, France (Haase et al., 2001), and Institut Geographique National (SGN), Paris, France, processing stations from the French network. Finally, in 2004, the Bundesamt für Kartographie und Geodäsie (BKG) in Frankfurt, Germany, started to contribute a European

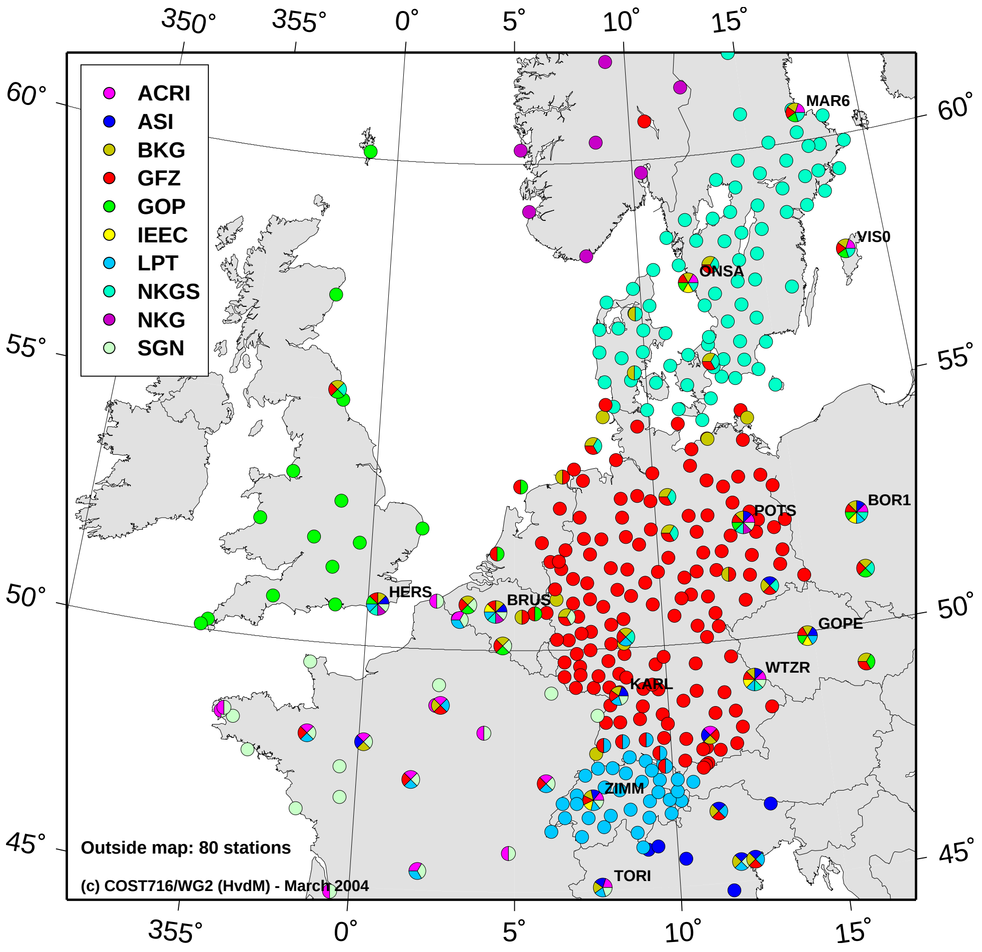


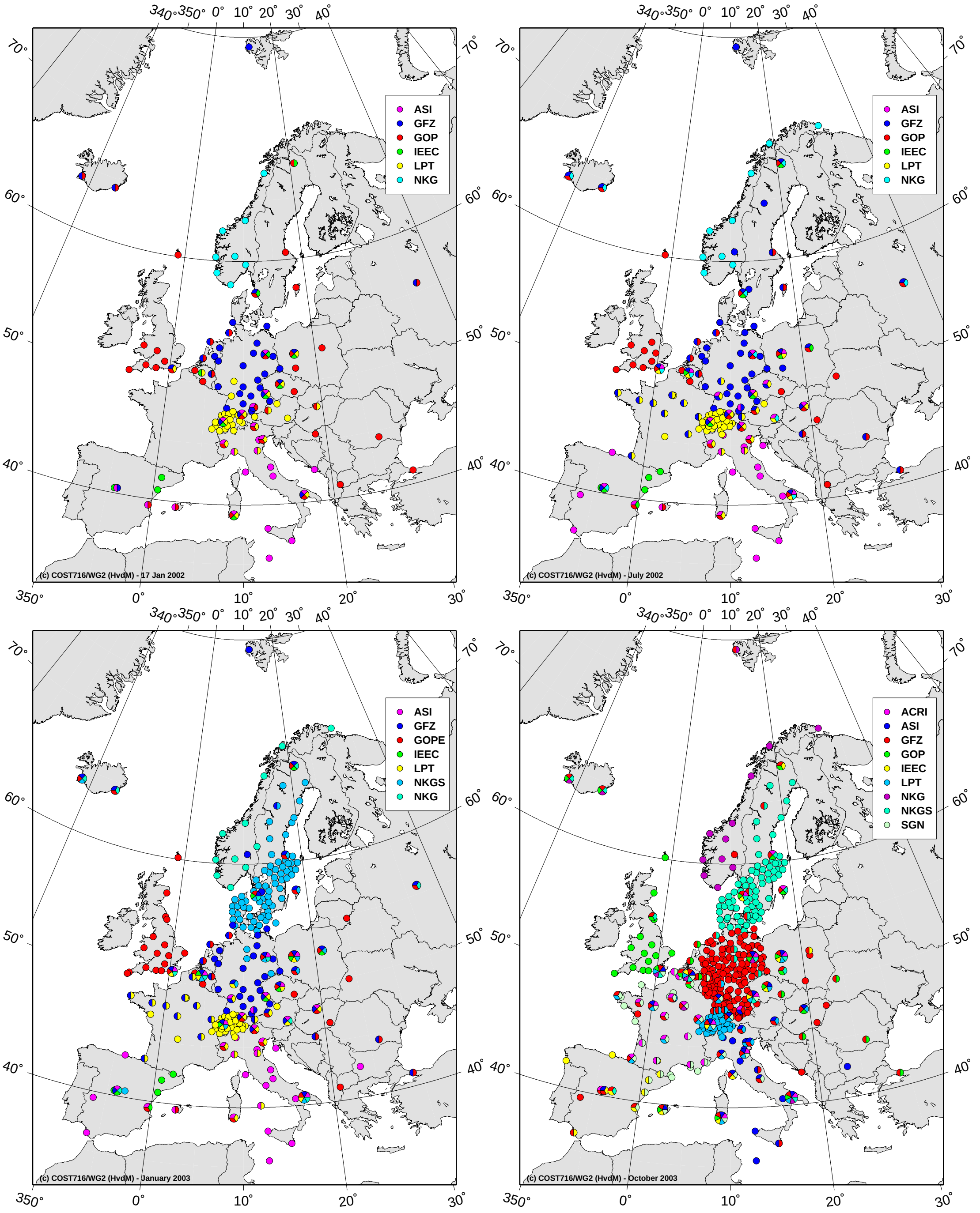
Figure 4.2: Detail of the near real-time demonstration network (March 2004).

data set, bringing the total number of analysis centres to 10. In addition to stations in their target area most of the ACs are analysing sites from the European Permanent GPS Network (EPN) and IGS network as well.

The evolution of the near real-time network is shown in Figure 4.3, giving the network status in January 2002, July 2002, January 2003 and October 2003. The current status, March 2004, is shown in Figure 4.1. Figure 5.3 in Chapter 5, gives an overview of evolution of the number of stations in the near real-time demonstration from May 2001 until March 2004.

In July 2002 six analysis centres were active processing a network of 150 stations, of which 69 stations were processed by GFZ, 43 by GOP, 35 by ASI, 13 by IEEC, 60 by LPT and 23 by NKG. GFZ and NKG each are also processing about 25–35 globally distributed stations which we have not counted. About 26 stations are processed by two analysis centres, 12 stations are processed by 3 analysis centres, 9 stations are processed by 4 analysis centres and 4 stations are processed by 5 analysis centres. The remaining 99 stations are processed by one analysis centre.

In October 2003 the network consisted of a total of 385 stations, as shown in Figure 4.3, of which 216 stations were processed by GFZ, 40 by GOP, 34 by ASI, 25 by IEEC, 56 by LPT, 20 by NKG Norway, 98 by NKG Sweden, 30 by ACRI and 48 by SGN. GFZ is also processing about 25 globally distributed stations. About 38 stations are processed by two analysis centres, 21 stations are processed



(c) COST716/WG2 (HvdM) - 17 Jan 2002

(c) COST716/WG2 (HvdM) - July 2002

(c) COST716/WG2 (HvdM) - January 2003

(c) COST716/WG2 (HvdM) - October 2003

Figure 4.3: Evolution of the COST 716 near real-time GPS network showing the GPS stations and analysis centres in January 2002, July 2002, January 2003 and October 2003.

by 3 analysis centres, 12 stations are processed by 4 analysis centres, 5 stations by 5 analysis centres, 2 by 6 analysis centres and 6 stations are processed by 7 analysis centres. The remaining 301 stations are processed by one analysis centre.

Finally, in March 2004, the network consisted of 424 stations. BKG added 83 stations to the network, but only 12 of them were new additions. The number of stations processed by the other analysis centres did not change significantly: 35 by ACRI, 41 by ASI, 208 by GFZ, 52 by GOP, 24 by IEEC, 61 by LPT, 109 by NKGS, 20 by NKG and 55 by SGN. About 44 stations are processed by two analysis centres, 23 stations are processed by 3 analysis centres, 19 stations are processed by 4 analysis centres, 11 stations by 5 analysis centres, 5 by 6 analysis centres, 2 by 7 analysis centres and 6 stations are processed by 8 analysis centres. The remaining 313 stations are processed by one analysis centre. Six sites have co-located receivers, therefore, the actual number of sites is 418, while the number of receivers (stations) is 424. The actual number of stations observed at any given time is a little less because of occasional station outages.

Stations are identified by a unique 4-letter code. On one occasion, two analysis centres used the same 4-letter code for different stations (TRYS). Also, the other way round happens: 6 stations using the same receiver were given different 4-letter codes by two analysis centres. Furthermore, there are also sites which operate more than one receiver and where analysis centres choose to process different receivers, or decided to process both receivers simultaneously. This is the case for 6 sites, and for 5 of them a analysis centre is processing both receivers simultaneously.

Each of the contributing analysis centres was relatively free to organize the processing as they think is best, as long as (i) properly validated ZTD with a well defined quality indicator are computed, and (ii) these data are made available within 1 hour and 45 minutes to a FTP gateway at the UK Met Office using hourly files in the COST 716 format. The time limit has been set by WG 3 based on requirements for NWP applications.

This means that the analysis centres are free to decide which stations they process, to choose the software and processing strategy they use and the interval at which ZTD parameters are estimated. The reason for this strategy is very straightforward. Within COST only support is given for coordination of activities. There is no funding to buy any hardware or support analysis centres. So, COST 716 has to build upon existing projects and initiatives. Another reason for not having strict guidelines is that, by having different analysis centres and strategies, it is possible to evaluate the advantages and disadvantages of each approach.

As each network handles the data issues within its own area, COST 716 has access to data that is not in the public domain or on anonymous FTP servers. Therefore, COST 716 is not limited to data available from only IGS and EUREF, but the spacing between the stations can vary significantly among the networks, as can be seen in Figure 4.1. In addition, each analysis centre will also need data outside its area in order to be able to (i) give absolute estimates of ZTD and (ii) improve orbits in near real-time.

The analysis centres use different strategies and software packages. The main characteristics of the various processing strategies are discussed in Section 4.3 and the general characteristics are given in Table 4.1.

For the exchange of ZTD data the COST v2.0 format is used. COST v2.0 is an ascii format that can be converted easily into BUFR, the standard binary data format used on the GTS network, so that it can be inserted in the regular ’meteorological’ data flow on a continuous basis. A proposal for a BUFR specification for GPS has been submitted to WMO and was approved by WMO to use on the GTS. The COST format has been adapted from the CLIMAP format to include slant delays, processing statistics, q/c information and includes also surface meteorological data and IWV. Although the COST format has been adapted to include slant delays none of the contributing networks is providing slant delays today. However, in view of the potential application of slant delays, see e.g. MacDonald et al. (2002) and Pany (2002), it was decided to define the format to handle also this data type. COST files can contain data for more than one station (virtual files). The COST 716 files are uploaded once per hour by the GPS analysis centres to an FTP gateway at the UK Met Office, where they remain on-line for one week. The data are mirrored by an FTP server in Delft, which also maintains an archive of all the data on-line. However, the COST format does not contain any co-variance matrix information, which would be needed for a combined product.

Presently, it is not foreseen to combine the ZTD estimated by individual networks, but to make results available as soon as possible. This means that for some stations two or more estimates of the ZTD will be available from different analysis centres. A combination step would only delay the results, and add an additional layer of complexity. Also, combination of results is not advisable because the analysis centres do not follow the same guidelines or use the same software, and therefore, a pure mathematical combination could degrade the individual results. Only a physically meaningful verification with NWP models or more precise post-processed data can show the properties of the individual solutions. Because we do not plan to combine the ZTDs, we can have different types of networks (regional and mesoscale) and different analysis strategies involving different sampling rates for the ZTD.

The planned duration for the trial in the Memorandum of Understanding of COST 716 was three months. However, even before the near real-time demonstration started, it was expected that the setting-up of the processing is a more costly and labour intensive task than the routine processing itself. So, at the start of the demonstration project it was already anticipated to run the demonstration at least one year. In the end the near real-time demonstration just continued to grow and it was decided not to stop during the COST 716 action. After the end of the COST 716 action the near real-time demonstration system continued to be run, with six analysis centres contributing from the European TOUGH project and four analysis centres participate on a voluntary basis.

The present approach was mainly intended for the NRT demonstration that has started in February 2001. It is likely that for operational work a different organization is needed. An important deliverable of the near-real time demonstration is an assessment of equipment and expertise needed to run the processing at meteorological institutes, without requiring too much geodetic expertise. These issues will be addressed in Chapter 7.

4.3 Processing strategies

4.3.1 Introduction

Each of the contributing analysis centres was relatively free to organize the processing as they thought was best, as long as properly validated ZTD with a well defined quality indicator is computed, and these data are made available within a target of 1 hour and 45 minutes to a FTP gateway at the Met Office using hourly files in the COST v2.0 format. This means that the analysis centres are free to decide which stations they process, to choose the software and processing strategy they prefer and the interval at which ZTD parameters are estimated. One reason for not having strict guidelines is that, by having different analysis centres and strategies, it is possible to evaluate the advantages and disadvantages of each approach. Although maybe advisable for a demonstration project, this does not necessarily mean that this should be the adopted strategy in an operational phase. In the operational phase it should be considered to adopt the same strategy for all analysis centres involved.

The ZTD is estimated along with several other geodetic parameters. The parameters that are estimated depend to a large extend on the domain of the GPS network. For example, to estimate precise satellite orbits and Earth rotation parameters (ERP) a world-wide network like the network of the International GPS Service (IGS) is needed. Other parameters that are estimated — in global, regional and local networks alike — are the daily station coordinates, satellite and receiver clock errors, ZTD and phase ambiguities. Delays due to the ionosphere are estimated by using a linear combination of phase measurements on two frequencies, thereby eliminating the first order ionosphere delay. Other short periodic effects, such as solid earth tides, ocean loading, phase wind-up, antenna elevation dependent delays, etc., are taken care of by using a-priori models.

Two different strategies can be used for the processing of local and regional networks:

1. Network approach using zero or double differences
2. Precise Point Positioning (PPP) approach

In the network approach several stations are processed together in a single least-squares adjustment or filter. If the network is large enough (global) satellite orbits and ERP parameters can be estimated, but more often in regional and local network satellite orbits and ERP parameters from IGS are used as-is without orbit estimation or relaxation, i.e. as a-priori data. Station coordinates, satellite and receiver clock parameters, ZTD and phase ambiguities are estimated in the least-squares adjustment.

In the Precise Point Positioning (PPP) approach both previously estimated satellite orbits and ERP, as well as satellite clock parameters, are used as a-priori data. Therefore, only station dependent parameters have to be solved in the PPP: station coordinates, epoch-wise station clock parameters, ZTD and phase ambiguities. One of the advantages of the PPP approach is that the processing can be done station by station instead of a network. In other words, the PPP approach will also work for a single station. This means that for a network of stations the computation time for the PPP is growing linearly with the number of stations, whereas in the network approach the computing time includes also a significant quadratic component. The downside of the PPP approach that it is much more difficult to estimate integer phase ambiguities, as is often done in the network approach (this is only possible in the PPP approach when several stations are processed together). However, as we will see later, most of the analysis centres which use a network strategy also refrain from estimating integer ambiguities.

It is essential in the PPP approach that orbits, ERP and satellite clock parameters are of excellent quality and come from the same source. These parameters are in general highly correlated. This is in particular a problem for near-time applications, because the IGS ultra-rapid products cannot provide an accurate clock prediction. Therefore, for near-real time applications the PPP is often preceded by a global network adjustment in order to get good orbits and satellite clocks, or near-real time satellite orbits and clocks from an other analysis centre is used.

Within the network approach broadly two different approaches exist: double and zero difference processing. In the double differencing approach the satellite and receiver clock parameters are eliminated on an epoch-by-epoch basis by forming differences of the observations. First, observations of two different receivers to the same satellite are subtracted, eliminating the satellite clock parameters, giving the so-called single difference. Next, two single differences are subtracted to eliminate the receiver clock parameter, giving the double difference. This greatly reduces the amount of parameters to be estimated in the batch least squares adjustment, leaving only station coordinates, phase ambiguities and ZTD to be estimated. In the zero-difference approach the satellite and receiver clock parameters are estimated along with the other parameters, usually using a Kalman-filter type of approach. The zero difference and double difference approach give in theory identical results, although the implementation in software may result in small differences.

The main advance of the double difference least-squares approach is that it results in normal equations, which later on can be combined to constrain the solution or combine different estimates. The main advantage of the zero difference approach is that it is a little bit more flexible with respect to changes in the tracking configuration. The other advantage is that it usually uses a Kalman filter (although a Kalman filter is sometimes also used in single or double difference processing), and is therefore is a little more flexible in modelling the time-behaviour of parameters such as ZTD.

The domain of the GPS network is important when using the network approach. In a local network only coordinate and ZTD differences between two stations can be estimated; this is because the satellite clock parameters have to be estimated as well. Absolute ZTDs can be estimated only when the network is covering a reasonable region, because then the same satellite is seen from different elevation angles at different stations that allow one to estimated both satellite clock parameters as well as absolute ZTD. It is for this reason that the analysis centres are processing a regional network, and not only a national network. Nevertheless, the size and domain of the networks within COST 716 are very different.

4.3.2 COST 716 processing strategies

The analysis centres use different software packages and analysis strategies, as outlined in Table 4.1. Four different software packages are used: EPOS from GFZ, GIPSY-OASIS II from Jet Propulsion Laboratory (JPL) of NASA, used by NKG, NKGS, ASI and IEEC, GAMIT from MIT which is used by ACRI, and the Bernese GPS software v4.2 (BSW) from the University of Berne, used by BKG, GOP, LPT and SGN.

GFZ and NKGS use Precise Point Positioning (PPP). GFZ computes its own orbits, clocks and Earth Rotation Parameters (ERP) using a network of 25 global stations. NKGS uses IGS Ultra Rapid orbits (IGU), but processes first a 20 station global network in network mode in order to improve orbits and estimate satellite clocks at intervals not provided by the IGS orbits.

The other analysis centres use a network approach. ACRI, ASI, BKG, IEEC and NKG use a sliding window approach (NET), while GOP, LPT and SGN, process the data on a hourly basis, and then stack the normal equations over the selected period (NEQ). The analysis centres using the network approach are using IGS Ultra Rapid orbits (IGU), except IEEC and NKG who are using JPL's rapid 15 minute orbits (JPL15). Previously, also NKG used 30–35 global stations to improve orbits and clocks, starting with IGS Ultra Rapids and based on ITRF2000, using a PPP strategy, but changed to the current procedure in 2003. In the network approach the satellite clocks are either estimated in case of network processing with GIPSY (undifferenced data), or eliminated by double differencing in case of BSW and GAMIT.

With the network approach it is not necessary to do orbit estimation. The present day accuracy of the IGS ultra rapid orbits is sufficient for the network approach. However, all analysis centres check the accuracy codes in the satellite orbits to exclude bad satellites, and ACRI uses orbit relaxation to relax three of the orbital parameters. To increase the robustness of the NRT processing ACRI, ASI, GOP IEEC, LPT and SGN also check the post-fit residuals to exclude possibly more bad satellites. ACRI, ASI, IEEC, GOP and LPT not only remove bad satellites automatically, but also remove bad stations using post-fit phase residuals. In general, when bad satellites and/or stations are removed, the processing times increase by about a factor two.

GOP is also providing ultra rapid orbits using a 3-hour update rate, as alternative to the IGS Ultra Rapid Orbits, and has studied its application within the COST 716 project (Douša, 2004). During a 3-month test period both GOP and IGS ultra rapid orbits were used, giving similar statistical results in terms of ZTD quality, though occasionally some stability problems were observed in both orbit products.

Only IEEC is estimating station coordinates simultaneously with the ZTD parameters in the near real-time processing. The other analysis centres keep the coordinates fixed onto values from ITRF or coordinate solutions computed by post-processing using longer time spans of GPS data (Pacione & Vespe, 2003; Gendt et al., 2004; Douša, 2002b; Haase et al., 2001; Brockmann et al., 2001). The coordinate

Table 4.1: Processing Options for the NRT Demonstration (March 2004).

	GFZ	**NKGS**	**NKG**	**ASI**	**IEEC**	**ACRI**	**BKG**	**GOP**	**LPT**	**SGN**
software	EPOS	GIPSY	GIPSY	GIPSY	GIPSY	GAMIT	BSW	BSW	BSW	BSW
strategy	PPP	PPP	NET	NET	NET	NET	NET	NEQ	NEQ	NEQ
Initial data:										
orbit	GFZ	IGU	JPL15	IGU	JPL15	IGU	IGU	IGU	IGU	IGU
ERP	GFZ	IGU	JPL15	IGU	JPL15	IERS	IGU	IGU	IGU	IERS
clocks	GFZ	-	-	-	-	-	-	-	-	-
Orbit/clock estimation:										
orbit/clock	both	both				3 orb $^{a)}$				
window	12h	24h				9h				
sites	25	20								
cpu	8m	10m								
Coordinate estimation:										
method	pp(PPP)	pp(PPP)	pred	pp(PPP)	$^{b)}$	pp	pp	nrt	pp $^{c)}$	pp
window	7 days	1 month	-	1 month	-	8 days	7 days	7 days	1 month	years
updates	daily$^{d)}$	monthly	-	monthly	-	quarterly	quarterly	daily	monthly	
ref.frame	ITRF00	ITRF00	ITRF00	ITRF00	ITRF00	ITRF00	ITRF00	IGS00	ITRF00	ITRF00
fiducials	all IGS	all IGS	none	17		5	13	all IGS	all IGS	sel.
$\sigma_{fiducial}$	1mm	1 mm		0.1 mm		3/6mm				
σ_{crd}	100 m	100 m				20/50mm				
Parameter estimation:										
window	12h	8h	12h	24h	12h	9h	4h	12h	7h	3h
interval	150s	300s	900s	300s	300s	60s	120s	30s	30s	30s
cutoff	7.5^o	15^o	10^o	10^o	10^o	10^o	10^o	10^o	10^o	10^o
σ_{obs}	$\cos z$	10 mm	10 mm	10 mm			$\cos z$	$\cos z$	$\cos z$	$\cos z$
coordinates	fixed	fixed	fixed	fixed	est.	fixed	fixed	fixed	fixed	fixed
gradients	yes	yes	yes	no	yes	no	no	no	no	no
oc.loading	Pgtks	Schrnck	Schrnck	Schrnck	Schrnck	Schrnck	Schrnck	Schrnck	Schrnck	Schrnck
PCV	IGS_01	IGS_01		IGS_01	IGS_01	IGS_01	IGS_01	IGS_01	IGS_01	IGS_01
exclusions	-	-	sat&sta	sat&sta	sat&sta	sat&sta	-	sta&sat	sta&sat	sat
sites	220	120	23	41	28	35	81	52	63	55
start time	hh:30	hh:20	hh:15	hh:18	hh:25	hh:30	hh:25	hh:30	hh:37	
cpu	6m	15m	5m	50m		20m	15m	20-30m	20m	25m
ZTD modelling:										
ZTD_0	Saast	exp(h)	exp(h)	exp(h)	exp(h)	Saast	-	-	-	-
mf_0	hNmf	hNmf	hNmf	hNmf	hNmf	hNmf	-	-	-	-
mf	wNmf	wNmf	wNmf	wNmf	wNmf	wNmf	hNmf	hNmf	hNmf	hNmf
method	pc/rw	rw	rw	rw	rw	pl	pc	pc	pc	pc
constraints	$2\mathrm{cm}/\sqrt{\mathrm{h}}$	$1.02\mathrm{cm}/\sqrt{\mathrm{h}}$	$1.02\mathrm{cm}/\sqrt{\mathrm{h}}$	$2\mathrm{cm}/\sqrt{\mathrm{h}}$	$1.02\mathrm{cm}/\sqrt{\mathrm{h}}$	$2\mathrm{cm}/\sqrt{\mathrm{h}}$	20mm	1.2mm	1.2mm	no
interval	30m	15m	15m	5m	10m	15m	60m	60m	60m	60m
epochs	14,44	0:15:45	0:15:45	0:15:45$^{e)}$	0:10:60	0:15:45	30	30	30	30
σ_{ZTD}	LSQw	LSQ		LSQ			LSQw	LSQw	LSQw	LSQw
max σ_{ZTD}	none	20 cm	20 cm	none			1cm		1cm	

a) Automatic re-weighting of 3 orbital parameters included with main parameter estimation.

b) Included with main parameter estimation.

c) Coordinates changed if difference exceeds 2 cm, else ITRF.

d) Coordinates are monitored daily and changed if necessary.

e) Averaged from 5 minute estimates.

solutions are updated regularly, e.g. in monthly intervals using post-processing (pp), sometimes using PPP, or using a multi-day combination of normal equation stacking (GOP). In Table 4.1 the update interval for the coordinates has been indicated (updates), the period over which the coordinates are computed (window), the number of fiducial stations that are used in the coordinate computation (fiducial) and the reference frame (ref.frame). GFZ monitors the coordinates daily and changes the coordinates when a change in the mean of daily repeatabilities is detected, using the average position of the last weeks' results. Also, a monthly check of the coordinates is made based on post-processed results. The section on coordinate estimation in Table 4.1 contains information on the actual constraint that is used for the fiducial station coordinates, as well as the other coordinates. If two values are given, then the first is the constraint for the horizontal coordinates, and the second is the constraint for the height coordinate.

All analysis centres use ocean loading, polar tides and solid earth tides corrections. Most analysis centres are using the ocean loading model and parameters by Scherneck (1991), except GFZ who is using the ocean loading model from Pagitakis (Pgtks).

The Bernese GPS software and EPOS (GFZ) uses elevation dependent weighting for the observations ($\cos z$). The standard deviation of the phase observations is

$$\sigma_{obs} = \hat{\sigma}_0 / \cos z \tag{4.1}$$

with z the zenith angle of the satellite as seen from the receiver, and $\hat{\sigma}_0$ the so-called standard deviation of unit weight estimated from the least-squares residuals. The a-priori σ_0 for the analysis centres using the Bernese software is 1 mm when using elevation dependent weighting ($\cos z$), and 2 mm without elevation dependent weighting (this is the standard deviation for a undifferenced L1 observation, the standard deviation for the ionosphere free linear combination is at least a factor three larger). This is important to know as this acts as a scale factor for the constraints. The other analysis centres use a constant for the standard deviation of the ionosphere free observations (σ_{obs}), as is indicated in Table 4.1.

Another important piece of information in Table 4.1 is which correction model for the antenna Phase Centre Variations (PCV) is used. Most analysis centres uses the model provided by IGS. Having the antenna phase centre corrections wrong, or using the wrong antenna type, will result in biases in the ZTD.

All of the analysis centres compute phase ambiguities, but none of them is trying to resolve the integer values for the double-difference phase ambiguities. Whenever analysis centres tried to resolve the phase ambiguities to integer values, the repeatability of the ZTD parameters became worse. Obviously, integer ambiguity resolution is extremely difficult in the near real-time processing because satellites might just have risen above the horizon during the last hour and their ambiguities may have large standard deviations. Also, the length of the window is shorter than during post-processing, and the quality of the orbits is not as good as during post-processing.

4.3.3 ZTD modelling options

An important part of Table 4.1 is dedicated to the modelling options for the ZTD parameter. There are significant differences between the analysis centres in the way they represent and estimated the ZTD.

In the GPS processing the Slant Total Delay (STD), denoted $\ell_{tot}(\varepsilon)$ in Equation (2.12), is calculated by using the functions mapping functions for the hydrostatic and wet delays together with their equivalent zenith values. The mapping functions and zenith hydrostatic delay have to be known a-priori; only the ZWD is estimated along with the other geodetic parameters. The ZHD and ZWD cannot be estimated both at the same time as this would destabilize the overall system. This is because the two mapping functions, although different, are still very similar and the number of available satellites is simply too small to distinguish both effects. The mapping functions most commonly used for GPS are the Niell hydrostatic mapping function (hNmf) and Niell wet mapping function (wNmf) which were computed by ray-tracing several years of radiosonde profiles (Niell, 1996). The Niell mapping functions are functions of elevation, latitude, altitude, and day of year. (See also Table 4.1.) The model for the STD is sometimes extended with additional parameters for horizontal gradients (which have their own mapping functions), which are estimated along with the ZWD.

The ZHD can be approximated using an estimate or accurate measurement of the surface pressure, or more precisely the pressure at the height of the GPS antenna (Saastamoinen, 1972). However, during the GPS data processing stage usually no accurate ground-pressure measurements are available to compute the ZHD, and thus an approximated value for the ZHD is computed. Several approaches are used, see Table 4.1:

- the a-priori ZHD is set to zero and the ZTD is estimated (as ZWD) using a single mapping function (BKG, GOP, LPT, SGN),
- the ZHD is computed using the model by Saastamoinen (1972) with meteorological parameters computed from a standard atmosphere with the height of the station above mean sea-level as input (GFZ)
- same as above, but including also an a-priori wet delay (ACRI)
- using the expression $\text{ZHD}_0 = 2.276 \times 1.1013\, e^{-h/H}$, with h the geodetic station height and $H = 8.621$ km a scale factor (ASI, NKG, NKGS, IEEC).

The estimated ZWD is not free from bias. The effect on the ZTD is, however, very small, as is illustrated by the following equation

$$\ell_{tot}(90^\circ) = \ell_h(90^\circ) + \ell_w(90^\circ) = \ell_{h,0} + \hat{\ell}_w + \left[\frac{m_h - m_w}{m_w} \cdot (\ell_h - \ell_{h,0})\right] \tag{4.2}$$

where $\ell_{h,0}$ is the a priori ZHD and $\hat{\ell}_w$ is the estimated value of the ZWD. The effect within the brackets may be neglected if the a priori ZHD is sufficiently close to the actual ZHD and a high quality mapping function for the hydrostatic delay is used.

From Table 4.1 it is clear that the analysis centres using the Bernese software (BSW) V4.2 cannot use an a-priori hydrostatic delay. Therefore, the BSW uses the hydrostatic mapping function instead of the wet mapping function in the estimation part. Experiments with a modified version of the Bernese software at the TU Delft have shown that this gives an error of about +3 to +4 mm in the estimated ZTD, depending on the ZWD values. Actually, this is different from the previous equation as the BSW uses the hydrostatic mapping function instead of the wet mapping function.

The way in which the ZWD is modelled, and therefore of ZTD, can be different for different GPS processing centres. The ZWD is modelled in some of the GPS analysis software as a random walk (rw) process, assuming a known a-priori power spectral density. In these cases the ZWD is estimated every epoch, but the model is further strengthened by assuming that the difference between two epochs has zero mean with a standard deviation related to the assumed power spectral density and interval. In other software packages the ZWD is modelled as a step function, or piecewise constant (pc), e.g. estimating one ZWD parameter every 20 to 60 minutes, or as a piecewise linear function. Also when the ZWD is modelled as a step function, relative constraints are applied between consecutive estimates of ZWD. The values that are used for constraining the relative ZTD parameters are given in Table 4.1 in the row “constraints”. Note that not the absolute value of the constraints is important, but the ratio with the standard deviation of the observations.

The actual interval used for the ZWD estimation updates, and therefore the interval for the ZTD, differ between the processing centres, see Table 4.1. The raw GPS data are usually provided at 30 second intervals using hourly files. However, several processing centres choose to decimate the GPS data into intervals of e.g. 5 minutes.

In Table 4.1 we have also indicated how the standard deviation for the ZTD is computed. The users of the Bernese software and GFZ compute the standard deviation of the ZTD from the inversion of the normal equations, but scale this standard deviation with the standard deviation of unit weight computed from the least-squares residuals (LSQw). The other analysis centres use the formal standard deviation (LSQ), which depends on the assumed a-priori standard deviation of the observations (which is also listed in the table). The standard deviations are certainly not homogeneous between different analysis centres, as can be seen in Section 4.4 and Figure 4.20 and 4.22.

Some of the analysis centres will not provide ZTD data if the standard deviation of the ZTD is higher than a certain threshold, max σ_{ZTD}, given in Table 4.1. ASI and GFZ do not apply a threshold. Instead, ASI does not provide ZTD for the whole network if the processing does not converge, as sometimes happens. GFZ uses other criteria for the quality check, e.g. if the number of satellites used for the estimation of ZTD on a certain interval is less than 4 GFZ does not provide the corresponding ZTD value.

The ZTD estimated by GPS are spatially correlated. This is the case both for the network and PPP approach. In the network approach errors in the a-priori satellite orbits and the estimated satellite clock parameters introduce correlations between the ZTD, which depend on the network size. In the PPP approach correlations between the ZTD are introduced because of common mode errors in the satellite orbits and clocks. Furthermore, in the near-real time processing many of the GPS processing centres fix (i.e. do not estimate) the station coordinates onto weekly and monthly averages in order to get a more stable ZTD time-series. Although this reduces the noise, it may cause small time varying biases.

Also, the ZTD estimation is very sensitive to elevation dependent effects (e.g. PCV). Errors in the calibration of satellite and receiver elevation dependent phase delays, or errors in the mapping functions, may result in small systematic effects of a few mm in the estimated ZTD. However, using the wrong antenna type in the GPS processing, or fixing the coordinates to the wrong values (e.g. after an earthquake), may result in gross-errors of occasionally up to 1–2 cm in ZTD.

4.3.4 ACRI-ST analysis centre

Olivia Lesne

ACRI-ST joined COST 716 in July 2003 by taking over the processing from CNRS, which participated in the benchmark campaign. ACRI-ST used the software and the processing strategy developed by Ge et al. (2002). The software used is the GAMIT package, developed by Massachusetts Institute of Technology and Scripps Institution of Oceanography (King, 2003). The network of GPS stations is shown in Figure 4.4. It consists mainly of stations in France (21), with an additional 12 European stations in order to facilitate the estimation of “absolute” ZTD.

The method to retrieve the ZTD parameters in near real-time over this network has been implemented operationally by CNRS in the framework of the MAGIC project (Haase et al., 1999, 2001).

Five IGS stations (ONSA, MATE, POTS, VILL, WTZR) were constrained to their ITRF00 positions using an a priori variance of 3 mm and 6 mm in the horizontal and vertical components respectively.

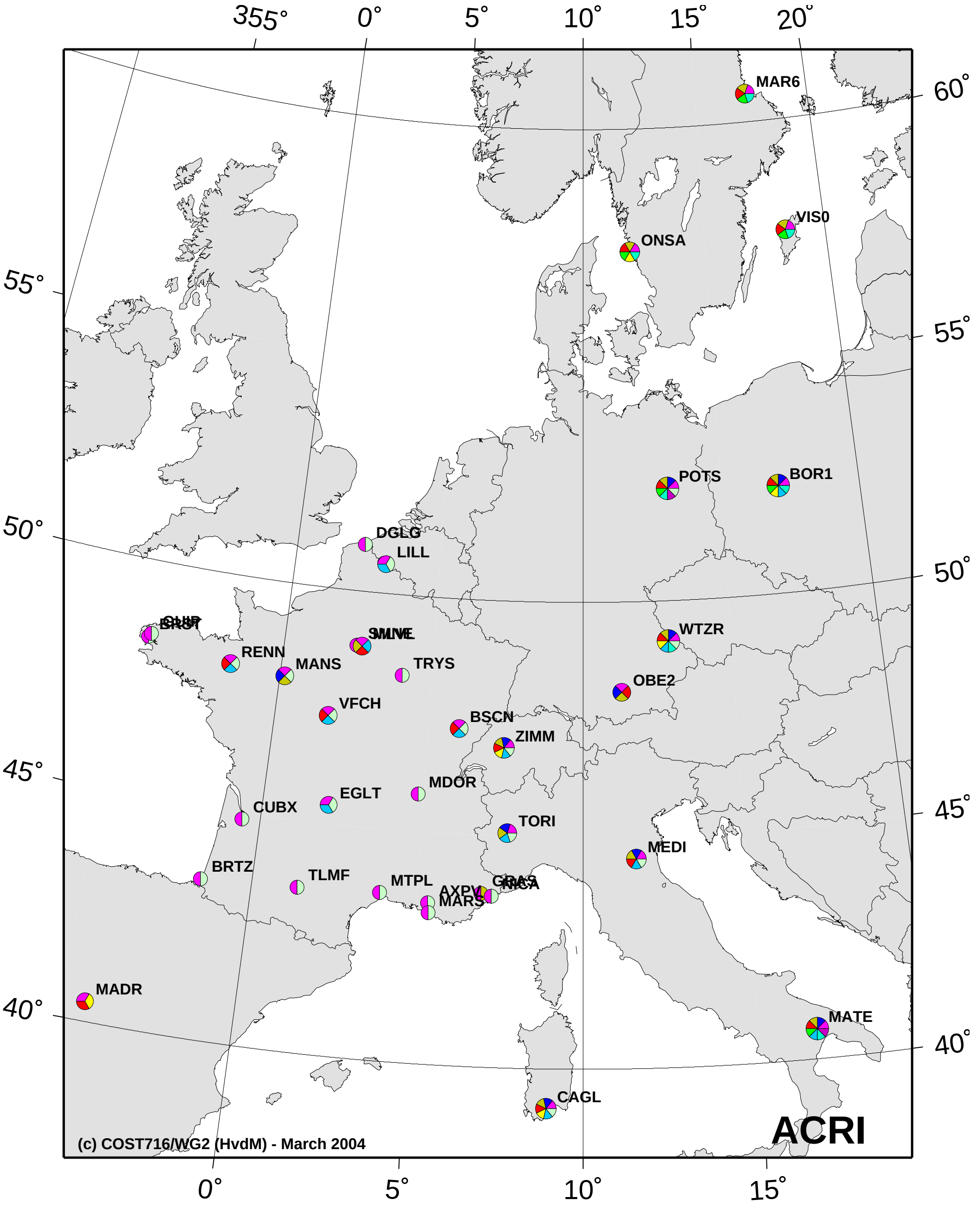


Figure 4.4: GPS stations processed by ACRI-ST (March 2004).

The other stations were constrained to positions deduced from regularly updated geodetic solution performed over a 8 days time period, using an a priori variance of 20 and 50 mm in the horizontal and vertical components respectively. The GAMIT software parameterises ZTD as a stochastic variation from the Saastamoinen model (Saastamoinen, 1972) with piecewise linear interpolation. The variation is constrained to be a Gauss-Markov process with a given a priori power density. ZTD parameters were estimated at each station every 15 minutes using a power density for the stochastic process ("tropospheric constraint") of 20 mm/$\sqrt{\mathrm{h}}$. We used the antenna phase centre variation models recommended by the IGS (Mader, 1999), the Niell hydrostatic and wet mapping functions (Niell, 1996) in order to reduce elevation dependent systematic errors (Fang et al., 1998), an elevation cut-off angle of 10°, a data sampling interval of 60 seconds, and the doubly differenced ionospheric-free combination of GPS phase observations. ZTD estimates are extracted from the end hour of the window.

The ACRI-ST processing strategy is based on the method developed by Ge et al. (2002), which consists of an iterative estimation of the constraints of one or several Keplerian parameters, estimated once per session (once every 9 hours in our case). CNRS coded this automatic orbit quality control strategy in the SOLVE module of GAMIT (King & Bock, 1999) and the operational near real-time data processing is completely automated. In order to minimize the computation time with minimal degradation to the solution quality, CNRS and ACRI-ST processed the GPS data using a 9-hour sliding window that is moved forward by 1 hour for each new hour of incoming data. CNRS experimented with various window lengths and found this one to be the best compromise between timeliness and ZTD accuracy. In particular, CNRS found that a 9-hour solution was sufficient to correctly reweigh the orbital parameters.

The hourly GPS data are retrieved by FTP from several IGS, EUREF and local data centres (see Section 4.7). There is currently a limitation in the data retrieval due to the delay in the availability of the hourly GPS data files, in particular data from the IGN data centre. For demonstration purposes, we tried to find a good compromise between the number of stations that are processed and the ZTD estimations delivery delay (percentage of data arrive within 1 hour and 45 minutes). The start time of the data download by FTP has been therefore chosen in order to have the maximum number of French stations (downloaded from IGN FTP server) in the processing but without degrading too much the delivery delay of our results. Data recovering by FTP therefore starts 25 minutes after the end of the data recording period, which allows in most cases for the retrieval of all the hourly GPS data files available from French stations. The time delay of the processing, which is currently about 15 minutes, is not a limiting factor in reaching a delay compatible with most meteorological applications.

4.3.5 ASI analysis centre

Rosa Pacione

In June 2001 Agenzia Spaziale Italiana (ASI) joined the COST 716 near real-time demonstration phase, processing a European network of about 15 stations. In March 2004 the network consisted of 41 stations covering the Central Mediterranean area with Italy as primary region. The Italian stations included in the analysis provide hourly data with a 10-minute latency, directly to ASI Geodetic Data Archiving Facilities (GeoDAF, `http://geodaf.mt.asi.it`), where they are archived and made available to users. All other stations belong to EPN and their data are available through the regular EUREF/IGS data centres. The GIPSY-OASIS II software is used for data reduction with the standard technique of network adjustment.

The IGS Ultra Rapid orbits, available 3 hours after both UTC midnight and UTC noon, are kept fixed but checked, and, possibly, “bad” satellites are automatically excluded based on the analysis of post fit phase observation residuals, as suggested by Springer & Hugentobler (2001). A 24-hour sliding window for data handling is applied, which means that the RINEX data of the last hour are merged with the previous 23 hours into a single file in order to have enough data to yield robust results. A sampling rate of 5 minutes and a cut-off angle of 10° are applied. The ZWD is estimated every 5 minutes with a stochastic model (random walk) and a constraint of 20 $\mathrm{mm}/\sqrt{\mathrm{h}}$. The station co-ordinates are kept fixed to values provided by combining 1 month of the post-processed solutions which will be described later, whose repeatability is at the centimetre level or better. They are updated every 30 days in order to take into account the tectonic (secular) movements of the area. The phase ambiguities are estimated as float and the satellite and stations clocks are estimated with respect to one reference clock (usually Wettzell). The Niell (1996) dry and wet mapping functions and the ocean loading corrections by Scherneck (1991) are applied. The information on the antenna phase centre variation (PCV) provided by IGS are applied as well. The ZTD estimates of the last hour are derived from the 24 hours batch; they are averaged to 15 minutes sampling rate, put into COST format and sent to the U.K. Met.Office. ASI provides four

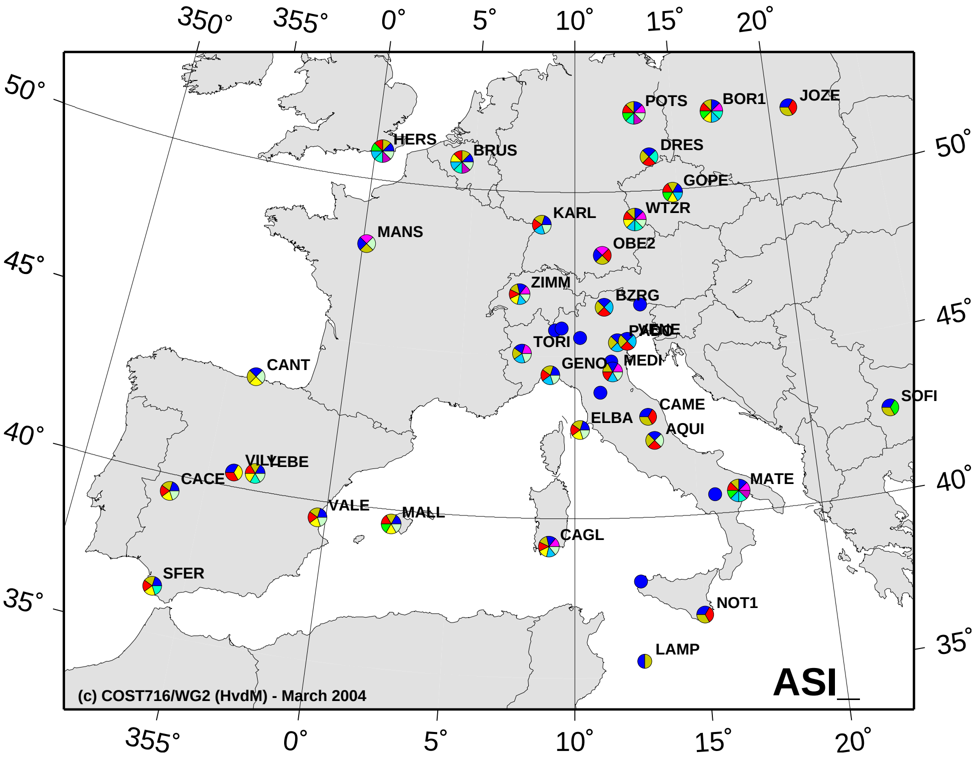


Figure 4.5: GPS stations processed by ASI (March 2004).

ZTD values per hour for each station. This high ZTD rate is a disadvantage concerning the measured latency, since it is measured as the difference in time between the time of the first ZTD estimates and the time of arrival of the COST 716 file.

A dynamic web page (`http://geodaf.mt.asi.it/GPSAtmo/ground.html`) is updated with the latest results and the hourly monitoring of active sites. For each site the coordinates, the receiver type, and the antenna type are reported. The following plots are made: quality Check (TECQ output), hourly files analysed for each day, coordinate repeatability, post-processed ZTD, NRT ZTD estimates, and pressure, temperature, and relative humidity, if available.

The processing starts every hour at hh:18min, and it takes about 50 min for 40 stations on an HP workstation with 512 Mbytes RAM. If a “bad” satellite or a “bad” station is detected based on post fit phase observation residuals, and subsequently removed, the CPU time increases by a factor of two, resulting in an overlap with the next hourly solution. The ASI experience shows that an average of 80% of the predicted solutions have been delivered; the statistics of the GPS hourly data availability per stations shows that 20% of them are available to the users too late to be processed in NRT mode or are lost. Also, data gaps cause problems in the analysis and instability in the ZTD estimates.

Every day at 6:00 in the morning, on the same HP workstation, a post-processed solution is run. The Precise Point Positioning approach (Zumberge et al., 1997) is applied, fixing Jet Propulsion Laboratory (JPL) fiducial-free satellite orbits, clocks and earth orientation parameters. ZTD estimated with a sampling rate of 5 minutes are averaged over 15 minutes and converted into COST format. The main features of the post-processed analysis are reported in Pacione et al. (2001). The main goal of the post-processed solutions is to provide both ZTD estimates for climate applications and station coordinates, which will be fixed, in the NRT data processing when enough accuracy is reached. As for meteorological applications,

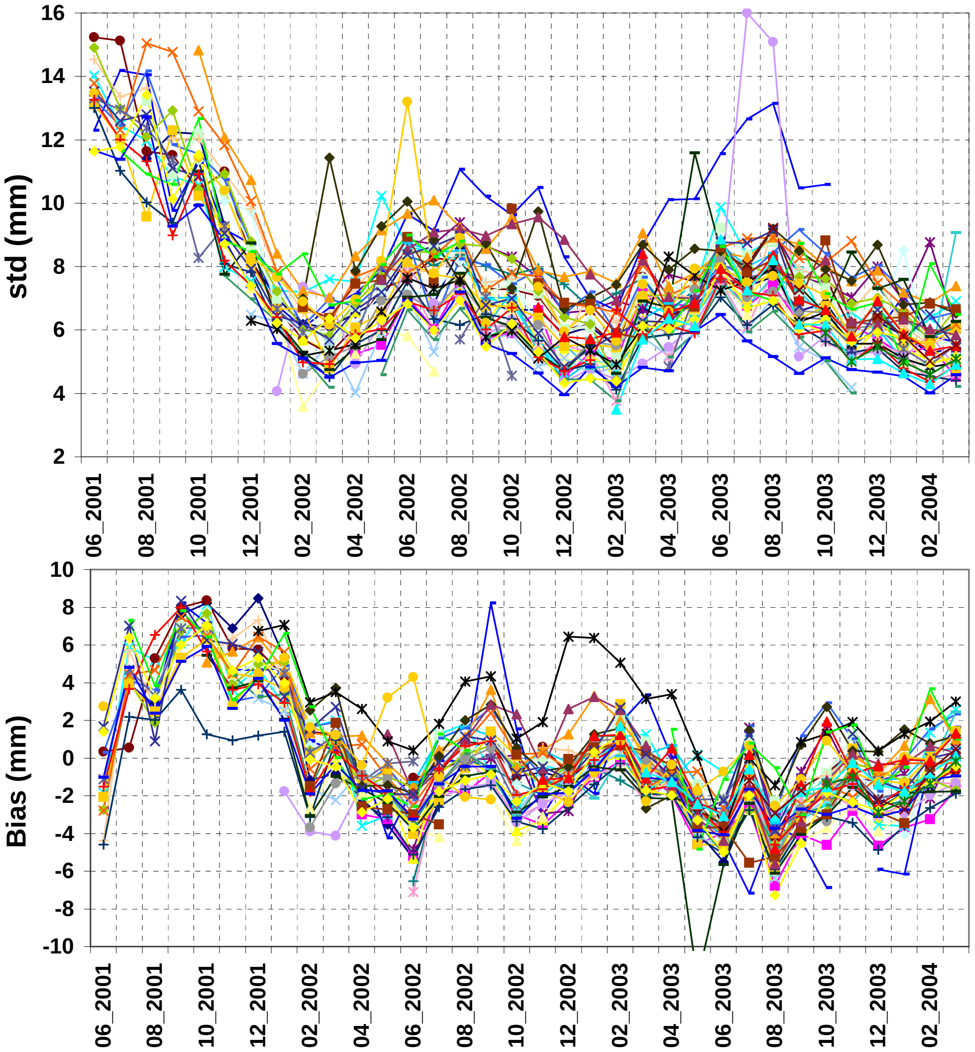


Figure 4.6: Standard deviation (top) and bias (bottom) of ASI NRT solution versus post-processed solution for the period of June 20001 until March 2004. Each line represents a station.

we need to monitor the terrestrial reference frame.

To assess the accuracy of the NRT ZTD, ASI compared post-processed versus NRT ZTD for the period June 2001–March 2004, see Figure 4.6. The monthly station bias ranges from -6 mm to 10 mm and the related standard deviation from 20 mm to 5 mm. The decrease in the standard deviation and in the bias amplitude is mainly due to the refinement of the processing. Two major changes occurred during the period of routine operation. The number of the analysed stations increased from 17—in June 2001—up to 41—in March 2004—just to ensure a better geometrical network configuration. Nevertheless, the main change concerns the handling of the station coordinates. During the year 2001, for each hourly batch processing, first the station coordinates were estimated relying on the available data and, afterwards, they were fixed in the ZTD estimation. This approach has two drawbacks: it is too much time-consuming, since every batch has to be run twice, and the coordinates fixed for ZTD providing are not very accurate, since they are estimated only over 24 hours of data. The method described so far has been applied starting from January 2002.

4.3.6 BKG analysis centre

Wolfgang Söhne

BKG joined COST 716 in June 2001 with the EUREF combined post-processed solution (see Section 4.6). The implementation of NRT processing environment at BKG was carried out in October 2003 but NRT processing on a regular basis started in March 2004. Most of the stations belong to the EPN, nearly all stations used are available from EUREF or IGS data centres. The station network is shown in Figure 4.7. Some far sites, e.g. in Greenland and Turkey, were additionally included to extend the size of the network to get the absolute troposphere estimation. Most of the time more than 70 of the 81 stations actually selected are available except some small periods with data provider outages.

BKG is using the sliding window approach with a four hours data span. While the pre-processing is done with 30 s sampling interval for the GPS data, the final processing use a sampling time of 120 s. The computation is carried out on a LINUX PC, an identical installation is available on another computer

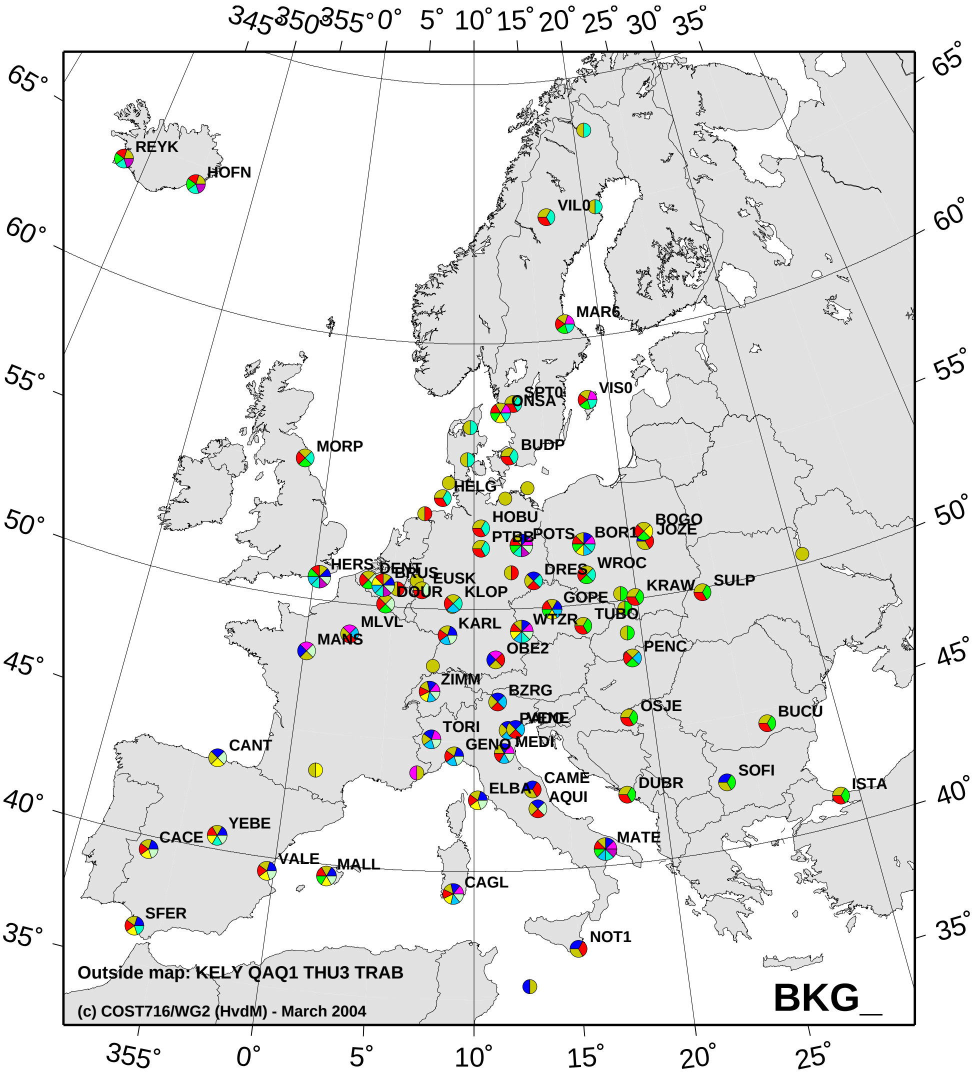


Figure 4.7: GPS stations processed by BKG (March 2004).

for tests. Starting computation at minute 25 of every hour there have been no problems with keeping in time (1 hour and 45 minutes) for delivering the results to UK Met Office.

For the first weeks of our NRT contribution the agreement with the other solutions was limited. There were recognizable jumps between the consecutive estimates and there were also outliers which usually affected more than one station. Some changes have been introduced since then, e.g. fixing of the coordinates, and parallel tests were made, e.g. longer time window, which were not adopted. Just the decision on no longer resolving the integer values for the double-difference ambiguities has finally led to a considerable improvement in agreement with the other contributions. Ambiguity fixing does not seem to work well within the NRT processing due to the short window length, and wrong fixed ambiguities degrade also the results of neighbouring stations. Another positive effect of skipping the ambiguity fixing step was that the interruptions of processing, which only occurred during the ambiguity fixing step from time to time (and which were not repeatable), have now disappeared.

4.3.7 GFZ analysis centre

Galina Dick

The GFZ in cooperation with three other large research centres of the German Helmholtz Association has started in 2000 the “GPS Atmosphere Sounding Project” (Gendt et al., 2001; Dick et al., 2001; Reigber et al., 2002; Tomassini et al., 2002) on using ground-based and space-based GPS observations for applications in numerical weather prediction, climate research and space weather monitoring. In the framework of the GASP project an operational determination of water vapour within a dense network in Germany and neighbouring countries was established in 2000 and is operating continuously since then. Nearly in parallel to GASP the GFZ analysis centre has participated in the European research activity COST 716 since February 2001.

In the final stage of GASP and COST 716 more than 200 sites (Figure 4.8) were analysed each hour to retrieve IWV with an time resolution of 30 minutes. The German network of GPS receivers is based on the satellite positioning system SAPOS of the German Land Surveying Agencies, which in 2003 comprises 250 sites in total. This large network allows for further significant densification if the ongoing studies will propose it. The data retrieval has been stabilized during the project by introducing Internet connection to the sites, so that 85% of the data are available within 5 minutes now. The network is supplemented by 24 GPS receivers from GFZ installed at synoptic sites of the German Weather Service. This guarantees optimal possibilities for validation of the GPS results. The data are transferred in hourly batches to GFZ, checked for quality and merged to usual daily RINEX files. In addition to the German sites about 25 sites from the neighbouring countries are added to enlarge the area of the monitoring, and about 20 stations from the global IGS network are added to enable GPS orbit determination and prediction as well as satellite clock determination.

For conversion of the adjusted ZTD into the integrated water vapour (IWV) the meteorological surface data at the stations is needed (the pressure for getting the zenith wet delay; the temperature profile, approximated by linear regression from surface data). For some stations, e.g. the 24 GFZ-DWD sites, local measurements are available. However, for most of the sites the needed pressure and temperature have to be interpolated using the synoptic sites of the DWD (about 200 sites with hourly sampling rate of data). For each site the smallest surrounding station triangle is used for a linear interpolation, correcting for the height differences beforehand. Stations with a height over 1000 m are excluded because of limitations of interpolation accuracy caused by errors in height correction. The quality of the interpolation is normally 0.3 hPa (RMS). In mountainside regions the error can reach higher values, but 0.5 to 1 hPa (corresponding to about 0.2 to 0.4 mm IWV) can be accepted for numerical weather prediction if these

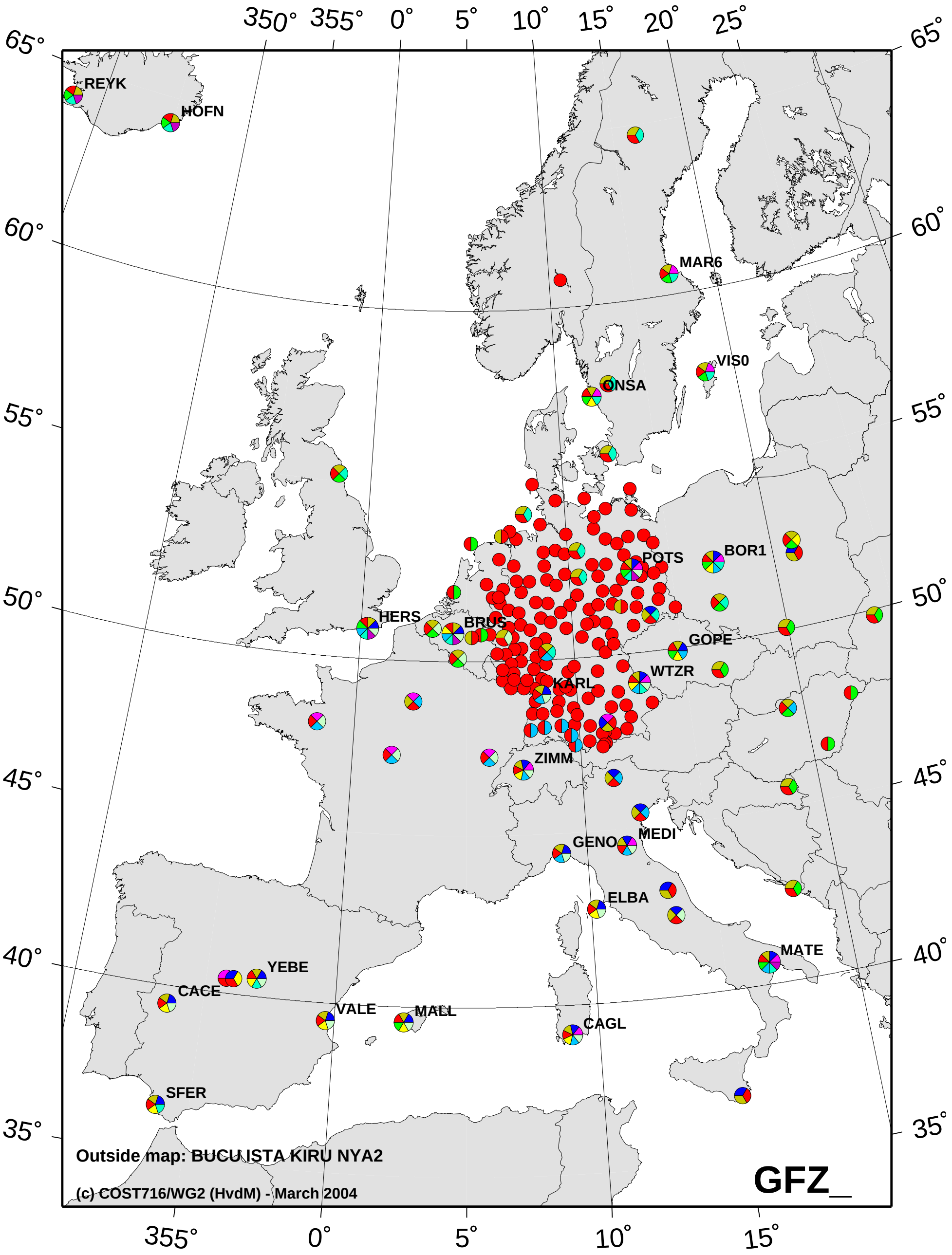


Figure 4.8: GPS stations processed by GFZ (March 2004).

are only random fluctuations. There are only a few sites that do not meet this limit. The pressure data are checked beforehand by mutual interpolation to eliminate sites, which can be regarded as outliers in the pressure field over Germany. That means, each pressure value is compared to the interpolated value using surrounding sited, and it is excluded if the difference exceeded given accuracy limit.

For the analysis the GFZ software EPOS.P.V2 (Gendt et al., 1999) is used, based on least squares adjustment of undifferenced GPS measurements and makes use of the IERS standards. The mapping function to derive the partial derivatives for the ZTD is that of Niell (1996). The station coordinates are determined in the ITRF reference frame using IGS final products and are then fixed during the NRT data

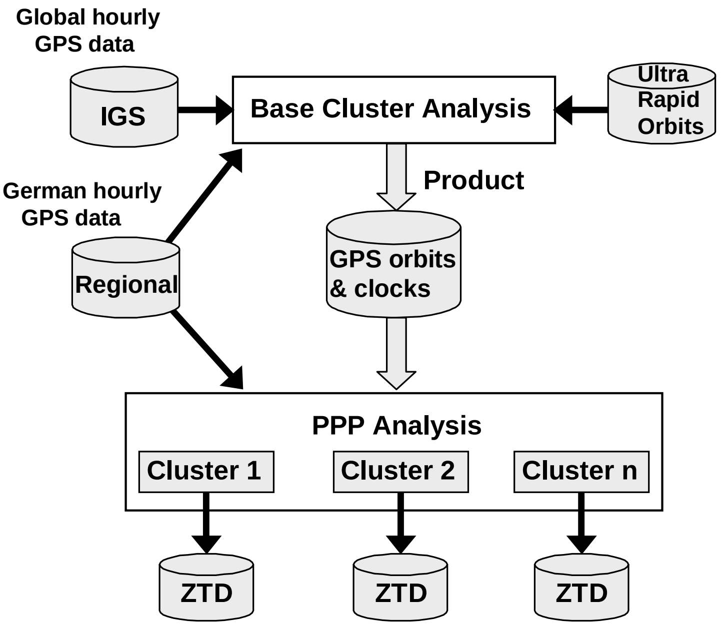


Figure 4.9: Analysis scheme for the generation of ZTD estimates using a network analysis for a basic station cluster and the precise point positioning (PPP) in parallel clusters.

processing. An accuracy check for the station coordinates is performed regularly, using the results of the coordinates adjustment from the post-processed analysis based on daily data batches. The various steps for of the analysis procedure are illustrated in Figure 4.9, main characteristic are given in Table 4.1.

A technique of parallel processing of a large number of stations in clusters with the PPP method, where each cluster may be processed on a separate computer, is implemented, which keeps the computation time within 15 minutes for about 200 stations even with increasing number of parameters like high sampling rate (15 or 30 minutes) and gradients for tropospheric estimates.

The NRT data analysis needs predicted orbits. Whereas the Ultra Rapid orbit predictions submitted to the IGS (Gendt et al., 1999; Zumberge & Gendt, 2001) are generated at GFZ twice a day, for internal use a 3-hourly repetition was chosen. The reduction of the maximum prediction interval from 15 to 4 hours improves the reliability of the predicted orbits significantly. In this step global hourly IGS data are analysed in 24 hour long data windows shifted each time by 3 hours.

Estimation of the tropospheric results has to be based on high quality GPS orbits and clocks, so that the hourly NRT data analysis starts with this “base” estimation step. Here predicted Ultra Rapid orbits of GFZ with 3h repetition (GFU 3h) are used as initials for the orbit and clock adjustment. To achieve sufficient quality in the GPS orbits, about 20 well-distributed global sites (base cluster) in a 12 hour data window are used for orbit estimation. For good clock coverage over Germany five additional GASP stations are included.

Data retrieval and processing are running on two LINUX PCs. One PC is devoted only to the data handling. Permanently all possible global and regional data centres are checked for new data. From the German sites the data are put directly into the incoming directories. All data are immediately reformatted, checked and accumulate to usual daily batches. A second PC is used for the data analysis, which takes about 20 minutes for the Ultra Rapid orbit analysis (every 3 hours) and 12–15 minutes for the determination of tropospheric results for the 220-station network each hour. Both PCs have a usual hardware with two CPUs of 1 GHz, 500 MBytes memory and 160 GByte disk space. The product delivery statistics reveals reliability for the hourly product files of 95%.

The data are analysed in sliding 12 hour long windows shifted each hour. The ZTD products are extracted from the last hour only. Because the applied random walk constraints are not so effective at the interval boundaries they do not have the highest quality. In addition to the 30-minute sampled ZTD values the ZTD gradients in north and east direction are estimated every 60 minutes. Even if the gradients itself are not considered to be an additional product, their estimation improves the ZTD products in case of frontal passages. The quality of the original ZTD results may be deteriorated by errors during the conversion into IWV (e.g. caused by instrumental problems for the surface data). Therefore the ZTD values are preferred for the assimilation. Nevertheless a conversion into IWV is preformed so that the results can be used to monitor the moving water vapour fields with rather detailed information over Germany.

As soon as the IGS final products are available the data are also analysed in a post-processing mode using daily data batches to obtain products with the highest accuracy. A first check of the NRT estimates using the post-processed products shows a NRT quality of the level of 0.6 kg/m^2 IWV. A regularly performed long-term validation with the collocated instruments like WVR and radiosondes show the agreement within their error budget of about ±1 kg/m^2 IWV.

Dynamical Web-sites with hourly update are available under `http://www.gfz-potsdam.de/pb1/pg1/gasp1/index_GASP1.html`.

4.3.8 GOP analysis centre

Jan Douša

The GOP analysis centre is a joint activity of the Geodetic Observatory Pecný of the Research Institute of Geodesy, Topography and Cartography (RIGTC) and the Department of Advanced Geodesy of the Czech Technical University in Prague (CTU). Under this collaboration, GOP officially operates as EPN and IGS analysis centre as of 1997 and 2004, respectively. For all activities, GOP uses the Bernese GPS software (Hugentobler et al., 2001).

The Czech Republic joined COST 716 officially in February 2001. GOP was among the first two analysis centres starting the demonstration trial. At that time this was possible due to preceding two-year experience with near real-time GPS processing in GOP. The strategy was developed during a period when IGS ultra-rapid orbits (Springer & Hugentobler, 2001) were not yet available and hourly GPS data flow was rather unstable. Within the first years (1999–2001), GOP had tried various solutions concerning the handling the orbits in near real-time: applying the individual satellite rejections, regional orbit relaxation or, finally, determining and applying the orbits from independent global solution. For more details, see Douša (2001b) and Douša (2001c). In 2001, the IGS ultra-rapid product had become very stable and most of the satellite orbits could simply be used without requiring orbit relaxation or other adjustments. This simplified the ZTD estimation for the COST 716 demonstration, and resulted in a more robust product. From that time onward, GOP used only the orbit quality checking approach in order to reject occasional bad satellite orbits, as described below. Nevertheless, there was still room for improvement related to the number of satellites included in the IGS ultra-rapid product, which was not always complete, and in reducing the update cycle of the orbit product. In 2002, GOP completed its own procedure for the global orbit determination, with updates every 3 hours. Since 2004, GOP officially contributes to the IGS ultra-rapid orbits.

The network processed in GOP consists of stations primarily located at the central or Eastern Europe (Fig. 4.10). Additionally, GOP also included several stations from the western part of Europe that were

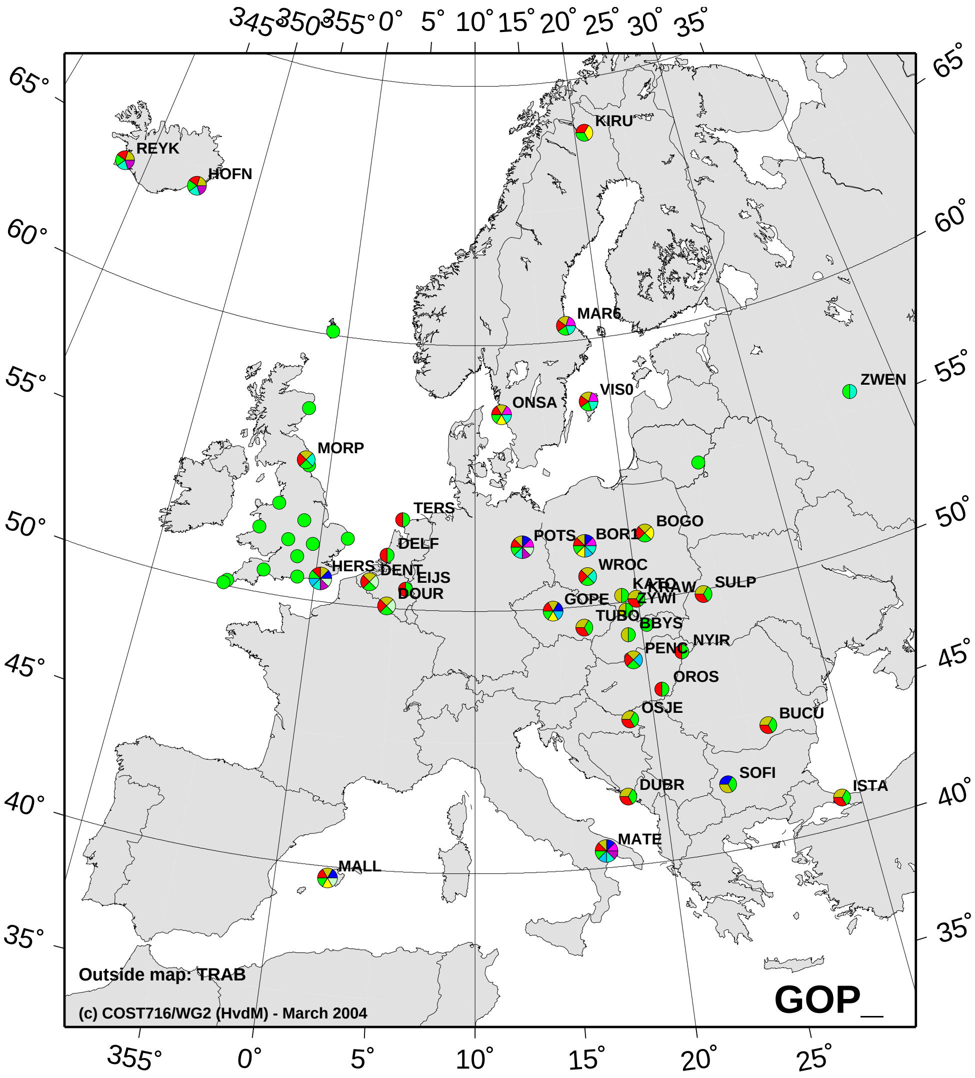


Figure 4.10: GPS stations processed by GOP (March 2004).

not analysed by any other analysis centre at the beginning of the near real-time demonstration, with stations in Belgium, the Netherlands and UK. About 8–10 sites were additionally selected on the European margins to extend the regional network for absolute troposphere estimation. Except 8 stations operated by Met Office UK, all other stations belong to the EPN and the data are collected through the regular EUREF/IGS data centres. This shows our strong dependency on the data flow within the public data sources.

The quality of the data flow is one the most important issues for the stable NRT processing. Together with initiating the global NRT orbit determination, a special data centre supporting NRT data flow was established in GOP (Douša, 2001a). The data centre was officially adopted by the EPN service in 2002. Data were mostly collected in the data centre during the first 30 minutes past hour, after which GOP started the NRT processing. Figure 4.11 shows the complete system of the analysis taking approximately 20–30 minutes for 50 sites on standard 1.4 MHz Linux PC. Besides the main steps of the analysis, the feedback arrows represent possible iterations due to the rejection of the low quality orbits.

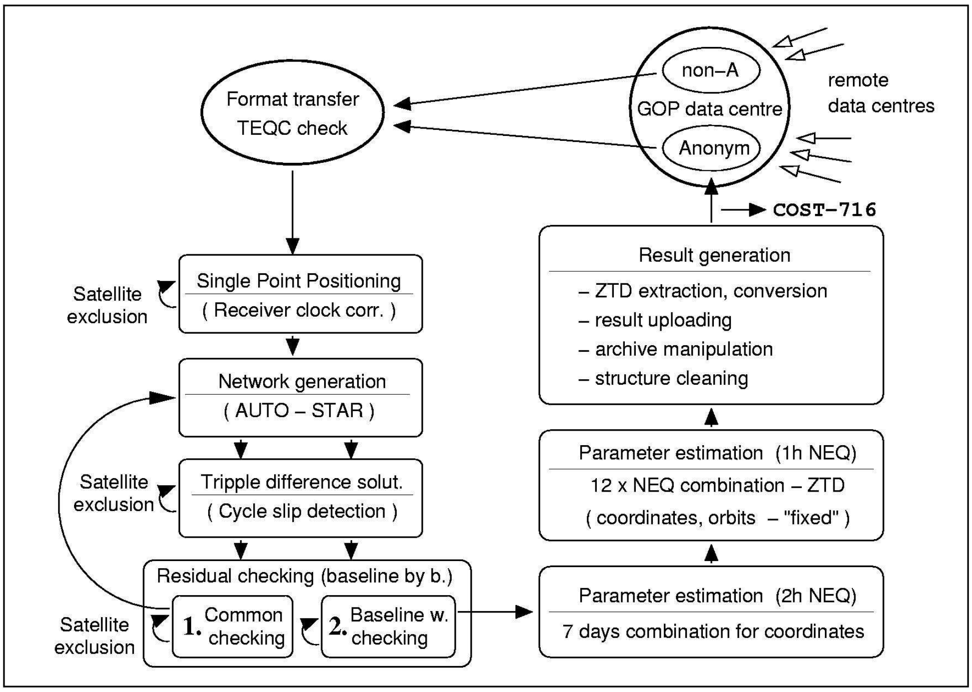


Figure 4.11: Flow chart of the NRT processing at Geodetic observatory Pecný.

The IGS ultra-rapid orbits are available every 6 hours. The most recent IGS ultra-rapid orbits are always immediately applied. Each is valid for at least the next 24 hours, so that when the next near real-time orbit update is not available, processing can continue. The product SP3 accuracy codes are used for a priori satellite rejection. For single point positioning, the satellite clocks from the concatenated broadcast ephemerids are applied.

The ambiguities are not resolved (fixed) to integer values in the GOP solution due to the very short preprocessing batch. There was not even a proof of positive impact in ambiguity fixing for ZTD estimates in GOP post-processing solutions (Douša, 2002a). The ZTD, with its short-term validity, is generally very susceptible to any single incorrectly fixed ambiguity.

Three special features of the GOP approach should be mentioned: a) the baseline definition, b) the length of a data-batch for basic pre-processing, and c) the handling of the bad orbits. These will be explained below.

The baseline definition works as follows. First, differences are applied between the receivers to define the network design. GOP uses so called AUTO-STAR strategy from the Bernese software, i.e. the baselines are generated from the central network site. The strategy was completed for the sophisticated central point selection optimizing number of observations over all baselines. The AUTO-STAR strategy has one practical advantage: problems with a single site (not central) can be solved by simply removing a single baseline without the need to reconstruct the whole baseline set. The disadvantage is that baselines are longer, and depend on the data quality of the central point and its stability of performance.

In the pre-processing step, GOP uses data for the last two hours, which had been set up primarily for alternative testing solutions. This approach was not necessary for the official GOP solution, however it was useful for evaluation of the orbit quality and, additionally, it improved robustness of estimated coordinates of all sites with often data gaps or with significant fluctuation in acquisition delay. All sites available in the data centres later than 30 minutes (but earlier than 90 minutes) were thus included in coordinate estimation though they were not used for requested ZTD estimation in the official product. This approach was also used for the initialisation of new station coordinates.

Concerning the method for orbit exclusion, the GOP analysis procedure historically consisted of two iterative steps. Both were based on checking the post-fit observation residuals. Screening the residuals for excluding the individual satellites from the whole network was performed within the first step, while the second provided monitoring and excluding of satellites on each baseline individually. With the IGS ultra-rapid orbits improving over time, only the first step is now sometimes relevant. For some baselines satellites are still rejected within the second step, depending on baseline length and its orientation with respect to the orbit errors.

4.3.9 IEEC analysis centre

Antonio Rius

In 1999 IEEC started with its GPS Near Real Time System (NRTS) for tropospheric program, as described in Flores et al. (2000). During the last years the system has been improved by adding a graphical user interface and by increasing the number of stations, while adapting the processing strategy to the COST Action meteorological requirements, and by migrating from Sun Solaris to INTEL Linux.

In its present state the NRTS gathers data from 19 Spanish stations and 10 from other European countries, see Figure 4.12. The selection of the stations was made on the basis of the potential utility of the results to the Spanish users (mainly the Instituto Nacional de Meteorología and Instituto de Astrofisica de Canarias).

The data producers are IGN (Instituto Geografico Nacional, Spain), ICC (Institut Cartogràfic de Catalunya, CATNET Network, Spain), IGS (International GPS Service), EUREF Permanent Network, and IAC (Instituto de Astrofísica de Canarias, Spain).

The data are processed using the JPL/CALTECH software package GIPSY-OASIS placed in the core of an application which implements functionalities for retrieving the raw GPS observables and the orbits and other needed ancillary information, and to provide ZTDs to the users in agreed formats. The system runs in autonomous form: the operation is limited to the monitoring of the results via a graphical user interface and the maintenance of the system, when needed. The main parameters are listed in Table 4.1.

4.3.10 LPT analysis centre

Elmar Brockmann

In November 2001, the Swiss Federal Office of Topography (swisstopo), formerly L+T and hence the abbreviation LPT, was ready to contribute to the COST 716 NRT demonstration phase. After changing the hardware facilities at LPT (use of 2 LINUX machines instead of 2 older AIX unix machines), the necessary computation power was available to meet the deadline of 1:45 hours for data submission.

For the NRT demonstration phase LPT used almost the identical processing options determined in the benchmark data set, as described in Section 4.4. In the NRT demonstration phase, all data are used (30 s data instead of 180 s sampling in the benchmark data set). Due to the smaller estimated RMS values of the ZTD estimates, we therefore also used slightly smaller relative constraints ($3.0 \cdot \sqrt{30/180}$=1.2 mm instead of 3.0 mm). More details of the processing may be found in Table 4.1.

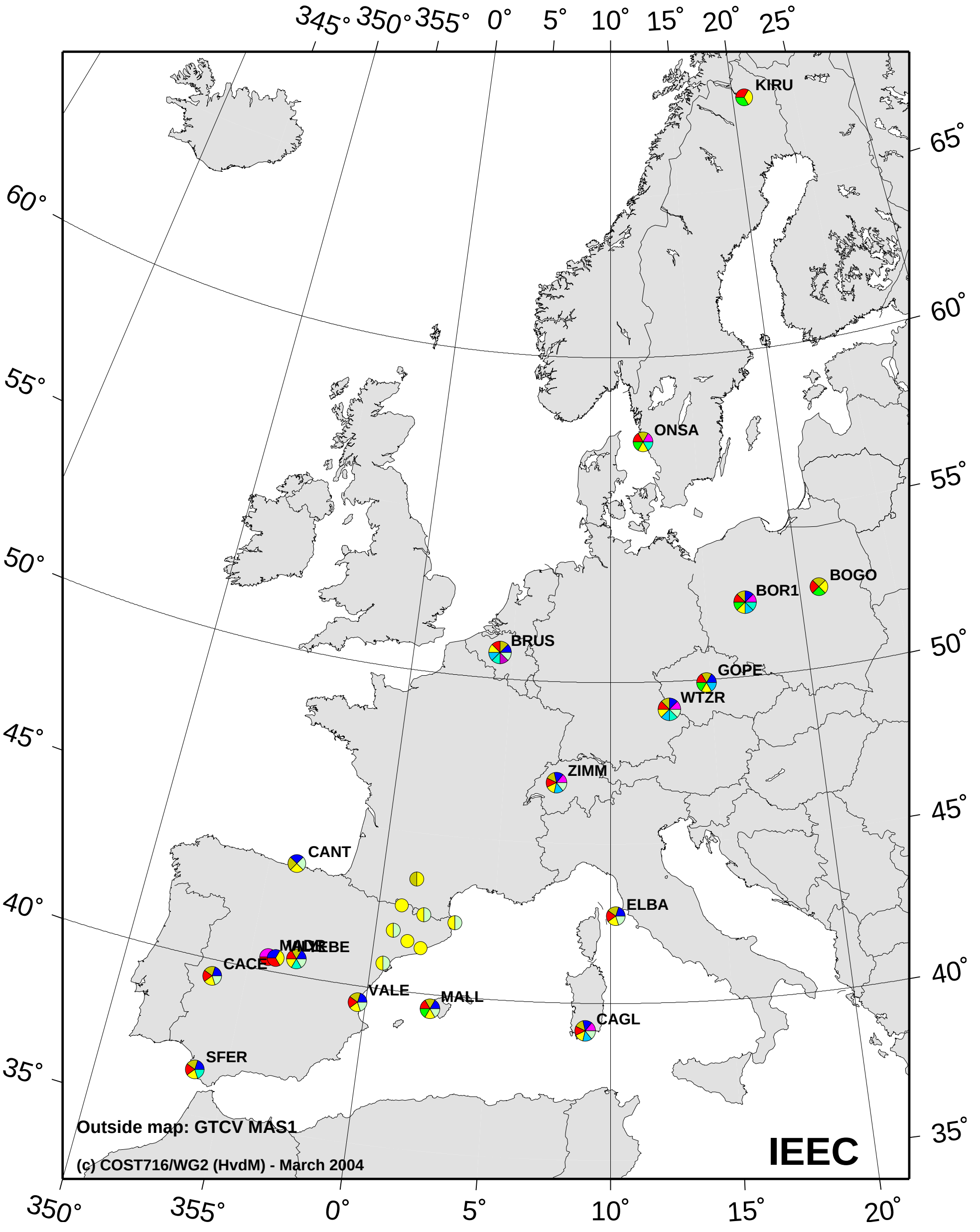


Figure 4.12: GPS stations processed by IEEC (March 2004).

The station network is shown in Figure 4.13. In addition to the 29 Swiss AGNES sites, more than 20 EUREF sites were processed. Furthermore, about 12 sites from other networks, mainly in France, are being used in order to improve the station distribution in the western part of Europe. This area is important because the dominating weather conditions from the Atlantic Ocean usually pass over France before they reach Switzerland.

The number of RINEX files used for the NRT processing is given in Figure 5.3 in Chapter 5. LPT started with approximately 45 sites. It can be seen clearly that on May 2, 2002, the number of processed sites was increased by also including all available French sites. Due to the fact that the data of the French sites were available much later, LPT waited until 37 minutes after the full hour before starting with the

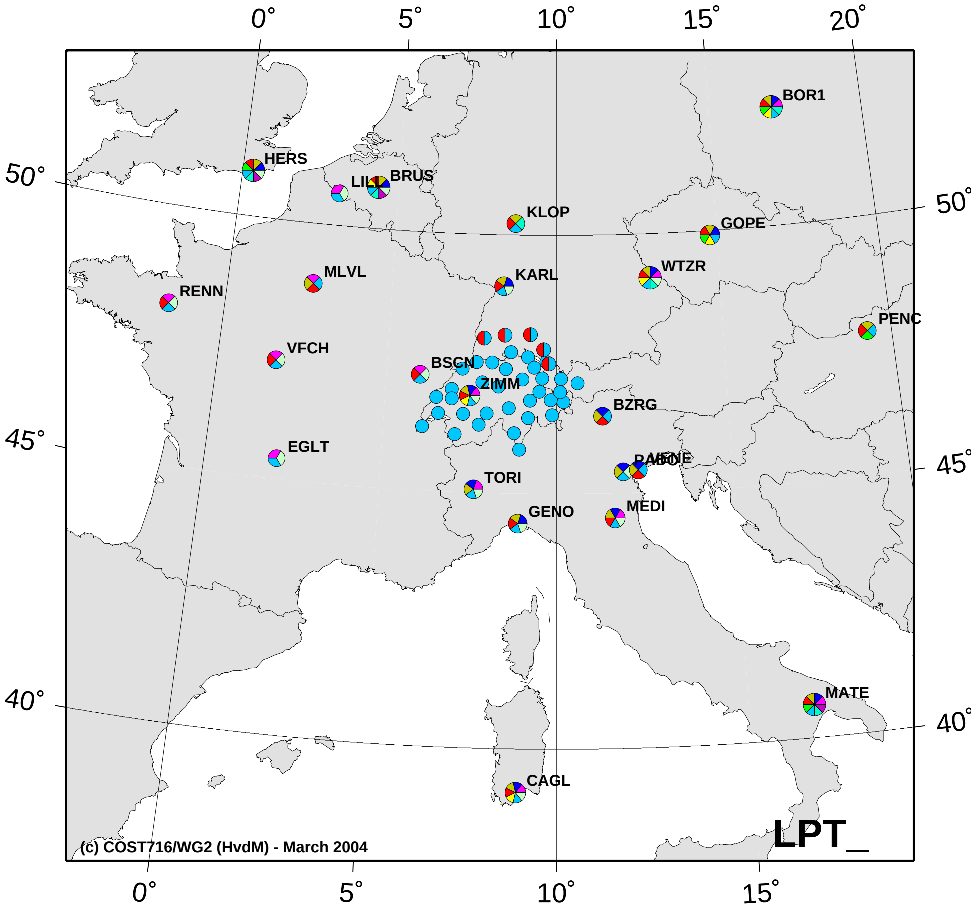


Figure 4.13: GPS stations processed by LPT (March 2004).

processing. Therefore, the completion and the submission of the results were also delayed, as can be seen from Figure 5.7 in Chapter 5. Nevertheless, the inclusion of these additional data was very much appreciated, especially by MeteoSwiss.

The larger number of sites caused many more processing problems than before the sites were included. Besides station problems, we also had stability problems with some programs under the high CPU load. Therefore, the success rate dropped down from 99% to 92%. Since August 2002, after some minor program modifications, the solutions were again more stable (98–99%) even though we did not change the processing scheme.

Most of the failures in data submission are due to problems within our analysis centre or due to missing ultra rapid orbit information or electrical power failure. Overall our submissions had a success rate of about 97% from December 2001 till November 2002.

The decreasing number of sites in Figure 5.3 is mainly due to the missing French data. Also the Austrian data delivery for the NRT processing is frequently too late.

LPT is processing also a true real-time network and is providing ZTD estimates of this network as a second solution. The domain of the real-time network is restricted to Swiss as only the AGNES stations provide data in real-time. This corresponds to the centre of the network shown in Figure 4.13.

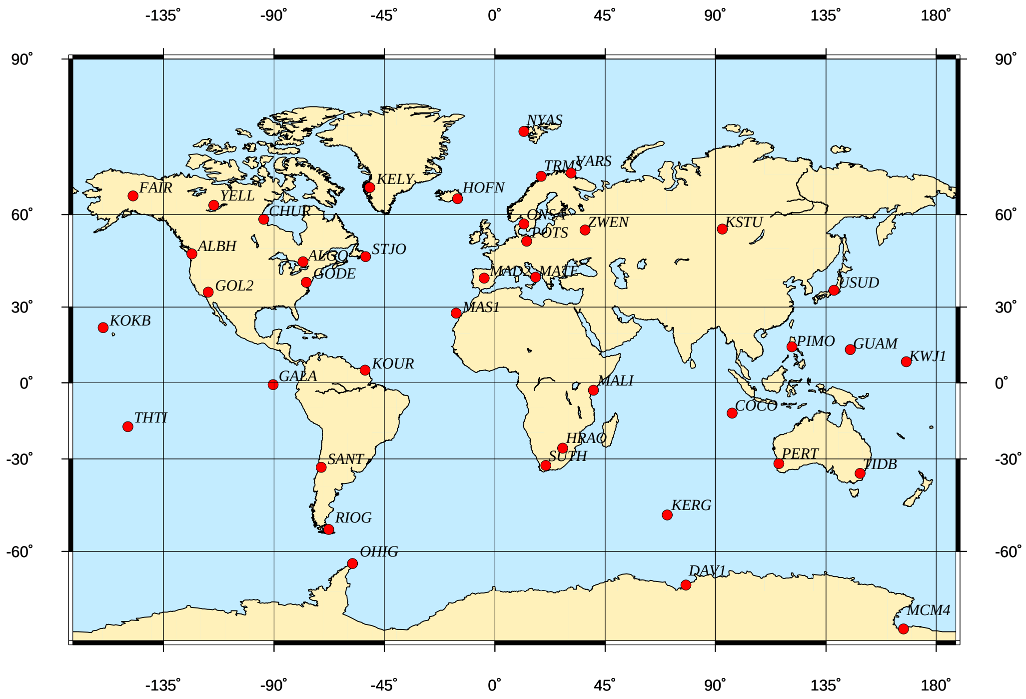


Figure 4.14: The GPS station tracking network used in the global NRT ZTD analysis at NKG (NMA).

4.3.11 NKG analysis centre

Oddgeir Kristiansen

The Norwegian Mapping Authority (NKG) started to submit ZTD data to COST 716 in April 2002, after having participated for a short period in October 2001. On April 2, 2003, NKG has changed their analysis strategy.

Previous analysis strategy

NRT processing of orbits, clocks and Earth orientation parameters (EOP) has been carried out at NMA (NKG) since mid September 2001. About 35 hourly globally distributed IGS stations, together with 3 Norwegian SATREF stations (see Fig. 4.14), were included. The processing of the global parameters was carried out in a fiducial approach, i.e. selected station coordinates were constrained to the ITRF2000 reference frame. A 24-hours moving window was used. Station coordinates, station clocks and zenith total delay were estimated together with the global parameters, i.e., orbits, EOP and satellite clocks. The satellite and clock bias were estimated as white noise process and the zenith tropospheric delay as random walk process.

The estimated orbits, clocks and EOP were used for the remaining sites to solve for station clocks and ZTD parameters in NRT precise point processing mode.

The computing time needed, to solve for orbits, clocks, and EOP from a globally distributed GPS data set, and to compute the ZTD, were:

1. Downloading of hourly RINEX files; 30 minutes, i.e. the GPS processing did not start before 1 hour 30 minutes after the first measurement.

2. Global GPS analysis; 1 hour 15 minutes

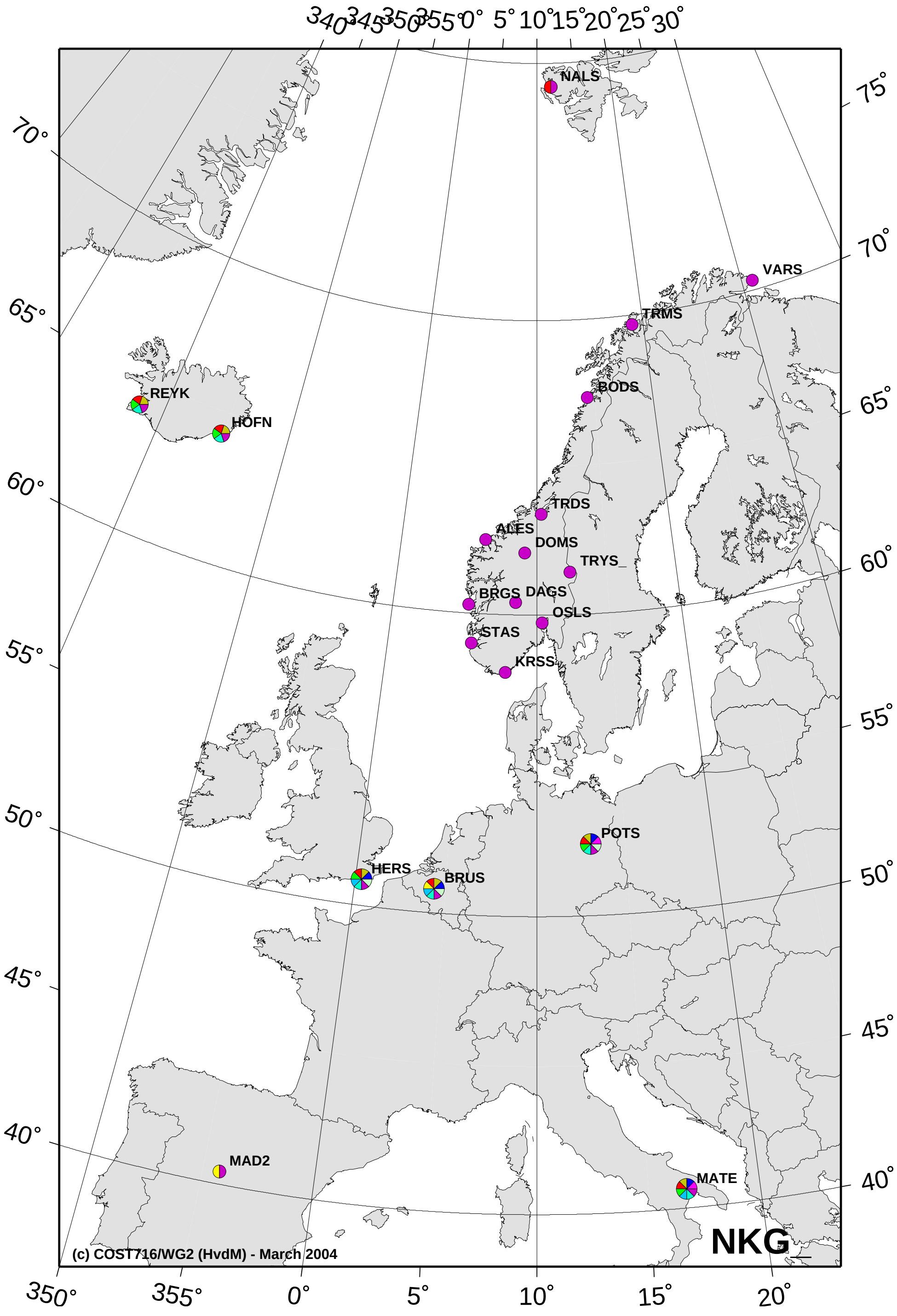


Figure 4.15: GPS stations processed by NKG Norway (March 2004).

3. Precise point processing; 10 minutes

The total delay was about 2 hour 55 minutes after the first measurement, which exceeded the requirement of 1 hour 45 minutes. Therefore, to speed up the processing time NMA decided to change the analysis strategy.

New analysis strategy

In the new strategy NMA is using very-rapid (15 min) orbits and EOP's from JPL. Furthermore, hourly RINEX files from the permanent Norwegian network together with hourly RINEX files from selected European IGS stations are used (see Figure 4.15). Table 4.1 summarizes the new analysis strategy used at NMA. The new strategy was implemented on 2 April 2003. The parameters that are solved for are ZTD, G_N and G_E gradients, satellite and station clock biases. Station and satellite clocks are solved for as white noise processes, using ONSA as reference clock. The ZTD is solved for as a random walk process. No integer ambiguity resolution is attempted. Both orbits, EOP's and station coordinates are constrained. The station coordinates from the IGS stations are computed at the current epoch using the velocities published by IERS in the ITRF2000 reference frame. The station coordinates from the Norwegian permanent stations are computed at the current epoch using velocity estimates estimated by NMA. A 12-hour moving window is used.

Downloading of the 13 NMA stations) takes place 2 minutes past the hour, while the downloading of 10 IGS stations is done 15 minutes past the hour, after which the processing is started. The current processing time is 5 minutes, using GIPSY/OASIS-II ver. 2.6.1 on a Linux (debian) computer.

4.3.12 NKGS analysis centre

Jan Johansson

The NKGS analysis centre was established in 2002 but has been working off line during several periods before January 1, 2004. The implementation of the operational NRT analysis of GPS data is based on one computer, using a Linux operating system, taking care of both data retrieval and data analysis. The computer is installed at the SWEPOS operational centre in Gävle, and thereby is directly connected to the SWEPOS real time data acquisition system. The NKGS approach for providing NRT estimates of ZTD includes the following steps.

First, the satellite orbit and clock information is retrieved. This information may, e.g., be acquired from the satellite message itself or from the rapid products provided by the analysis centres of the IGS. A first evaluation of the quality of the products is conducted.

Sometimes, the orbit and clock parameters from the first step need to be improved. This improvement is based on the processing of a globally distributed network of more than 20 stations belonging to the IGS network. The hourly data files from these stations are collected over the Internet from the global archives. The actual retrieval of the data takes about one minute to complete. The new hourly data files are then merged to the data from the previous 23 hours in order to cover a full day. This data set is processed using the GIPSY-OASIS software using “network” processing. In this approach, one station clock is used as a reference, while all the other station and satellite clocks are estimated. The coordinates of all stations are fixed. The coordinates of the orbits are constrained but still estimated. Furthermore, phase ambiguity parameters and tropospheric signal propagation delays have to be estimated. The elevation cut-off angle is set to 15°. The Niell dry and wet mapping functions are used (Niell, 1996). NKGS correct for ocean loading effects based on a model developed by (Scherneck, 1991). The retrieval and merging of the data and the actual data analysis usually takes in total about 10 minutes to complete.

The data from the local and regional stations need to be collected at the local and global archives. The data from the 57 Swedish stations are transferred by the SWEPOS operational centre, hosted at the NLS, directly to the Linux computer performing the final processing. The hourly files are compiled from the real-time data flow by the SWEPOS operational centre. Usually all data are available at the Linux ZTD processing engine within 20 minutes after a full hour. The hourly data files from 26 Danish stations

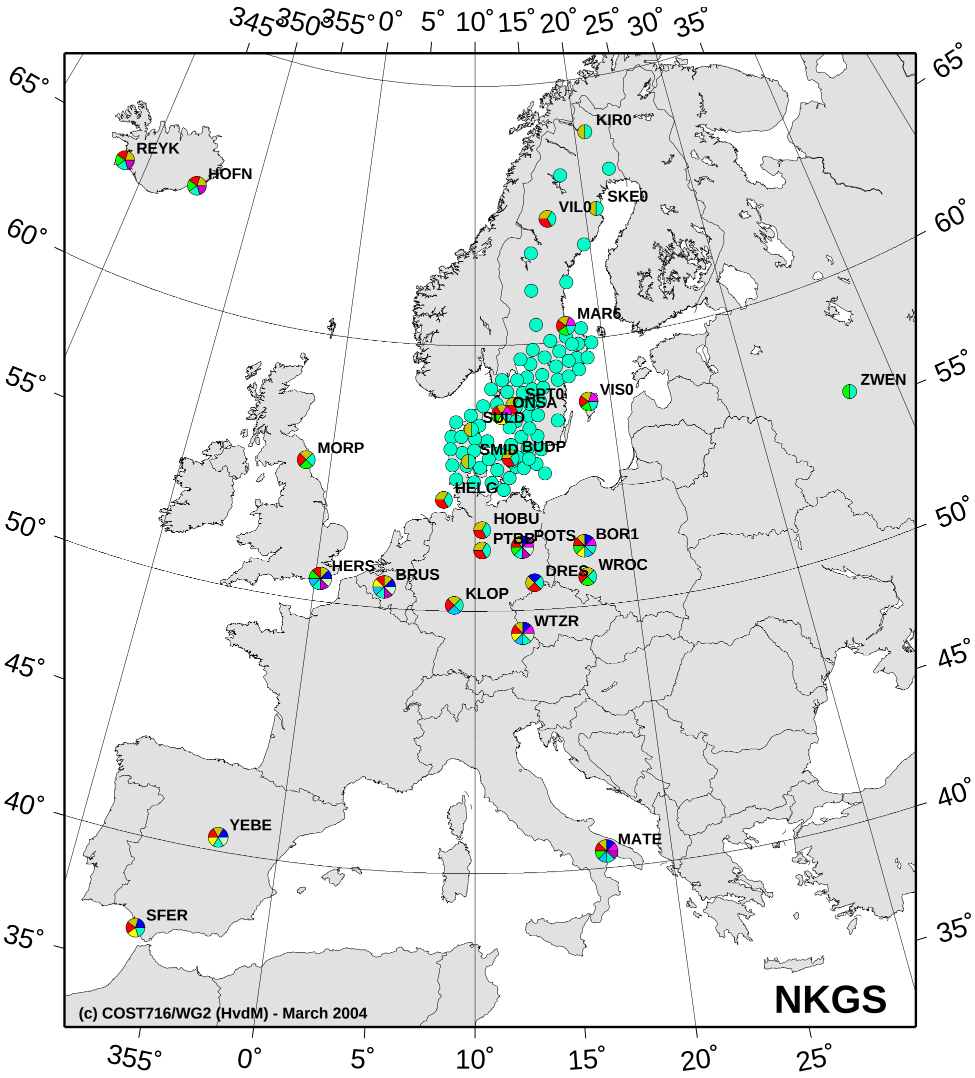


Figure 4.16: GPS stations processed by NKGS (March 2004).

are provided by a commercial company. These data are for the moment only available to NKGS on a research basis and are provided via FTP to a local data archive at the Onsala Space Observatory about 15 minutes after a full hour. The Linux computer used for the analysis is retrieving this data via FTP from Onsala about 20 minutes past each full hour. Finally, hourly files from approximately 20 stations from the region surrounding Sweden is collected from the regional data archive in Europe. In total data from more than 110 stations are acquired. This part of the processing takes only a few minutes. The network is shown in Figure 4.16.

When all local and regional hourly data files are retrieved, they are merged with data files collected from the same station over the previous 7 hours (i.e. in total the data processing cover 8 hours). In this manner, the used data window is moved by one hour. The use of the data from previous hours is essential in order for the output from the GIPSY-OASIS Kalman filter to stabilize.

Utilizing the improved orbits and clocks, together with data from the latest 8 hours from all stations, all data are processed using the PPP technique. In the processing, the Kalman filter is set up to estimate stations clocks, phase ambiguity parameters, ZTD, and tropospheric gradients. The latter parameters are updated every 15 minutes, while the clocks are solved for every epoch and the phase ambiguities are modelled as constants over the data interval. In all other aspects, NKGS use the same models as those mentioned in relation to the network solution for orbits and clock improvement. If data from all stations are available, this part of the data processing takes about 10 minutes.

When all stations are processed the ZTD output is converted to COST format and sent via FTP to the server at the UK Met Office and the corresponding server at the SMHI. The whole processing of 110 stations takes 20–25 minutes.

The installation described above was first implemented during 2002. Over the first year NKGS encountered several problems due to several changes at the Onsala Space Observatory and the SWEPOS operational centre the processing was interrupted during 8 months and restarted in September 2003. There are now two Linux computers with identical installations. The main computer is hosted by the NLS and located near the SWEPOS operation centre while the other remains at the Onsala Space Observatory.

A remaining problem is related to the retrieval of data from the Danish stations. The data flow is interrupted for a few hours just after midnight (UTC) every day. The agreement with the commercial company behind the Danish network is that they will provide data free of charge but on a best effort basis. They are working on an improvement.

4.3.13 SGN analysis centre

Bruno Garayt and Alain Harmel

The SGN analysis centre, located in Saint–Mandé at IGN is one of the two operational centres of the French GPS permanent network RGP (the second centre is located in Marne-la-Vallée at LAREG). The task of the operational centres is: to collect GPS data, to do a data quality check, to deliver data on the Internet, to do hourly, daily, and weekly processing, and to deliver products on the Internet. The following processing steps are carried out:

- hourly processing (at SGN only).
  Along with the 1-hour data associated with IGS predicted orbits (IGU), hourly solutions are performed in sliding 3-hour windows. The results are used for
  - an immediate data quality control,
  - providing near real time sub-products as atmospheric behaviour parameters.

  The network of hourly stations providing ZTD data for COST 716 is shown in Figure 4.17.
- daily processing (at SGN only).
  Through the availability of rapid orbits IGS products (i.e. after 28 hours), a daily solution is processed. The involved products are intended to refine a reference control assessment and provide more accurate atmospheric models.
- weekly processing for national reference maintenance (at SGN and LAREG)
  The network processed consists of about 55 stations, and it includes all RGP stations and some EPN ones from neighbouring countries.

The computation is carried out with the Bernese GPS processing 4.2, on a UNIX machine. Most of the processing options can be found in Table 4.1, except the ambiguities are resolved using the QIF strategy

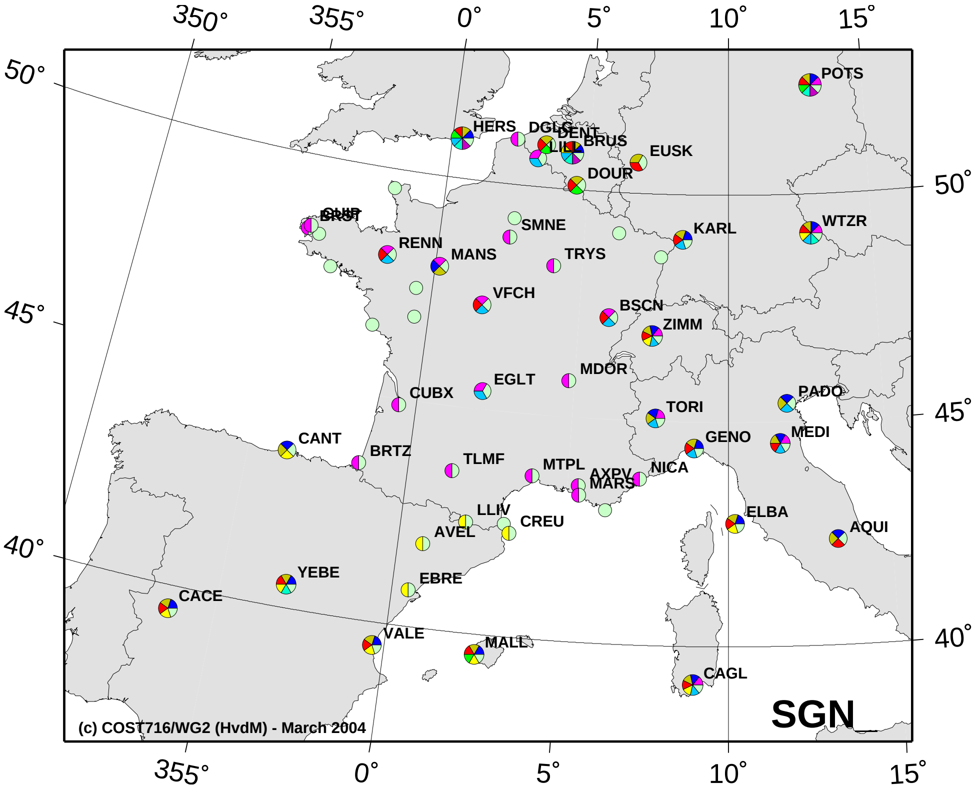


Figure 4.17: GPS stations processed by SGN (March 2004).

and integer values are introduced in the final solution, and the estimated coordinates are aligned to an ITRF2000 realization coming from a multi-annual coordinate solution, and then kept fixed for the ZTD final solution.

The ZTD parameters, as well as parameters of an ionosphere propagation model, are freely available within about 1 hour after the last observation. ZTD parameters in the SINEX format are available from `ftp://arethuse.ign.fr/pub/troposphere` and local ionosphere models (with a 1 to 2 TECU accuracy) are available from `ftp://arethuse.ign.fr/pub/ionosphere`. Also, computed ZTD parameters are mapped as a grid of differences with interpolated values coming from a “Saastamoinen” standard troposphere model. This information is available at the SGN website `http://geodesie.ign.fr/RGP/index.htm`.

4.4 Benchmark dataset

At the Oslo workshop, in 2000, it was decided that all groups in WG2 will first process a benchmark data set, before starting with the near real-time demonstration, to test the algorithms, data flow, formats and assimilation into Numerical Weather Prediction (NWP) models.

The GPS data processing has been tested on 15 days of GPS data which were processed off-line, but to near-real time quality, for the period of June 9–23, 2000. In contrast to the actual demonstration, where analysis centres are processing different GPS sub-networks, all analysis centres processed a common network. The idea was to have a campaign that can be used to (i) test and validate the algorithms, data

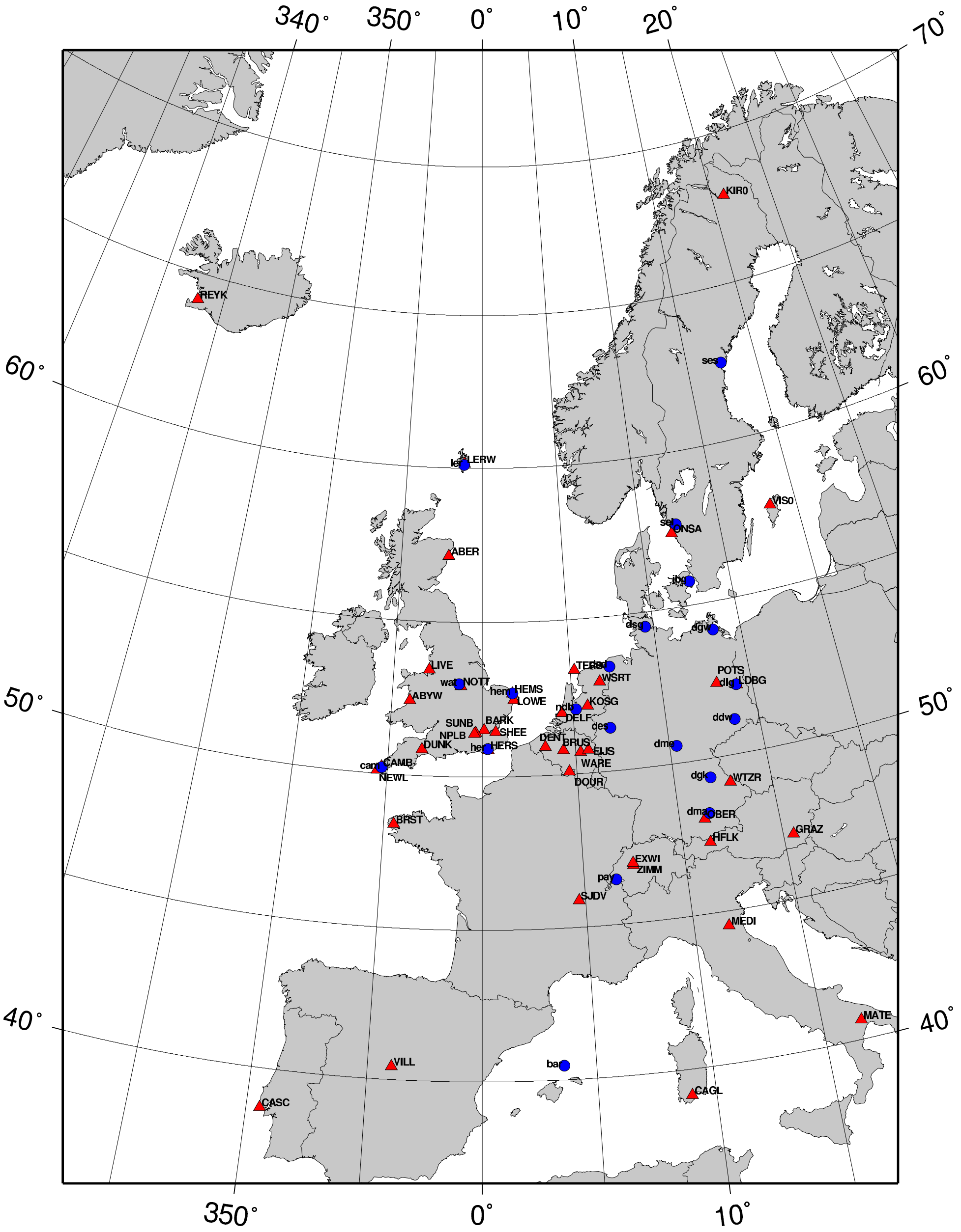


Figure 4.18: Map of GPS stations (triangles) participating in the benchmark campaign 9–23 July, 2000, with nearby radiosondes (circles).

flow, formats and assimilation into NWP models for the near real-time demonstration project, (ii) can serve as a benchmark against which to test various processing environments and assimilation into NWP, and (iii) to show the potential use of GPS-ZTD for NWP already in an early phase of the project. Of the 44 common stations, about 25 were centred around the North-Sea, of which 15 in the UK, thus forming a dense sub-network (Figure 4.18). This area and time was selected because the early part of the period was characterized by fine weather associated with a high pressure system over the UK, but which rapidly broke down, giving heavy rain with little warning in the NWP forecasts. The selected period did not have a strong atmospheric flow (dynamics) and showed predominantly convective weather phenomena.

It is expected that under these conditions GPS will contribute significantly to improving NWP forecasts of precipitation. The other stations were selected close to sites where radiosondes are launched, or near sites equipped with radiometers for validation purposes.

The benchmark data set was processed by 7 GPS analysis centres: ASI, CNRS, GFZ, GOP, IEEC, LPT and NKGS. These analysis centres also participated in the NRT demonstration that started in 2001, except for CNRS Geosciences Azur which role was later taken over by ACRI-ST, using the same software and strategy.

The benchmark data set consisted of 44 stations with in total 646 daily RINEX files (with a sampling interval of 30 s).

Many of the selected 44 stations were processed by all analysis centres, while several analysis centres added other stations to their solutions. In total 102 sites were processed by 7 analysis centres; 44 sites were used by 3 or more centres, 2 sites by 2 centres and 56 sites by 1 centre. For comparison purposes also four analysis centres produced solutions with post-processed quality which included 69 sites (with 43 sites processed by 3 or more centres, 1 site by 2 centres and 25 by only 1 centre).

Table 4.2: Analysis procedures used in the benchmark campaign.

	s/w	stations (+extra)	orbits	elev. cut-off	data window@int	ZTD interval
ASI	GIPSY	42 (+5)	JPLPRE	10°	12 hr @ 30 s	15 min [a]
CNRS	GAMIT	41 (+4)	IGU	15°	9 hr @ 30 s	15 min
GFZ	EPOS	41 (+24)	GFZADJ	15°	12 hr @ 150 s	1 hr
GOP	BSW	43	IGU	8°	12 hr @ 30 s	20 min
IEEC	GIPSY	23 (+30)	JPLPRE	10°	24 hr @ 300 s	15 min
LPT	BSW	44	IGU	10°	7 hr @ 30 s	1 hr
NKGS	GIPSY	39 (+46 [b])	IGU	15°	12 hr @ 300 s	15 min [a]

a) Averaged from 5 minute estimates.

b) Not included in COST files.

The processing strategies and software are shown in Table 4.2. Most analysis centres used IGS Ultra rapid orbits, except GFZ who used its own ultra rapid orbit product and ASI who used JPL precise orbits. CNRS, GFZ and NKGS also estimated additional orbit parameters. All but one applied corrections for ocean loading, but the strategies for the fixing of coordinates were very different.

4.4.1 Comparison between individual solutions

Hans van der Marel and Gerd Gendt

ZTD estimates from individual analysis centres have been compared side–by–side. This was done for the near real-time as well as the post-processed solutions.

The results of this pairwise comparison are shown in Figure 4.19 for the post-processed solutions. The number of common stations is given in lower-triangle of Table 4.3, the number of common observations of ZTD is given in the upper-triangle. There is in general a good agreement between the individual solutions, but as can be observed from the plots there are several instances when there are outliers for one of the analysis centres.

The mean bias and standard deviation of the pairwise comparison is given in Table 4.4 and Table 4.5. In the lower-triangle the mean bias is given, the standard deviation is given in the upper-triangle. Ta-

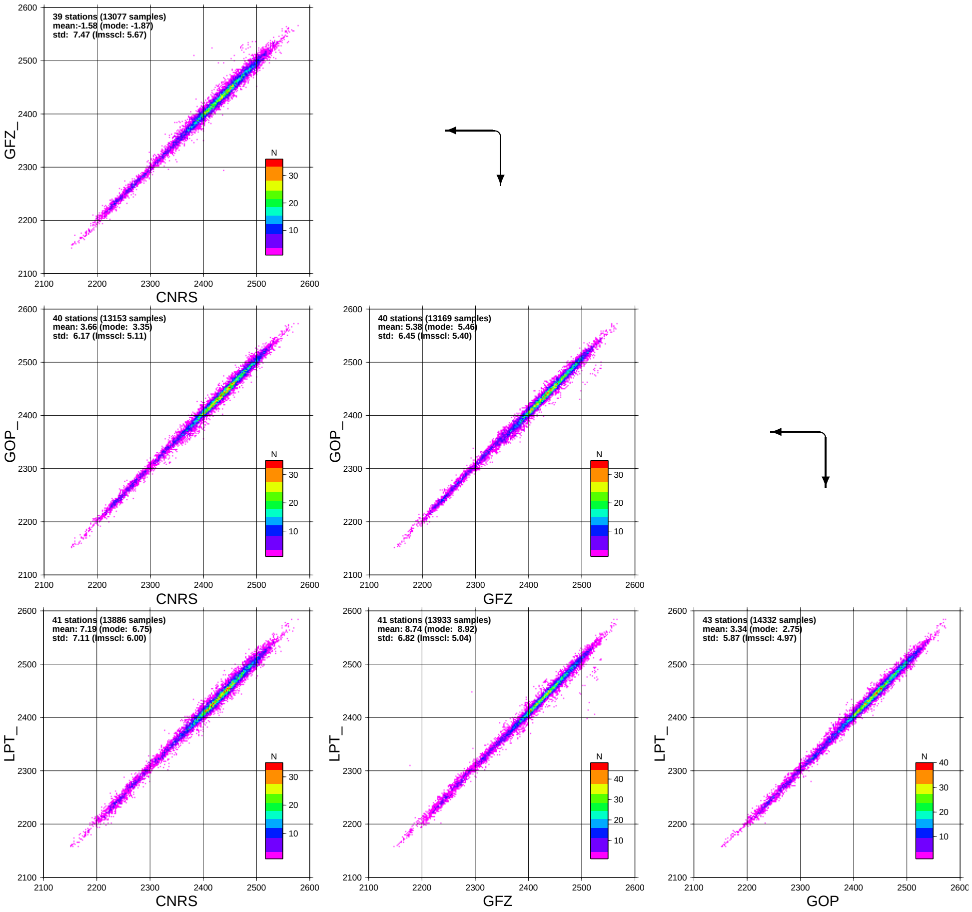


Figure 4.19: Pairwise comparison of ZTD between individual post-processed solutions.

ble 4.4 contains the mean bias and standard deviation using all observations, without any outlier rejection. Table 4.5 gives the more robust “Least Median of Squares” (LMS) estimate of the mode (mean bias) and scale (standard deviation). Clearly, there is a significant bias between the individual post-processed solutions. The largest bias is between GFZ (EPOS) and LPT (BSW), the smallest between GFZ (EPOS) and CNRS (GAMIT). The bias between LPT and GOP, both using the Bernese software (BSW), is somewhere in between. This is an indication that the bias is (not only) software related. The standard deviation is at the 6–7 mm level. The more robust LMS estimate of the standard deviation is 5–6 mm. The best agreement is between the two Bernese software solutions, also these solutions seem to contain fewer outliers, but the differences in terms of standard deviation are very small indeed.

The bias and standard deviation have also been computed using the method of Section 4.4.2. In this case the bias is computed on a station-by-station basis, and differences in ZTD in excess of 2.5 times the standard deviation have been removed. The results are given in Table 4.6, with the bias and scatter of the bias in the lower-triangle, and the standard deviation in the upper-triangle. These results confirm our earlier findings that the overall consistency in terms of standard deviation is 5–6 mm. The standard deviation, or scatter, of the station-by-station biases is between 1.5–2.5 mm.

The individual near-real time solutions have been compared in a similar way. Figure 4.21 gives the matrix of scatter plots for the near real-time solutions, using the same scale as in the plot for the post–

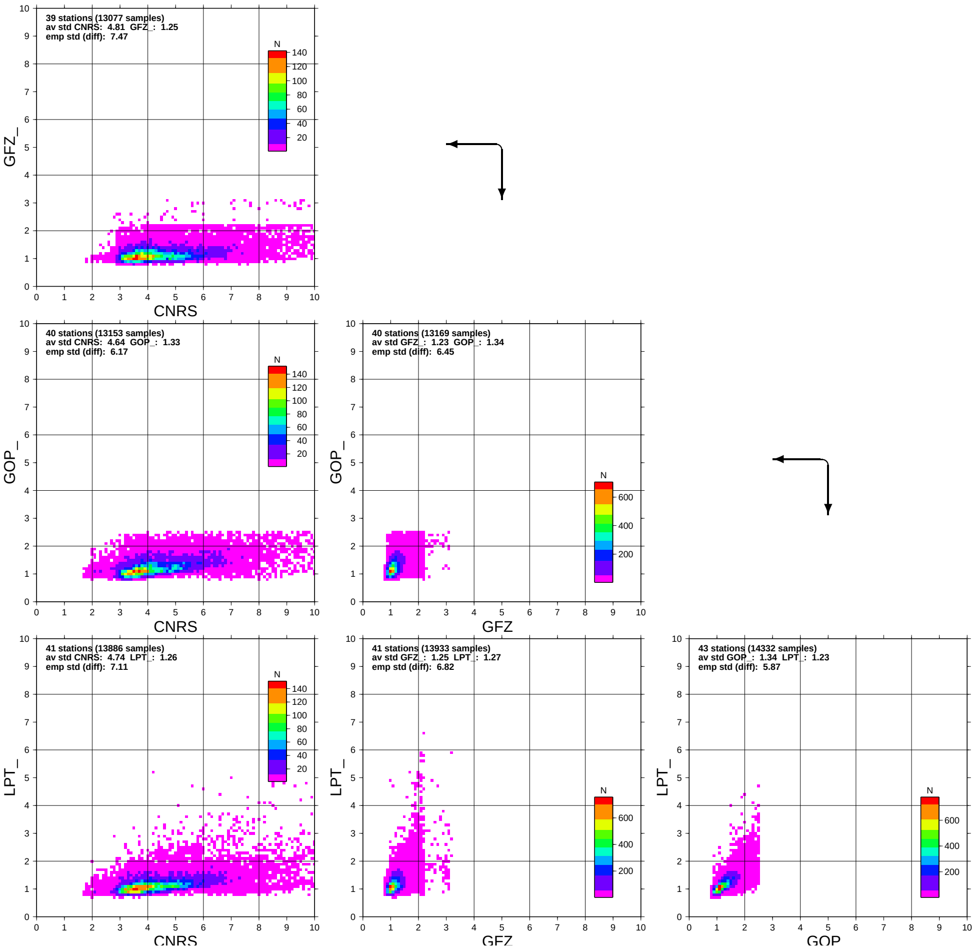


Figure 4.20: Pairwise comparison of the standard deviations provided by the individual post-processed solutions.

Table 4.3: Pairwise comparison of individual solutions (post-processed) with number of common stations (lower triangle) and observations (upper triangle).

	CNRS	GFZ	GOP	LPT
CNRS	–	13077	13153	13886
GFZ	39	–	13169	13933
GOP	40	40	–	14332
LPT	41	41	43	–

processed solution (Figure 4.19). The number of common stations is given in lower-triangle of Table 4.3, the number of common observations of ZTD is given in the upper-triangle. The number of off-diagonal elements, or outliers, in Figure 4.21 is larger than for the post-processed solutions. The IEEC solution has a cluster of ZTD that is clearly off compared to the other solutions, and the NKGS solution has a couple of estimates which have the same value, probably the a-priori estimate of the delay which has not been improved by actual observations. Also, the ASI solution seems to be a little more noisy. All this

Table 4.4: Pairwise comparison of individual solutions (post-processed) with mean difference (lower triangle) and standard deviation (upper triangle) (units: mm ZTD).

	CNRS	GFZ	GOP	LPT
CNRS	–	7.47	6.17	7.11
GFZ	−1.58	–	6.45	6.82
GOP	+3.66	+5.38	–	5.87
LPT	+7.19	+8.74	+3.34	–

Table 4.5: Pairwise comparison of individual solutions (post-processed) with LMS mode (lower triangle) and LMS scale or standard deviation (upper triangle) (units: mm ZTD).

	CNRS	GFZ	GOP	LPT
CNRS	–	5.67	5.11	6.00
GFZ	−1.87	–	5.40	5.04
GOP	+3.35	+5.46	–	4.97
LPT	+6.75	+8.92	+2.75	–

Table 4.6: Pairwise comparison of individual solutions (post-processed) with standard deviation in the upper triangle and bias with scatter of bias (from site to site) in the lower triangle (units: mm ZTD).

bias/stdev	CNRS	GFZ	GOP	LPT
CNRS	–	5.0	4.5	5.6
GFZ	−2.1±2.1	–	4.8	4.9
GOP	+3.6±1.8	+5.6±1.6	–	5.0
LPT	+6.8±2.4	+8.8±2.0	+3.2±2.0	–

does not mean much as these outliers may be accompanied by large standard deviations in the COST files.

The mean bias and standard deviation of the pairwise comparison is given in Tables 4.8 and 4.9. In the lower-triangle the mean bias is given, the standard deviation is given in the upper-triangle. Table 4.8 contains the mean bias and standard deviation using all observations, without any outlier rejection. Table 4.9 gives the more robust “Least Median of Squares” estimate of the mode (mean bias) and scale (standard deviation). Table 4.10 gives the bias and scatter of the bias in the lower-triangle, and the standard deviation in the upper-triangle, computed using the method of Section 4.4.2. In this case the bias is computed on a station-by-station basis, and differences in ZTD in excess of 2.5 times the standard deviation have been removed.

Again, there are significant biases between the individual near real-time solutions, as was the case also with the post-processed solutions. The largest bias is again between GFZ (EPOS) and LPT (BSW), the smallest between solutions from ASI and IEEC, both using GIPSY, and GOP and LPT both using the Bernese, but also NKGS using GIPSY and the two Bernese solutions (GOP, LPT) have small biases. What is immediately clear from Table 4.8, compared to Table 4.9, is that the near real-time solutions contain a lot of outliers. For example, GFZ and IEEC included estimates of ZTD which completely

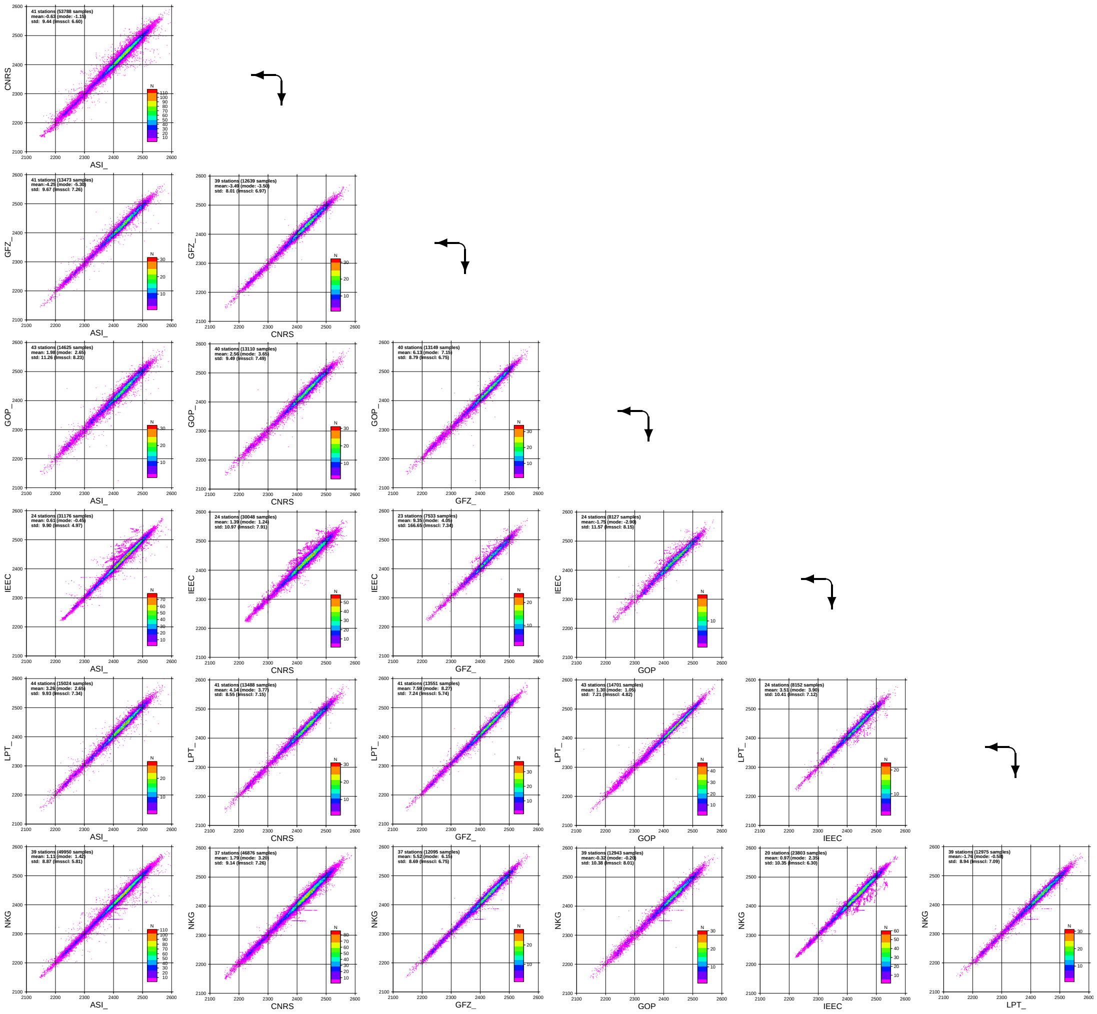


Figure 4.21: Pairwise comparison of ZTD between individual NRT solutions.

disagreed, and which other analysis centres apparently rejected. However, again these estimates may be valid if the corresponding standard deviation of the estimate in the COST file is large as well.

The standard deviations in Table 4.9 and Table 4.10 are larger than the standard deviations of the corresponding post-processed solutions. The standard deviations are at the 5–8 mm level. The smallest standard deviations, about 5 mm, are between the ASI, IEEC and NKGS solutions, all using GIPSY, and LPT and GOP solutions, both using Bernese. The highest standard deviations, 6–7 mm, are between solutions using different software packages. It should be noted that ASI, IEEC and NKGS used a higher sample rate than the other analysis centres, which can be seen clearly from Table 4.7 where the number of common observations is listed. In Table 4.9 we have compared the nearest estimates, but in Table 4.10 the ZTDs have first been averaged into hourly values, and is therefore more consistent between analysis centres.

Also the standard deviation of the ZTD parameters have been compared side-by-side. The standard deviations are given in the COST 716 files and were computed by the analysis centres. The results of the pairwise comparison for the standard deviations are shown in Figure 4.20 for the post-processed

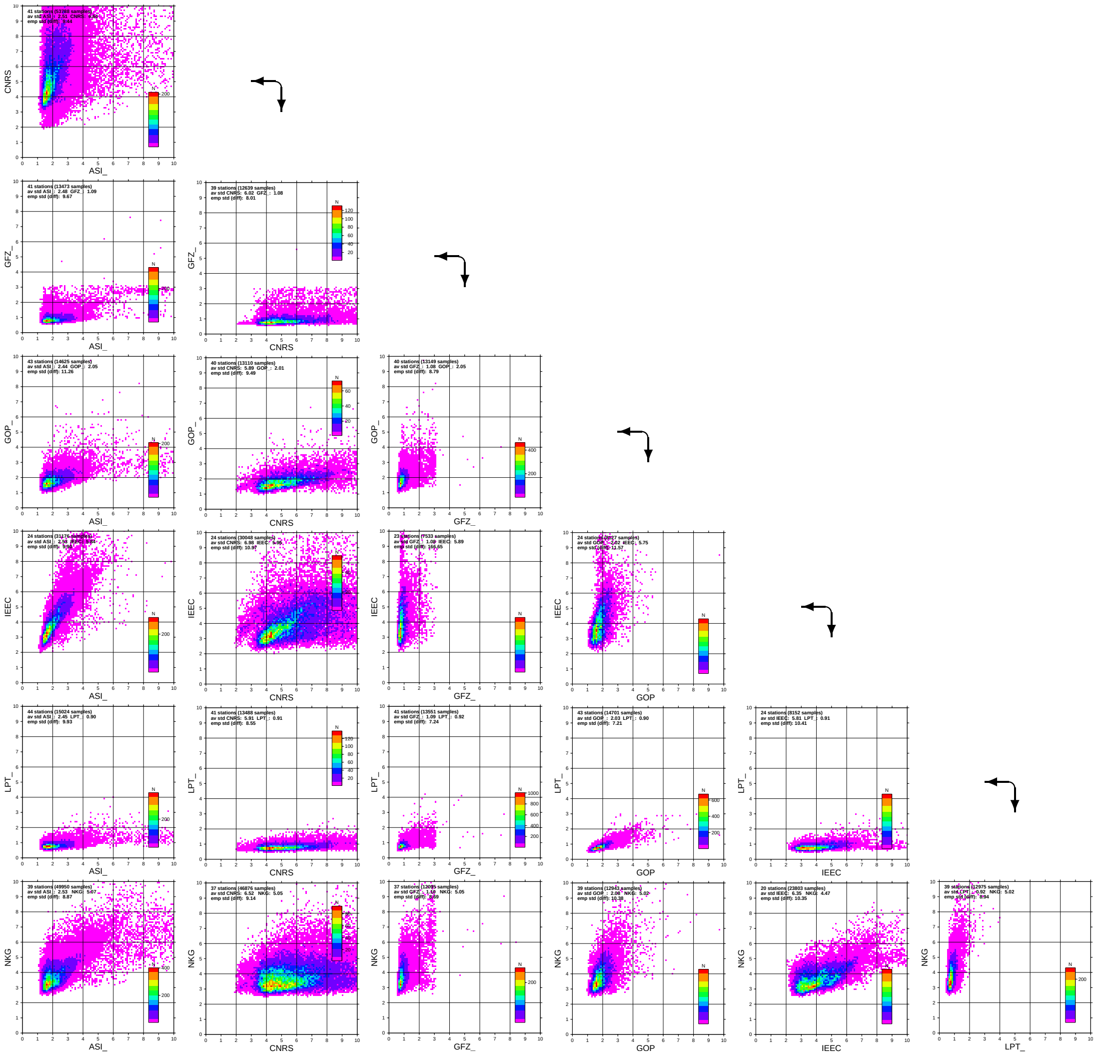


Figure 4.22: Pairwise comparison of the standard deviations provided by the individual NRT solutions.

Table 4.7: Pairwise comparison of individual solutions (NRT) with number of common stations (lower triangle) and observations (upper triangle).

	ASI	CNRS	GFZ	GOP	IEEC	LPT	NKGS
ASI	–	53788	13473	14625	31176	15024	49950
CNRS	41	–	12639	13110	30038	13488	46876
GFZ	41	39	–	13149	7533	13551	12095
GOP	42	40	40	–	8127	14701	12943
IEEC	24	24	23	24	–	8182	23803
LPT	44	41	41	43	24	–	12975
NKGS	39	37	37	39	20	39	–

Table 4.8: Pairwise comparison of individual solutions (NRT) with mean difference in the lower-triangle and standard deviation in the upper-triangle (units: mm ZTD).

	ASI	CNRS	GFZ	GOP	IEEC	LPT	NKGS
ASI	–	9.44	9.67	11.26	9.90	9.93	8.87
CNRS	−0.63	–	8.01	9.49	10.97	8.55	9.14
GFZ	−4.25	−3.49	–	8.79	166.65	7.24	8.69
GOP	+1.98	+2.56	+6.13	–	11.57	7.21	10.38
IEEC	+0.61	+1.39	+9.35	−1.75	–	10.41	10.35
LPT	+3.26	+4.14	+7.59	+1.30	+3.51	–	8.94
NKGS	+1.11	+1.79	+5.52	−0.32	+0.97	−1.76	–

Table 4.9: Pairwise comparison of individual solutions (NRT) with LMS mode (lower triangle) and LMS scale or standard deviation (upper triangle) (units: mm ZTD).

	ASI	CNRS	GFZ	GOP	IEEC	LPT	NKGS
ASI	–	6.60	7.26	8.23	4.97	7.34	5.81
CNRS	−1.15	–	6.97	7.49	7.91	7.15	7.26
GFZ	−5.30	−3.50	–	6.75	7.34	5.74	6.75
GOP	+2.65	+3.65	+7.15	–	8.15	4.82	8.01
IEEC	−0.45	+1.24	+4.05	−2.90	–	7.12	6.30
LPT	+2.65	+3.77	+8.27	+1.05	+3.90	–	7.09
NKGS	+1.42	+3.20	+6.15	−0.20	+2.35	−0.58	–

Table 4.10: Pairwise comparison of individual solutions (NRT) with standard deviation in the upper triangle and bias with scatter of bias (from site to site) in the lower triangle (units: mm ZTD).

bias/stdev	ASI	CNRS	GFZ	GOP	IEEC	LPT	NKGS
ASI	–	6.3	6.6	8.2	5.2	7.1	4.5
CNRS	−0.5±1.0	–	6.7	7.6	8.0	7.2	6.7
GFZ	−4.6±2.1	−3.8±2.4	–	7.1	7.3	5.9	6.9
GOP	+1.9±3.0	+2.6±2.7	+6.3±1.9	–	8.2	4.9	8.2
IEEC	−0.2±0.8	+0.6±1.5	+3.9±2.6	−2.1±3.8	–	7.2	5.6
LPT	+3.0±2.2	+3.9±1.8	+7.8±1.7	+1.2±1.6	+3.8±2.2	–	7.3
NKGS	+1.4±2.1	+2.5±1.9	+6.0±1.3	−0.0±2.1	+2.6±2.4	−1.5±1.2	–

solutions and in Figure 4.22 for the near real-time solutions, using the same scale in both figures. It is clear from these figures that the analysis centres and software use different methods to compute the standard deviation of the estimated ZTD parameters. Again there is a good agreement between analysis centres using the same software package, such as LPT and GOP, and ASI, IEEC and NKGS, although there is sometimes a slope. The slope is also related to the different sample rates used for the data and for the estimation of ZTD. The standard deviations provided by LPT, GOP and GFZ are not in line with the pairwise comparisons of ZTD and are probably too optimistic. The standard deviations given by CNRS, ASI, IEEC and NKGS, which are generally larger, are more in line with our pairwise comparisons.

4.4.2 Comparison with a combined post-processed solution

Gerd Gendt and Hans van der Marel

NRT and post-processed results were computed by the individual analysis centres (ACs) using the benchmark data. Whereas the post-processed analysis is based on daily batches using the best orbits and random-walk-like constraints to stabilize the solutions within the day, the NRT analysis is concentrating on the last hour, using and often fixing predicted orbits. The main drawback for the NRT analysis, besides the non-optimal orbits, is the missing possibility of constraining the solution at the end of the data interval. For post-processed result this is only the case at the day boundaries, where sometimes jumps from day to day occur, but the central points have a much higher accuracy. Therefore post-processed results are a good candidate for a validation of the NRT products.

In our COST action we are faced with solutions from many ACs, and to get a compressed overview it makes sense to use a reference solution to compare all individual results with. An obvious reference is a combined solutions from all available inputs. The ACs have applied sampling rates from 15 to 60 minutes. For the combination and for computing all the differences between the various results the submitted solutions are unified by forming hourly means.

The combination algorithm can be summarized shortly as follows (Gendt, 1996, 1998):

Step 1: Determination of a preliminary combined solution to define the weights and bias-corrections for the final combination. For the combination only epochs are used were all ACs have ZTD estimates, otherwise a missing AC value may result in a jump for the combined series. Estimates with a difference larger than 20 mm ZTD are excluded. Differences between combination and the individual AC solutions yield standard deviations and site dependent biases for each AC that are used for the final combination.

Step 2: The final combination uses weights for each AC derived by the standard deviations from Step 1. Mean ZTD are computed where the AC estimates are corrected by the site dependent biases from Step 1. This way all epochs can be used and a gap in the series of one AC will not result in a jump in the final solution. Outliers are eliminated with a threshold of 2.5·rmsepoch.

Table 4.11: Comparison of individual NRT and post-processed (PP) solutions with combined NRT (NRTCOMB) and combined post-processed (PPCOMB) solutions (units: mm ZTD).

		NRT - NRTCOMB		NRT - PPCOMB		PP - PPCOMB	
Centre	sites	Stdev	Bias	Stdev	Bias	Stdev	Bias
ASI	43	3.86	−0.13 ± 1.29	4.14	−0.69 ± 1.75		
CNRS	41	4.62	−1.05 ± 1.12	5.34	−1.51 ± 1.26	3.2	−2.2 ± 1.3
GFZ	41	4.26	−4.56 ± 1.38	4.84	−5.04 ± 1.44	2.9	−3.9 ± 1.3
GOP	42	4.92	1.71 ± 1.85	6.41	1.19 ± 1.69	2.8	1.4 ± 1.0
IEEC	23	4.49	−0.87 ± 1.82	5.11	−1.12 ± 1.76		
LPT	43	4.02	2.94 ± 1.23	5.14	2.35 ± 1.05	3.3	4.8 ± 1.3
NKGS	39	4.29	1.43 ± 1.12	4.45	0.83 ± 0.99		
NRTCOMB	43			2.85	−0.59 ± 0.56		

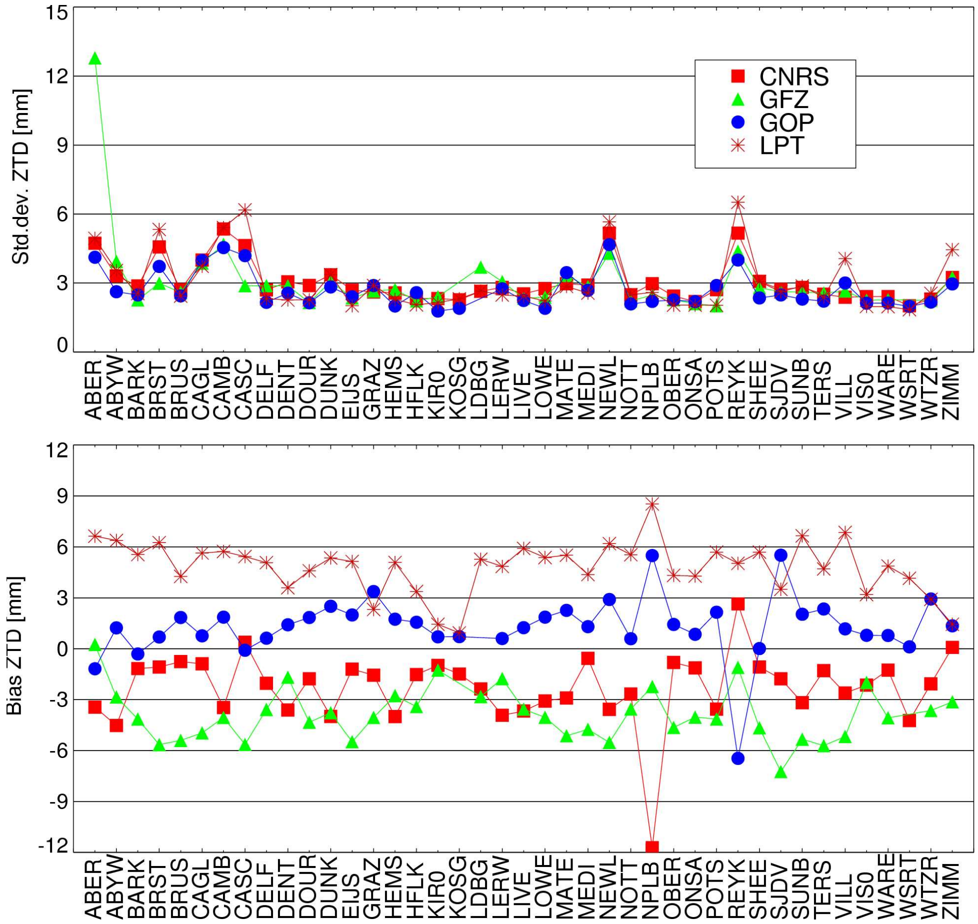


Figure 4.23: Standard deviation (top) and biases (bottom) of the individual post-processed solutions with respect to the combined post-processed solution.

The described combination procedure is used to generate two combined products:

combined Post-processed solution (submissions from 4 ACs, total 69 sites)

- 43 sites used by 3 or more centres
- 1 site used by 2 centres
- 25 sites used by 1 centre

combined NRT solution (submissions from 7 ACs, total 102 sites)

- 44 sites used by 3 or more centres
- 2 sites used by 2 centres
- 56 sites used by 1 centre

All following comparisons will consider only those sites which were used by at least 3 analysis centres. This gives more realistic statistics. One should have in mind that the site-specific biases in the combined solution may scatter from site to site if different ACs had contributed to different sites. However, if the biases are small and the number of ACs is rather large then this effect is not much pronounced. Looking into the AC specific biases in Figure 4.23 one can easily imagine the influence of missing ACs on a site

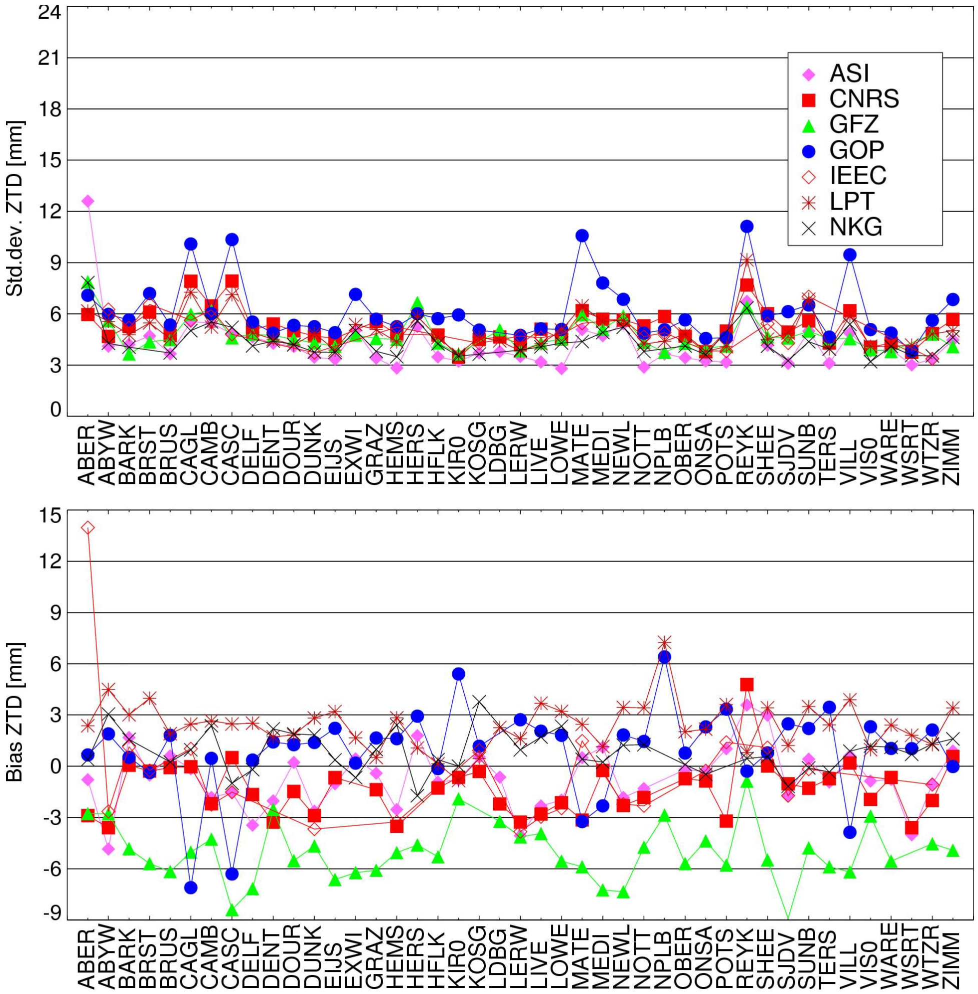


Figure 4.24: Standard deviation (top) and biases (bottom) of the individual NRT solutions with respect to the combined post-processed solution.

bias in the combined solution. The different number of contributing ACs (4 or 7) is the main reason why both combined products have a difference in the mean bias (Table 4.11, last line).

Post-processed results are summarized in Figure 4.23 and Table 4.11, where the 4 contributing ACs are compared to the combined post-processed solution. The standard deviation for all ACs is at the 3 mm ZTD level. Higher values can be found for few sites located near the boundary of the used network (e.g. REYK, NEWL, CAMB, ABER, BRST, CASC) where usually the quality is not as high as in the central parts of the network. The repeatability of the bias from site to site (the bias correlation between the sites in the network) for each ACs is very high, the scatter from site to site is only slightly larger than 1 mm ZTD. However, the bias level from AC to AC vary from -3.9 for GFZ to +4.8 for LPT, that covers a range of 8.7 mm in ZTD, which amounts to nearly 1.5 kg/m^2. The different biases are caused by the strategies applied by the ACs in using mapping functions, elevation cut-off angles, et cetera. The consistency of all submitted post-processed solutions corresponds to a level of about 0.5 to 1 kg/m^2 in the water vapour content, for standard deviation and bias. Of course there is no information on the absolute bias of the solution because no external error free reference is known. The total bias of the combination is also a

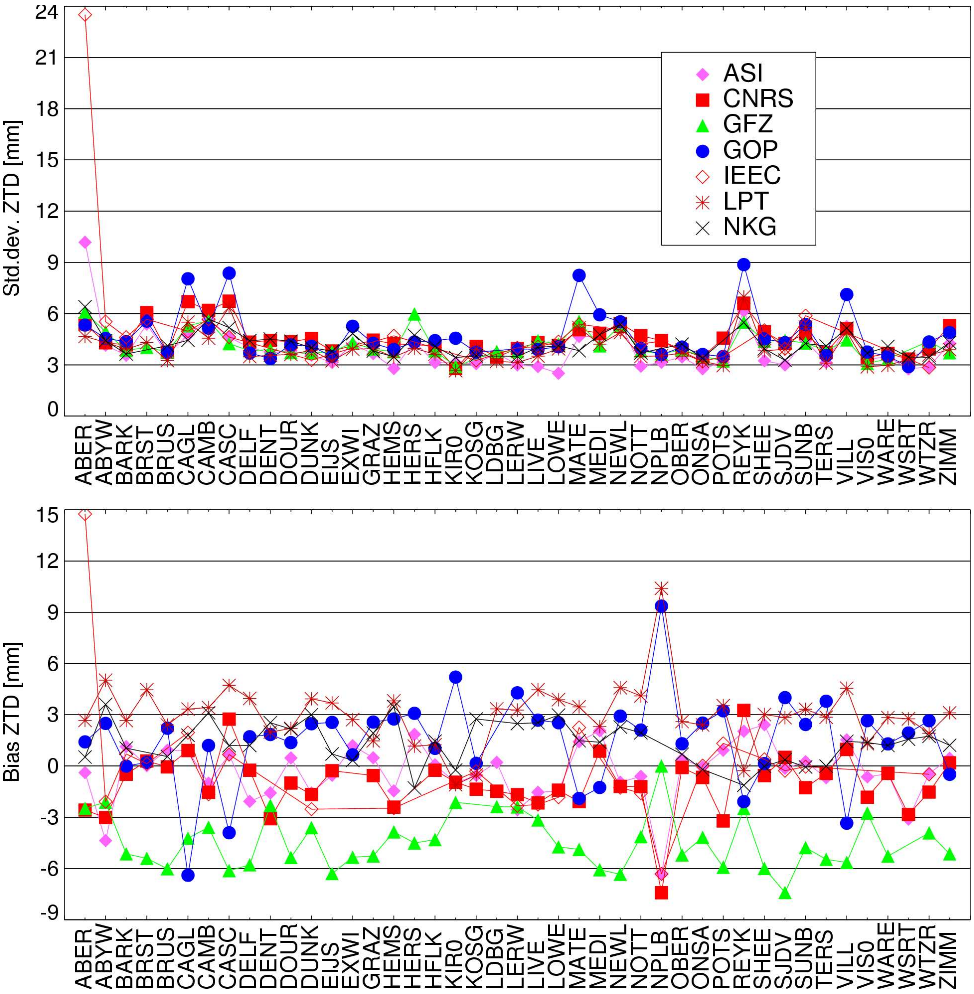


Figure 4.25: Standard deviation (top) and biases (bottom) of the individual NRT solutions with respect to the combined NRT solution.

function of the number of contributing ACs. On the other hand a constant bias over the whole network would not be very critical, because it can be accounted for in further applications.

The difference of both combined solutions is very small, the mean bias and the site dependent bias scatter are at the level of 0.5 mm ZTD (Table 4.11).

After the evaluation of the combined solutions they can be used to validate the individual NRT submissions. First, all NRT solutions are compared to the combined post-processed solution in Table 4.11 and Figure 4.24. The peak to peak ACs biases (GFZ to LPT) are here 7.4 mm ZTD and the bias scatter from site to site is slightly larger than for the post-processed solutions (ranging from ±1.0 to ±1.7 mm). The standard deviations for the NRT solutions have a level of about 5 mm (4.2 to 6.4 mm ZTD), which correspond to about 1 kg/m^2 in IWV and better. As for the post-processed solutions also here the lower accuracies for sites at the network boundaries can be seen.

The differences to the combined NRT-solution are nearly the same as to the post-processed combination, as can be seen from Table 4.11 and Figure 4.25. The biases are shifted according to the mean bias between the two combined solutions by about 0.5 mm ZTD. The standard deviations are even slightly smaller for this variant, because the NRT submissions themselves are entered into the combined solutions.

Summarizing the comparisons one can state that the consistency of the NRT AC solutions is about 1 to 1.5 kg/m^2 in IWV, while the post-processed solutions are approaching the 0.5 kg/m^2. Not accounted for in these numbers is an unknown bias which may reach the same amount.

4.4.3 Comparison with radiosonde data

Hans van der Marel and Siebren de Haan

The ZTD from the benchmark campaign has been compared ZTD computed from radiosonde measurements. The radiosondes, and the distance to the nearest GPS stations, are listed in Table 4.12. The ZHD has been computed from the observed surface pressure using the Saastamoinen model (Saastamoinen, 1972). The surface pressure has been corrected for the height of the GPS antenna. The IWV has been computed by integrating the radiosonde profile, using the measured pressure, temperature and dew-point temperature of the radiosonde. Two corrections were made: a correction for the height difference between the GPS antenna and radiosonde, and a correction for the top of the atmosphere. The IWV was then converted to ZWD using the relation for the mean temperature from Klein Baltink et al. (2002).

The results of the comparison with radiosondes are given in Figure 4.26. The standard deviation is clearly correlated with distance between the GPS point and the radiosonde, except for two sites in the

Table 4.12: Radiosondes using in the benchmark campaign, with the distance to the nearest GPS stations and the height of the radiosonde and GPS stations above mean sea level (MSL). The distances are accurate to a few km due to truncation errors in latitude and longitude, so the tenths of km are misleading, but we keep them as these values have been used to plot the data.

Radiosonde Site/Country	GPS station	Distance km	H_{RS} m	H_{GPS} m
Cam/UK	CAMB	2.8	87	86
	NEWL	20.4		11
Ded/DE	WSRT	66.5	5	41
Dlg/DE	LDBG	1.2	98	134
	POTS	73.8		104
Hem/UK	HEMS	1.7	13	17
	LOWE	25.4		9
Her/UK ^{a})	HERS	4.4	52	31
Ler/UK	LERW	4.4	84	81
Ndb/NL	KOSG	43.8	2	53
	DELF	55.7		31
Pay/CH	ZIMM	81.3	490	907
	EXWI	84.5		578
Sel/SE ^{a})	ONSA	37.9	155	9
Jbg/DK	ONSA	184.4	40	9
Wat/UK	NOTT	9.8	117	49

a) Radiosonde has not yet been processed.

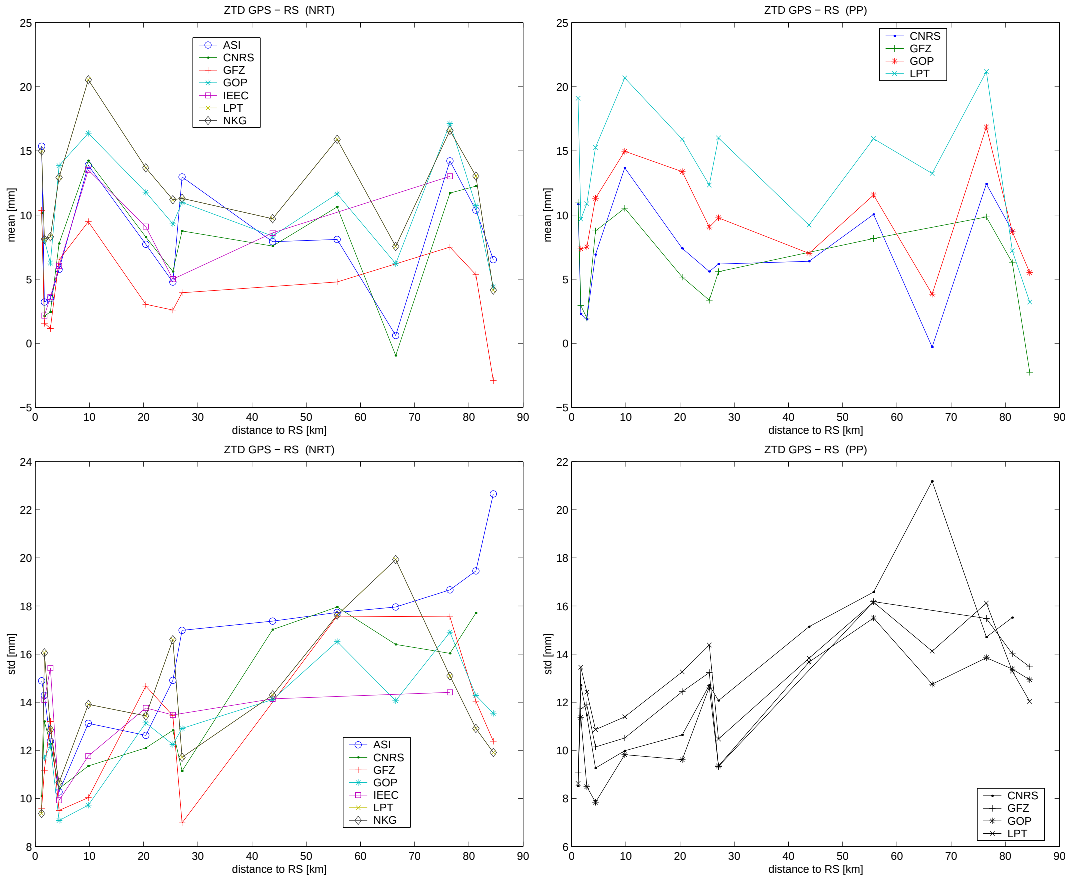


Figure 4.26: Mean and standard deviation of the difference in ZTD with nearby radiosondes as function of the distance to the radiosonde. The top row shows the mean, the bottom row the standard deviation. The plots on the left are for the NRT processing, the two plots on the right are for the post-processed solutions.

UK, CAMB and HEMS, at 1.7 and 2.8 km distance. There is no explanation yet why CAMB and HEMS behave differently, but is seems to be related to the radiosonde data or our procedure for computing ZTD from the radiosonde. The correlation with distance between the GPS and radiosonde point is understandable, as the difference in IWV increase with distance. However, in our results also another effect is included. Although we have corrected the pressure for the height difference between GPS and Radiosonde in the computation of ZHD, we did not take into account pressure gradients between the radiosonde and GPS station. Despite this, the standard deviation is in line with results reported by e.g. Klein Baltink et al. (2002), who found a slightly smaller standard deviation for the ZWD of 9 mm, using one year of post-processed data in the same area. The bias is almost independent of distance. The height difference between the GPS and radiosonde were small, except for ZIMM and EXWI at 81 and 84 km, and should not play a role in the bias computation. Also, our height correction scheme seems to work well for both ZIMM and EXWI. On the average a bias of roughly 10 mm is found in ZTD. This is larger than e.g. reported in Klein Baltink et al. (2002), who found a bias (in ZWD) of almost a factor 2 smaller depending on the ZWD.

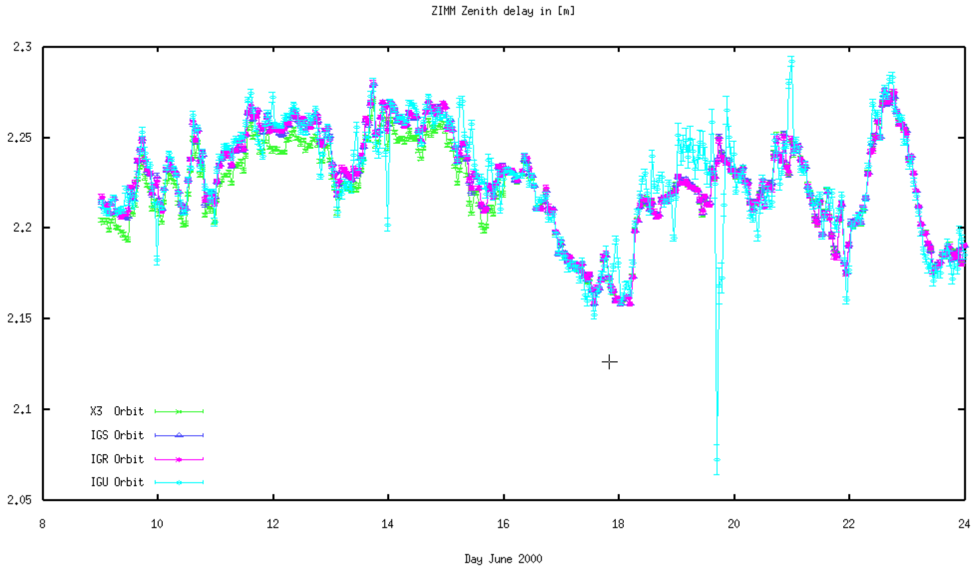


Figure 4.27: ZTD estimates from the 24-hour session processing for site ZIMM using different orbit information.

4.4.4 Other experiments with benchmark data

Elmar Brockmann

Swisstopo (LPT) processed the benchmark data set, consisting of 646 daily 30-second RINEX files, using various processing options in order to define the processing strategy for the true NRT processing. The processing of the data was done with Bernese 4.2 (Hugentobler et al., 2001). A two-step approach was performed:

1. Processing of 24-hour sessions (a "typical" post-processing solution) in order to have a reference solution for the estimated zenith total delays (ZTDs) and to determine a best possible set of station coordinates.
2. Processing of hourly data using different processing strategies. The goal is to achieve results which are as close as possible to the reference solution.

The parameterisation of the reference 24-hour solutions is quite straightforward. LPT used the same modelling which was used for the daily analysis of the Swiss AGNES network. To demonstrate the impact of the orbits, LPT processed the 24-hour sessions using different orbit types (IGS orbits, CODE orbits, rapid orbits, and ultra rapid orbits). The ZTD estimates for site ZIMM are shown in Figure 4.27. Whereas the X3 orbits (CODE), IGS orbits and rapid orbits show similar results, the quality is considerably worse when using the ultra rapid orbits. LPT used all available satellites without a satellite exclusion scheme. Excluding the worst satellites solves the problems of outliers in Figure 4.27 (e.g. on day 19). This is important to remember when comparing the hourly processed solutions using the ultra rapid orbits with the reference solution afterwards.

The data of the benchmark data set were split into hourly data in order to simulate a near real-time processing of hourly data. LPT processed a series of 10 different processing settings in order to evaluate the best possible options. LPT mainly analysed the following processing options:

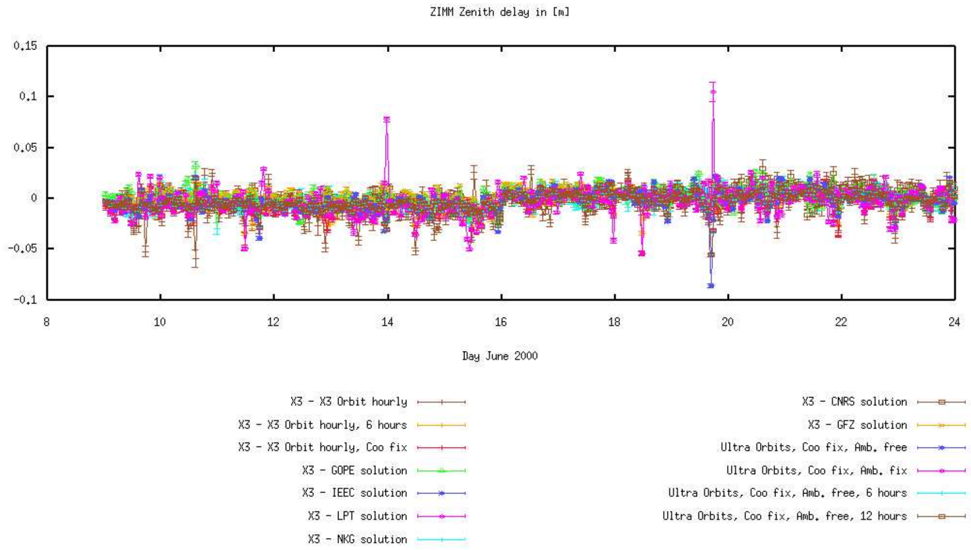


Figure 4.28: Differences of ZTD estimates of ZIMM for different solution types with respect to the post-processed reference solution. Although it is impossible to make out the individual solution types in this figure, the scatter gives an idea of how the various solutions differ.

- orbit type (IGS orbits, CODE orbits, rapid orbits, and ultra rapid orbits)
- coordinate fixing
- ambiguity resolution
- number of accumulation hours
- relative weights between consecutive ZTD parameters

The difference between some of the solutions with respect to the reference solution is shown in Figure 4.28. The figure gives an approximate idea of how the various solutions differ. In addition, the near real-time solutions of the other processing centres GOP, IEEC, NKGS, CNRS and GFZ were added to the plot.

Statistical values (offset and RMS) have been computed for each station with respect to the reference solution. The sites at the network boundaries have larger RMS values for almost all solution types. The summary as an average of all sites is given in Table 4.13.

From Table 4.13 one also can easily conclude that the ambiguity resolution approach using only one hour of data was not successful. The RMS values compared to the reference solution are considerably larger. The same is also true for the solutions where the station coordinates were not fixed. The solutions with fixed coordinates show a better agreement with the reference solution. The use of IGS ultra rapid orbits instead of CODE, IGS final, or IGS rapid orbits is also visible. Nevertheless these orbit products of higher quality will never be available in time and are therefore not applicable for the near real-time processing.

In these studies of the benchmark data set LPT used the ultra rapid orbits without any outlier rejection procedure. Also LPT did not try to do an orbit improvement adjustment using a larger station reference

Table 4.13: Comparison of different NRT solution types w.r.t. post-processed reference solution. The offset and RMS are an average of all possible involved stations. Hourly ZTD values were compared.

Type	Description	Offset	RMS
CQ	Code orbits, amb. free, coor. estim., 1 hour accumulation	0.50 ± 1.48	11.36 ± 3.42
CT	Code orbits, amb. free, coor. estim., 6 hour accumulation	3.24 ± 1.82	7.47 ± 2.94
CF	Code orbits, amb. free, coor. fix, 1 hour accumulation	3.35 ± 1.75	9.29 ± 4.45
UF	Ultra orbits, coor. fix, amb. free, 1 hour accumulation	2.31 ± 1.24	8.48 ± 2.45
UX	Ultra orbits, coor. fix, amb. fix, 1 hour accumulation	5.66 ± 3.24	12.15 ± 2.90
UR	Ultra orbits, coor. fix, amb. free, 6 hour accumulation, no relative constraints	2.27 ± 1.16	6.48 ± 1.55
US	Ultra orbits, coor. fix, amb. free, 12 hour accumulation, no relative constraints	2.27 ± 1.16	6.48 ± 1.55
U1	as UR, but compare hour -1	2.27 ± 1.15	5.90 ± 1.31
U4	as UR, but compare hour -4	2.22 ± 1.16	5.77 ± 1.24
UT	as UF, but 3 days accumulation, 0.03 mm rel. constraints	2.02 ± 1.26	8.80 ± 2.63
UU	as UF, but 7 days accumulation, 0.03 mm rel. constraints	2.05 ± 1.20	7.12 ± 1.76

network. Later on, LPT implemented a satellite rejection procedure based on the double-difference residuals for the NRT demonstration phase. A maximum of 2 satellites may have to be excluded in case of satellite problems. But due to the improved quality of the ultra-rapid orbits an exclusion of a satellite happens very rarely.

A very efficient method for avoiding that a bad satellite quality affects the ZTD estimates is a combination of the normal equations of the last several hours (3–12 hours) and the application of relative constraints between consecutive ZTDs of a site. LPT adjusted the constraints in a way that under “normal” conditions without bad satellites, the constraints will have almost no influence on the estimates. In the case of bad satellites the complete solution is usually considerably weaker. In that case, the relative weights do not allow that the weak ZTDs cause an outlier in the ZTD series during periods with satellite problems. In other words: the previous hours determine the ZTD parameters of that problematic period under the assumption that the situation does not change. Such a procedure is therefore not perfect (and neither from the statistical point of view). It would be better that the ZTD values are used together with their uncertainties. At this early stage of the project such a sophisticated method of using ZTD values for the numerical weather prediction was not yet realistic. Therefore, we applied the method of using relative constraints between consecutive ZTD estimates.

LPT tested several relative weight models and also several lengths of accumulation intervals in order to determine the best possible choice of the settings. When using no relative weights and using fixed station coordinates, a longer accumulation interval is useless because only the data of the last hour estimate the ZTD parameters (see also Table 4.13 solution type UR and US).

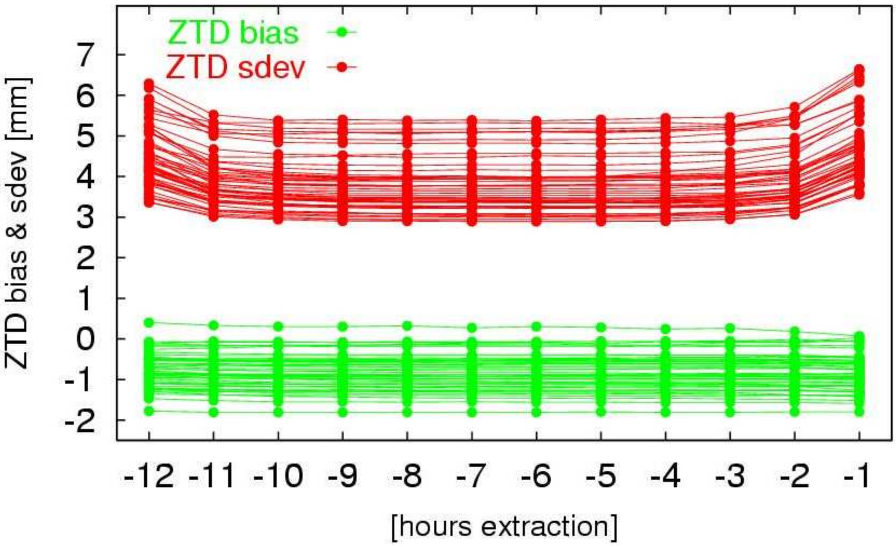


Figure 4.29: Comparison of ZTD from the last hour, second-last hour, etc., with the post-processed solution.

Just for getting a feeling of the quality of the estimates, LPT compared the second-last hour of the NRT solution and the fourth-last hour with our reference solution. Even without using relative constraints there is a better agreement with the reference solution visible (in terms of RMS). The last hour (and also the first hour) is clearly the estimate with the most uncertainty. This effect is illustrated also clearly in Figure 4.29 where the scatter of the ZTD from the last hour, second-last hour, etc., is compared with a post-processed solution, showing a 20% improvement at the expense of 2–3 hours delay.

From the tests with different accumulation periods using relative constraints, Table 4.13 shows only the solution types UT and UU. There LPT used an accumulation interval of 3 / 7 hours (last hour plus previous 2 / 6 hours) and relative ZTD constraints of 0.03 mm between consecutive ZTD intervals. Finally, LPT decided on solution type UU as NRT solution of LPT.

When generating the estimates in the COST 716 format, LPT excluded all estimates with a formal error of 1 cm ZTD. These weak estimates have their origin mainly in too small a number of observations. In Table 4.13 the LPT NRT solution therefore agrees slightly better with the reference solution as solution type UU.

LPT solved for hourly ZTD estimates. Tests were also made based on 20 minute intervals, which resulted mainly in an increased noise of the ZTD estimates.

It is worth mentioning that the agreement of NRT solutions from other analysis centres with the LPT reference solution is of the same order as the solutions shown in Table 4.13.

4.4.5 Conclusions from the benchmark data set

The individual solutions for the benchmark were compared with combined solutions of NRT and post-processed quality (Table 4.11 and Figure 4.24). The overall consistency between the solutions is about 5–6 mm measured in standard deviation for the Zenith Delay, or better than 1 kg/m^2 in Integrated Water Vapour, with systematic biases between the analyses centres of -5 to 2.4 mm. Pairwise comparisons between the individual solution revealed higher standard deviations, mainly due to irregularities in the data. Slightly improved biases and standard deviations are expected for the NRT demonstration, as the NRT demonstration can benefit from recent advances in the IGS Ultra Rapid orbits. Also post-processing has a favourable impact on the standard deviations, because the final, and more precise, IGS orbits can be used instead of the predicted orbits, and because the data can be processed in longer batches and the ZTDs are not always at the end of the batch (the last hour), as is the case for the NRT processing.

The ZTD from the benchmark campaign has been compared ZTD computed from radiosonde measurements. The agreement between ZTD from GPS and radiosonde is roughly between 10 and 15 mm for the near real-time processing for nearby stations, and slightly better for post-processing. The bias between GPS ZTD and radiosonde is between 5 and 20 mm, depending on the station and the GPS processing centre.

The standard deviations are certainly acceptable for NWP, but the biases between the different analysis centres are a bigger problem for NWP. The biases make it difficult for NWP to combine data from different analysis centres, and also may make the predictions systematically too wet, or too dry.

There are several reasons why we find biases between the analysis centres. The GPS-ZTD depends on the mapping function, elevation dependent weighting, and elevation dependent phase centre corrections that are used in the analysis. This becomes apparent when the analysis centres are using different elevation dependent correction models, but also when they use different elevation cut-off angles as is the case in the benchmark campaign and the NRT demonstration, which may result in station and analysis centre dependent biases in the ZTDs of up to several mm. The GPS-ZTD is also dependent on the cut-off angle because the elevation dependent phase centre corrections and mapping functions may still contain errors. All analysis centres use the Niell mapping function which depends only on latitude, day of year and height of the station, and has been derived from a limited set of radiosonde profiles (Niell, 1996). However, there are differences in the way the a-priori hydrostatic delay is computed, which will result also in biases of a few mm. Recent work by Niell (2000), Niell (2001) and Rocken et al. (2001) has shown that the Niell mapping function may contain seasonal and latitude dependent biases, and that the elevation dependency of the ZTD can be eliminated by using mapping functions based on weather models. This could be an explanation for the biases in Table 4.11 and Figure 4.24, although this will not be the only explanation. The different orbits that are used, and the different strategies for fixing the stations coordinates and the different coordinates of the fixed stations are also responsible for these biases.

The GPS Zenith Total Delays from the Benchmark campaign have been assimilated into Numerical Weather Prediction models of the UK Met Office, SMHI, DWD and DMI in order to study the effect on the weather forecast. Results from assimilation trials by WG 3 using the COST 716 benchmark data have been reported in Cucurull & Rius (2002), Higgins (2001), and Tomassini et al. (2002). Some of the assimilation trials of have used “bias reduction” schemes, basically a station dependent running average of the mean bias with respect to the NWP model, to eliminate these bias problems. For more information on assimilation results see Chapter 6.

4.5 NRT demonstration: special cases, problems, and comparisons

The monitoring of the NRT data flow and quality of the NRT solutions is described in detail in the next chapter (Chapter 5). In this section some special cases and problems encountered during the three years of NRT processing are presented, and some additional internal comparisons are given.

4.5.1 Delay of RINEX data

Rosa Pacione

The first step in near real-time processing is to fetch GPS hourly data, so the NRT processing can not start until a sufficient number of hourly files is available at the data provider. This "waiting time" is a bottleneck for the NRT processing. It is different for each processing centre and it is mainly due the delay in data delivery from the tracking sites to the data centres. For the EUREF data centres the percentage of hourly data files arriving with a specific time delay is computed on a regular basis and it is available at `http://epncb.oma.be/_dataproducts/datacentres/index.html`.

About 80% of the hourly files are available within 15 minutes after the full hour and the NRT processing can not start before this "waiting time". For example, the data delivery for the French stations takes a little bit longer, since only 75% of the hourly data are available 16 minutes after the full hour.

The start time of the processing after the full hour is indicated in Table 4.1 . Some of the analysis centres wait 37 min to get as much data as possible before starting the processing, which then takes less than 20 minutes in order to complete the processing in time.

4.5.2 Analysis of orbit quality

Galina Dick

Besides the official IGS Ultra Rapid orbits with an update cycle of 12 hours, two internal orbit products are generated at GFZ as described in Section 4.3.7. The 12 hour and 3 hour-predicted orbits can be fixed during the ZTD estimation, or the orbits can be adjusted by the data itself (named GASP orbits – hourly estimated orbits from NRT analysis based on 12 hour data windows). In Figure 4.30 all three orbits are compared to the Final GFZ orbits (estimated high quality GPS orbits, official product of GFZ IGS Analysis centre), which have an accuracy of about 2 cm and can be considered as truth in our case. For the well behaving satellites the predicted orbits have already reasonable quality and may be fixed without problems. The 3h-predictions are in the mean 5 cm better than the 12 hour ones. For the well behaving satellites the predicted orbits have a quality comparable to the adjusted GASP orbits. But for the bad behaving or not so well modelable satellites (e.g. satellites in eclipse) one can gain significant improvements by orbit relaxation. In the mean we end up with 12 cm for those orbits compared with 17 cm and 22 cm for the 3 hour and 12 hour predictions, respectively. Further improvements for the GASP orbits can be expected by using 24 instead of 12 hour data intervals.

The influence of orbit accuracy on the accuracy of ZTD has been investigated at GFZ. The data for April 2002 were analysed using three variants for the orbits, taking relaxed GASP orbits or fixing the two prediction variants. The difference to the post-processed results improved by 8% in the standard deviation switching from 12 hour to 3 hour-predicted orbits, and taking the adjusted orbits even by 13% (see Figure 4.31). The bias change between the various variants is small (site scatter $\approx$0.3 kg/m^2). Having a level of 0.6 to 0.7 kg/m^2 IWV for all variants one can state that also fixed predicted orbits can be chosen, which demonstrates the high quality of the IGS and internal GFZ Ultra Rapid products.

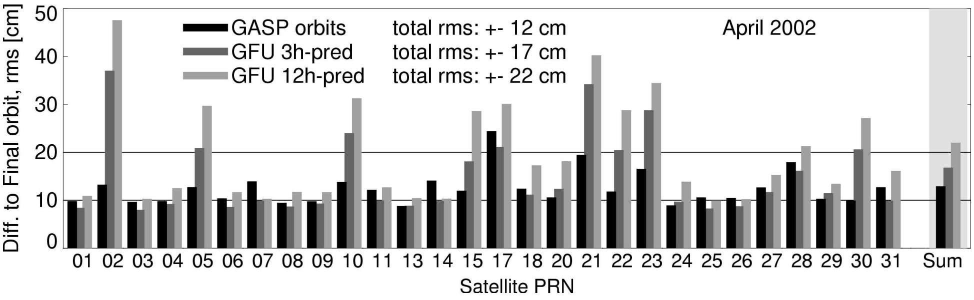


Figure 4.30: Quality of adjusted relaxed orbits from NRT analysis based on 12 hour data windows (GASP orbits) and predicted orbits with 3 hour and 12 hour repetition (GFU 3h-pred, GFU 12h-pred) are shown for April 2002. As a measure of quality the RMS differences to the Final GFZ orbits (product of GFZ IGS Analysis centre) are given for each satellite as well as the total RMS over all satellites.

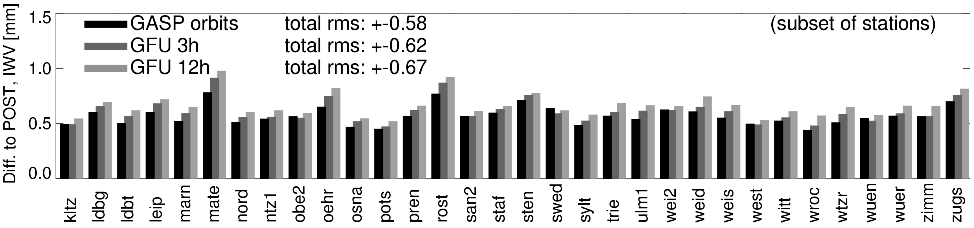


Figure 4.31: Quality of ZTD estimates using three different types of orbits — relaxed orbits from NRT analysis based on 12 hour data windows (GASP orbits) and predicted orbits with 3 hour and 12 hour repetition (GFU 3h-pred, GFU 12h-pred). As a measure of quality the RMS differences to the post-processed ZTD are given for each station (subset is plotted here only) as well as the total RMS over all stations. The ZTD delay is converted to IWV and expressed in unit of kg/m^2 or mm precipitable water vapour.

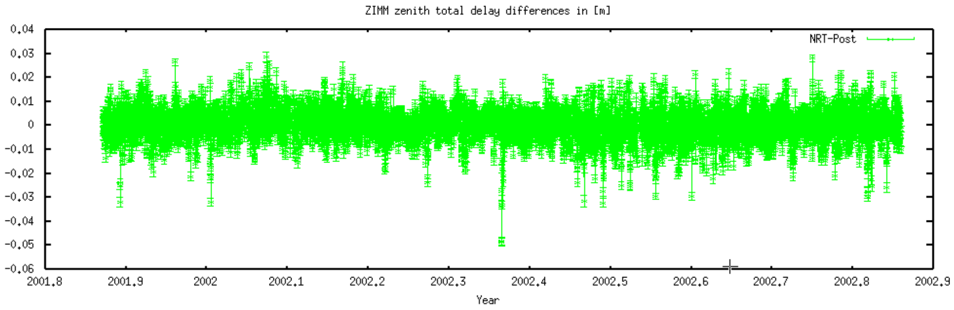


Figure 4.32: Differences of the ZTDs estimated in NRT w.r.t post-processing. 8212 compared hourly ZTDs, mean offset 0.4 mm, RMS 6.4 mm.

4.5.3 Comparison to post-processed solutions

Elmar Brockmann and Jan Douša

A comparison of the LPT NRT solution for one year (Dec. 2001–Dec. 2002) is given in Figure 4.32 for station ZIMM. Significant seasonal variations are not visible. The mean offset of more than 8000 hourly ZTD parameters (NRT compared to the post-processing solution) is smaller than 0.4 mm. The RMS of this comparison is 6.4 mm and is within the range of 6–7 mm which was found for the benchmark data set for LPT's favourite processing options (Table 4.13).

The GOP near real-time solution is also compared routinely with a post-processed solution by GOP, showing an internal consistency between these solutions on the level of 4–6 mm, with bias below 1 mm (Douša, 2002b). These results are similar to those reported for the benchmark data set.

GOP has compared one year of GPS IWV with IWV computed from (reduced) radiosonde profiles, resulting in a consistency of 1.2–2.0 kg/m^2, or 8–13 mm in terms of ZTD (Douša, 2002b).

4.5.4 Comparison to EUREF combined post-processed solution

Siebren de Haan and Hans van der Marel

Since June 2001 the EUREF Permanent GPS network (EPN) is computing a combined troposphere product which provides weekly files with hourly estimates of the Zenith Total Delay. See Section 4.6. More than 50 of the EUREF stations are processed also in near real-time within COST 716. For these stations, one month data was compared to the post–processed EUREF solution.

The mean features of the EUREF solution during this period were:

- Each station is processed by at least 3 LAC's.
- Bernese software is used by 12 LAC's (BEK, BKG, COE, GOP, IGE, IGN, LPT, NKG, OLG, ROB, UPA, WUT), Microcosm (ASI) and Gipsy (DEO) are used by 2 LAC's
- 10° elevation cut-off and elevation dependent weighting of the observations
- use of IGS precise orbits (so-called IGS final orbits)
- re-substitution of the weekly coordinate solution and constraining to ITRF
- use of the Niell hydrostatic mapping function
- one ZTD parameter every hour

As an example, the ZTD comparison for the sites MATE are discussed. More comparisons can be found on `http:www.knmi.nl/samenw/cost716/EUREF/index.html`.

MATE is processed by ASI, GFZ, GOP, and LPT in NRT. In Figure 4.33 the time series of ZTD is shown for the period between 2001/12/02 and 2001/12/29. EUBK denotes the solution from EUREF as obtained by BKG; EUGF is the solution of from EUREF by GFZ. In Table 4.14 the statistics are shown with respect to all processing centres processing MATE (in the December 2001).

A few remarks can be made concerning the interpretation of the results:

- EUREF is a combined solution of 14 analysis centres, of which the majority is using the Bernese software (12 centres). This explains why the systematic biases with the NRT solutions from LPT and GOP, who are using Bernese as well, and use a similar processing method, are smaller than the others who use different softwares and approaches. It is clear that the EUREF combined solution is a very consistent solution. Every station is processed by at least three analysis centres. However, this is no guarantee that the combined solution is not free of biases.
- In the EUREF combined solution a ZTD parameter is computed every hour. The NRT solutions from ASI, GFZ and IEEC use a shorter interval to estimate the ZTD. This is in part responsible for the somewhat higher RMS values.

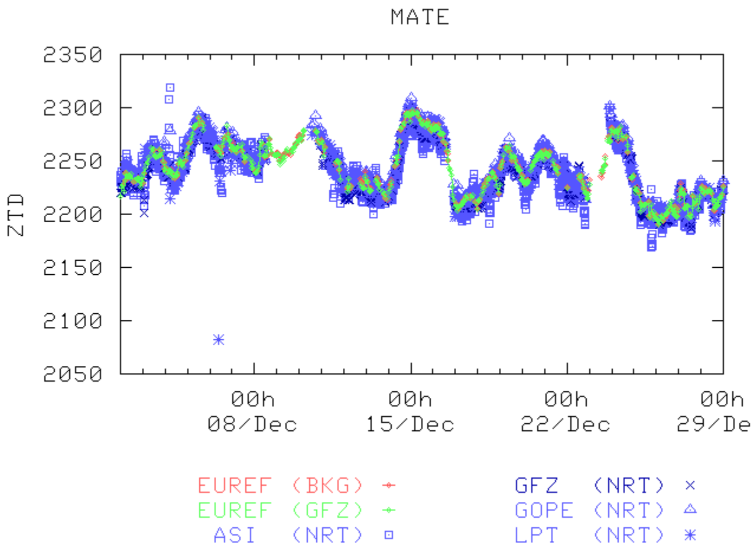


Figure 4.33: ZTD time series for the site MATE. EUBK is the solution from BKG using EUREF data; EUGF is the solution as obtained by GFZ.

Table 4.14: Statistics of ZTD comparison over the period 2001/12/02 and 2001/12/29 for the site MATE. The total number of observations per processing centre were: EUBK (506), EUGF (502), ASI (1889), GFZ (910), GOP (472) and LPT (510).

COLLOCATED STATISTICS Number collocated obs. 292				PAIRWISE STATISTICS				
	bias (mm)	RMS (mm)	dTime (s)		num	bias (mm)	RMS (mm)	dTime (s)
EUBK-EUGF	0.43	1.34	0.34	EUBK-EUGF	500	0.36	1.39	0.34
EUBK-ASI	5.46	9.43	34.25	EUBK-ASI	399	4.72	9.97	101.84
EUBK-GFZ	2.92	5.95	820.21	EUBK-GFZ	380	3.09	6.25	815.08
EUBK-GOP	−1.83	6.71	0.34	EUBK-GOP	370	−1.76	7.00	0.34
EUBK-LPT	0.25	6.86	0.34	EUBK-LPT	402	0.39	7.05	0.34
EUGF-ASI	5.03	9.15	33.90	EUGF-ASI	395	4.33	9.80	102.53
EUGF-GFZ	2.49	5.89	819.86	EUGF-GFZ	376	2.70	6.23	813.83
EUGF-GOP	−2.27	6.96	0.00	EUGF-GOP	366	−2.20	7.30	0.00
EUGF-LPT	−0.18	6.92	0.00	EUGF-LPT	398	0.05	7.14	0.00
ASI -GFZ	−2.54	7.79	785.96	ASI -GFZ	441	−1.72	8.78	793.88
ASI -GOP	−7.29	10.27	−33.90	ASI -GOP	429	−7.00	10.52	−23.08
ASI -LPT	−5.21	9.45	−33.90	ASI -LPT	465	−4.88	10.08	−17.42
GFZ -GOP	−4.76	7.50	−819.86	GFZ -GOP	424	−4.38	7.20	827.83
GFZ -LPT	−2.67	6.78	−819.86	GFZ -LPT	457	−2.77	7.17	833.04
GOP-LPT	2.08	5.50	0.00	GOP-LPT	458	2.12	6.52	0.00

4.5.5 Miscellaneous data problems (LPT)

Elmar Brockmann

The AGNES site SAME (Samedan) seems to be located on an unstable ground. From the post-processing solutions LPT has variations mainly in the vertical component of about 4 cm. It is suspected that the groundwater flow in this region is responsible for the "jumps" in the vertical direction. Horizontal movements are not detectable.

The coordinates are constrained for the NRT processing on ITRF values, or, if not available, on an averaged value over a longer time period of several months to years. LPT applies a coordinate correction only in the case of significant coordinate changes. In the case of SAME LPT changed the coordinates twice (+4 cm on Feb. 20, 14:30, 2002 and −4 cm on Apr. 30, 16:30, 2002). In both cases a jump is also visible in the ZTD/IWV estimates of approximately 1.5/0.2 cm. The order of magnitude corresponds to the rule of thumb: a change in the height affects the ZTD estimates by a factor of 1/3 and the IWV estimates by a factor of only 1/18.

A 4 cm jump in the coordinate series is already an extreme case. Nevertheless, the impact to the ZTD/IWV estimates and their use for numerical weather prediction is small.

An interesting phenomenon happened for station FHBB on Sep. 12, 2002 (11:00). In order to evaluate a possible interference of GPS with UMTS, the Swiss telecommunication company Swisscom carried out a special test near the GPS antenna. The UMTS signals (GHz spectrum) were generated with a "typical" power density in the direction of the GPS antenna. The effects on the GPS receiver were significant. There was a data loss of more than 90% and the resulting GPS analyses therefore show a poor performance.

Sometimes, problems in one site can cause problems in all others. On one occasion LPT had problems in the data processing due to a single site; the CODE observations of site MATE caused problems which affected all other stations. After that event LPT implemented a scheme for eliminating data in such cases. There are a lot of other interesting events or problem cases. We at LPT usually regarded such events as a motivation for implementing procedures to avoid such problems in the future.

4.6 EUREF combined post-processed solution

Wolfgang Söhne and Hans van der Marel

Within EUREF a well distributed and dense network of more than 150 stations across Europe called EUREF Permanent Network (EPN) has been established. Since 1996, this network has been routinely processed primarily for coordinate estimation. Because of the great number of stations and for reasons of redundancy there was the decision to analyse the network in smaller parts. In total 16 so-called Local Analysis Centres (LACs) are producing weekly coordinate solutions. These solutions are delivered to the analysis coordinator of the EPN in SINEX format to produce the final weekly combined solution (Habrich, 2001).

With the experience of the coordinate combination in mind, EUREF established a troposphere coordination group which after reorganization was turned into a EPN Special Project "Troposphere Parameter Estimation". In June 2001 the Special Project started working. Similar to combining weekly SINEX files for the derivation of a combined coordinate product a combined troposphere solution is produced. The inputs are the individual daily troposphere solutions of the LACs with a sampling rate of one hour.

The individual analyses at the LACs are carried out in post processing mode on the basis of the best available orbits and earth rotation parameters, i.e. the IGS final products.

Each site within the EPN is included by at least three (and at the most five) LACs to get a stable combination result, to detect outliers and to get precision numbers. Fourteen of the LACs are using the Bernese GPS software, only two centres are producing their solutions with different software. The individual solutions are combined following the IGS standards (Gendt, 1997), i.e. an epoch-wise combination of the single solutions as weighted mean. A rigorous outlier detection is implemented which works in consecutive steps.

In IGS, a troposphere working group was established in 1997 to form a new product. Seven analysis centres are contributing with daily troposphere files with a time resolution of two hours. Most of the centres are using their own analysis software. Since 1998 the combined ZTD estimates have been offered as an official IGS product. One weekly file for each site with a sampling rate of two hours is produced.

Actually two institutions are carrying out the troposphere combination, BKG and GFZ, using different programs. The mean bias of the combined solutions is in the range of ±0.2 mm ZTD with an RMS of ±0.6 mm (Söhne & Weber, 2002).

As a result two weekly files are produced (accessible via anonymous FTP `ftp://igs.ifag.de/EUREF/products/wwww`):

- The first one is a summary file (XXXwwwwd.TSU) which contains some statistics about e.g. the biases between the individual solutions, frequencies of the analysed sites, accuracies of individual AC solutions, and the number of rejected observations.
- The second one is the output file (XXXwwwwd.TRO) with the combined troposphere estimates from which the estimates for a single site can easily be extracted due to its SINEX structure.

Herein 'XXX' is the acronym for the combination centre and 'wwww' means the GPS week. 'd' denotes the day of week where '0' means Sunday and '7' indicates a weekly solution. The coordinates as a necessary part of this file are taken from EUREF's official combined weekly SINEX solution.

Post-processed solutions, like the one by EUREF, could be useful for climate monitoring and climate research. However, for climate applications the accuracy requirements on meteorological observations are the most stringent because they are needed for long-term statistical analysis and the determination of very small trends. In general, it may take decades to carefully extract the signal, i.e. the climate change, from instrumental noise.

The homogeneity of the time series is very important. Non-climate influences such as moving the stations, changes in the vicinity of the sites or changes in the observation and/or analysis strategy should be avoided or at least reported. In the special case of GPS, "instrumental noise" may be introduced by different sources: changes in processing strategies at the participating analysis centres, including changes in troposphere parameter resolution and troposphere parameter modelling; change of the reference system; change of number of participating analysis centres. GPS networks used for estimation of ZTD parameters should not be too small ($>$ 800 km). Then the problem of biases due to the fact that one satellite is seen from different points nearly under the same elevation angle can be avoided.

The long-term stability seems to be a challenging goal. A continuous monitoring over a longer time span is necessary, at least for a period of one decade minimum, precise bookkeeping of any changes and investigations concerning the analysis and combination strategies. In order to obtain the long term stability changes in the processing strategy are not in order, although this conflicts with the need to include the latest insights and innovations in the processing. The only solution to this dilemma is re-processing of the data at intervals of 5–10 years. Therefore, for climate applications it is important that the raw GPS data (in RINEX format) is stored, together with accurate bookkeeping of the changes that occurred at any of the sites. The role of the NRT and post-processing in this is that the accurate monitoring of these solutions possibly can provide indications of changes in the station environment.

4.7 Conclusion

To demonstrate the application of ground based GPS data for NWP, a near real-time demonstration was started in March 2001. In March 2004 the near real-time demonstration involved ten processing centres, each processing a GPS network in near real-time, delivering estimates of ZTD within a nominal time interval of 1 hr 45 min to a gateway at the UK Met.Office. Over 420 GPS stations were processed, many of which are processed by more than one analysis centre.

The near real-time demonstration has exceeded all expectations. The number of analysis centres and the number of stations that are processed are much larger than was expected at the beginning of the action. Also the duration of the experiment exceeded all expectations. The MoU asked for a three-month experiment. At the end of the COST 716 action not only three years of data has been produced, but the experiment continues to be run. Although the experiment exceeded expectations, the startup of the near real-time demonstration in 2001 was rather slow and it was not until the end of 2001 until a sizable number of analysis centres was participating.

Before the near real-time demonstration experiment was started, the algorithms, data flow, formats and assimilation into Numerical Weather Prediction (NWP) models were first tested on 15 days of GPS data which were processed off-line, but to near-real time quality, for the period of June 9–23, 2000. In contrast to the actual demonstration, where analysis centres will process different GPS sub-networks, all analysis centres processed a common network of 44 stations. The overall consistency between the solutions was about 5–6 mm for the ZTD (1 kg/m^2), but with biases between the analysis centres of about the same magnitude. These numbers have been confirmed during the near real-time demonstration.

The near real-time demonstration experiment has shown to meet operational requirements in terms of timeliness and accuracy. It was shown that it is possible to compute ZTD for NWP within 1 hour 45 minutes using existing GPS networks with an accuracy sufficient for NWP and forecasting applications.

Many of the analysis centres are now capable of delivering more than 75% of the data within 1 hour 45 minutes. Actually, the amount of data processed versus the latency is a delicate balance: waiting longer would mean more data, but also longer delay. Most of the data sets of the top performers arrive just within 1 hour 45 minutes, as each waits as long as possible for the raw GPS data to arrive. Sometimes, analysis centres are waiting 30–35 minutes for the data to arrive in order to complete the processing in 10 minutes time. Also, the latency is measured as the difference in time between the time of the first ZTD estimate and time of arrival of the COST 716 file, which has as side effect that an increase in the ZTD rate will result in somewhat worse latencies even when the actual processing time remains the same. Therefore, analysis centres providing a higher ZTD rate are somewhat in a disadvantage concerning the measured latencies.

Although these results are already quite satisfactory, there is room for improvement. The latency of the hourly raw GPS data, and in particular the reliability thereof, is a limiting factor that has to be improved by the station managers and data centres. It should be possible for all station managers to provide the data within 10 minutes after the full hour. Another limiting factor that still needs some improvement is the availability of satellite orbits and clocks. In particular for the Precise Point Positioning approach highly accurate and timely available satellite orbits and clocks are of the utmost importance. This requires the processing of a global network.

There are still several issues with the processing strategies and processing options. There is still a wide variety of choices made by the different analysis centre, for instance, some are estimating the ZTD every 15 minutes, others average the ZTD over 60 minutes. The demonstration experiment used a bottom-up approach, but the time could have come for a more top-down approach specifying a set of recommended processing options or guidelines. Also, the development of the software continues and there are several areas in which improvements have been made or are pending, such as correction for higher order ionospheric effects, improved mapping functions (dry/wet), antenna and station related calibrations, and prediction of a-priori ZHD, which all will affect the quality of the estimated ZTD.

The near real-time demonstration experiment in a sense was focused on near real-time delivery. In hindsight, after the first two years we could maybe have focused a little more on accuracy, quality description and synchronizing processing options. A significant amount of work is still needed in order to derive a good quality indicator for the ZTD in the COST files, and to understand the statistical properties of the ZTD data in the files.

In summary, the demonstration experiment has been a great success. It provides a very valuable data set for validation and forecasting experiments. For the demonstration phase, the current NRT performance is shown (Chapter 5) to be capable of meeting the requirements, and the indicated improvement is desirable for a future operational scenario.

List of data providers

Code	**Name**	**Used by**
	IGS Global Data Centres (GDC)	
IGNI	IGS GDC, Institut Géographique National, France	ACRI, ASI, BKG, SGN
CDDIS	IGS GDC, Godhard Space Flight Center, USA	ASI, BKG, GFZ, SGN
SIO	Scripps Institution of Oceanography, USA	SGN
BKGI	IGS RDC, Federal Office of Carthography and Geodesy, Germany	ACRI, ASI, BKG, GFZ, IEEC
	IGS Regional Data Centres (RDC)	
BKGE	EPN RDC, Federal Office of Carthography and Geodesy, Germany	ACRI, ASI, BKG, GFZ, IEEC, LPT, SGN
BKGL	IGLOS RDC, Federal Office of Carthography and Geodesy, Germany	BKG
	EPN Local Data Centres (LDC)	
ASI	EPN LDC, Agenzia Spatiale Italiana, Italy	ACRI, ASI, BKG, SGN
DUT	EPN LDC, DEOS, TU Delft, Netherlands	GFZ, GOP
IGNE	EPN LDC, Institut Géographique National, France	ACRI, ASI, BKG, GFZ
GOP	EPN LDC, GOPE, Czech Republic	BKG, GOP
OLG	EPN LDC, Austria	ASI, BKG
ROB	EPN LDC, Royal Observatory, Belgium	BKG, SGN
	National Data Centres	
AGNES	Automatisches GPS Netz Schweiz, swisstopo	LPT
AGRS	Active GPS Reference System for the Netherlands	*DUT*
ESGT	Ecole Supérieure des Géomètres et Topographes	SGN
IAC	Instituto de Astrofísica de Canarias, Spain	IEEC
IESG	The British Isles GPS Archive Facilities	GOP
ICC	Institut Cartogràphic de Catalunya, Spain	IEEC
IGN	Instituto Geogràfico National, Spain	IEEC
REGAL	Réseau GPS permanent dans les Alpes	ACRI, LPT, SGN
RGP	Réseau GPS Permanent, France	SGN
SAPOS	SAtellite POSitioning Service, Germany	GFZ
SATREF	Norwegian Mapping Agency, Norway	NKG
SWEPOS	National Land Survey, Gävle, Sweden	NKGS
DKNET	GPSnet.dk, Trimble centre Danmark	NKGS
	Others	
UNAVCO	University NAVSTAR Consortium, Boulder, USA	SGN

EPN Local Data Centres often provide data for more stations than are strictly part of the EUREF Permanent Network.

IGS global and regional data centres, and the EPN regional and local data centres, collect data from receivers operated by many individual institutions. It is not practical to acknowledge each institution individually that makes data available for free through IGS and EUREF. However, let us point out here that without the data from these institutions actions like COST 716 would simply not have been possible. Therefore, for all those anonymous and non-anonymous institutions and station operators: thank your very much, and take great pride in your work!

Data provider URL's (when available):

Code	**ip name**	**service**
IGNI	`ftp://igs.ensg.ign.fr`	anon-ftp
CDDIS	`ftp://cddisa.gsfc.nasa.gov`	anon-ftp
SIO	`http://sopac.ucsd.edu`	http
BKGI	`ftp://igs.bkg.bund.de`	anon-ftp
BKGE	`ftp://igs.bkg.bund.de`	anon-ftp
BKGL	`ftp://igs.bkg.bund.de`	anon-ftp
ASI	`ftp://geodaf.mt.asi.it`	anon-ftp
DUT	`ftp://mgp1.geo.tudelft.nl`	ftp
IGNE	`ftp://lareg.ensg.ign.fr`	anon-ftp
GOP	`ftp://pecny.asu.cas.cz`	anon-ftp
OLG	`ftp://olggps.oeaw.ac.at`	anon-ftp
ROB	`ftp://omaftp.oma.be/dist/astro/euref/`	anon-ftp
AGNES	`http://www.swisstopo.ch/de/geo/agnes.htm`	data not free
AGRS	`http://www.agrs.nl/`	data not free
ESGT	`ftp://gps.esgt.cnam.fr/data_1/`	anon-ftp
REGAL	`ftp://kreiz.unice.fr/regal`	anon-ftp
RGP	`ftp://lareg.ensg.ign.fr/pub/rgp2/nrt/data_30/` `ftp://rgpdata.ign.fr/pub/data`	anon-ftp
SAPOS	`http://www.sapos.de`	data not free
SATREF	`http://www.satref.no/`	data not free
SWEPOS	`http://swepos.lmv.lm.se/english/index.htm`	data not free
DKNET	`http://www.gpsnet.dk`	data not free
UNAVCO	`ftp://data-out.unavco.org/pub/rinex`	anon-ftp

Contact information for the analysis centres

Code	Address	Contact
ACRI	ACRI-ST, 260 route du Pin Montard, BP 234, 06904 Sophia Antipolis, France. `http://www.acri-st.fr` or `http://www.acri-st.fr/tough/` for the TOUGH Project	Olivia Lesne (oli@acri-st.fr)
ASI	Agenzia Spaziale Italiana, Centro di Geodesia Spaziale, 'G.Colombo', 75100, Matera, Italy. `http://geodaf.mt.asi.it/GPSAtmo/ground.html`	Francesco Vespe (francesco.vespe@asi.it)
BKG	Federal Agency for Cartography and Geodesy, Richard-Strauss-Allee 11, D-60596 Frankfurt am Main, Germany. `http://www.bkg.bund.de`	Wolfgang Söhne (wolfgang.soehne-@bkg.bund.de)
GFZ	GeoForschungsZentrum Potsdam, Telegrafenberg A17, D-14473 Potsdam, Germany. `http://www.gfz-potsdam.de/pb1/pg1/gasp1/index_GASP1.html`	Gerd Gendt (gend@gfz-potsdam.de)
GOP	Geodetic Observatory Pecný, Research Institute of Geodesy, Topography and Cartography, Zdiby 98, 250 66, Czech Republic. `http://www.pecny.cz/gop/`	Jan Douša (dousa@fsv.cvut.cz)
IEEC	Instituto de Ciencias del Espacio (CSIC), Institut d'Estudis Espacials de Catalunya (IEEC), Edif. NEXUS, 204 Gran Capita, 2-4, 08034 Barcelona, Spain. `http://www.ieec.fcr.es/english/recerca/gnss/rtmain.html`	Antonio Rius (rius@ieec.fcr.es)
LPT	Federal Office of Topography (Bundesamt für Landestopographie), Department of Geodesy, Seftigenstrasse 264, CH-3084 Wabern, Switzerland. `http://www.swisstopo.ch/de/geo/pnac.htm`	Elmar Brockmann (Elmar.Brockmann-@swisstopo.ch)
NKG	Statens kartverk (Norwegian Mapping Authority), Geodesidivisjonenn, Kartverksveien 21, Service box 15, N-3504 Hønefoss, Norway	Oddgeir Kristiansen (oddgeir.kristiansen-@statkart.no)
NKGS	Onsala Space Observatory, Chalmers University of Technology, S-439 92 Onsala, Sweden.	Jan Johanssen (jmj@oso.chalmers.se)
SGN	Institut Geographique National (IGN), Ecole Nationale des Sciences Géographiques (ENSG), Laboratoire de Recherches en géodésie (LAREG), 6-8 Avenue Blaise Pascal, 77455 Marne-La-Vallée Cedex 2, France. `http://geodesie.ign.fr/RGP/index.htm`	Bruno Garayt (Bruno.Garayt-@ensg.ign.fr)

Chapter 5

Data Flow, Data Monitoring and Validation

Dave Offiler, Siebren de Haan and Sylvia Barlag

5.1 Introduction

This chapter summarizes the results of monitoring and validation of COST-716 near-real time (NRT) data delivery over the full demonstration phase of the project (May 2001 to March 2004 inclusive). The last year of this period was also coincidental with the TOUGH NRT demonstration phase.

The status as at end of March 2004 is:

- 10 NRT Processing Centres (+ LPTR)
- 430 unique active stations
- $>$1.1 million obs/month (c.f. 40,000 in May 2001)
- Performance is gradually improving or stable
- 7 centres fully meeting delay target
- All other centres very close to meeting target (75% in 2 hours or less)
- Delay is not correlated with quality
- Some centres prefer to trade-off no. of available sites for delay
- Dissemination of BUFR via GTS started 1 March 2004
- Issues of data quality (bias, noise) to be solved.

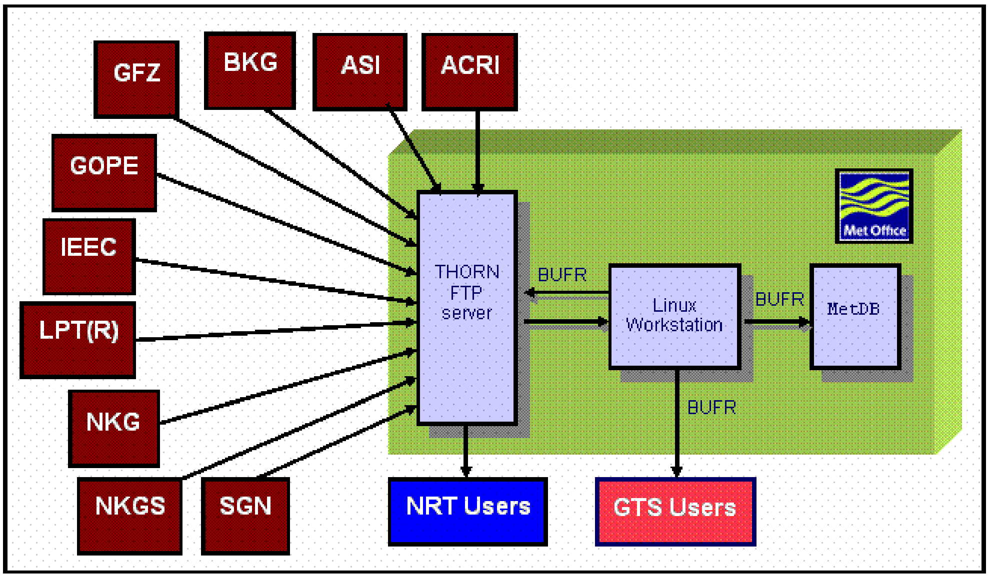


Figure 5.1: Schematic illustrating the flow of the NRT data.

5.2 Set-up and maintenance of NRT data exchange facilities

5.2.1 Data flow

A private account on the Met Office's THORN FTP server was set up in January 2001 to act as the focal point for near-real time (NRT) data exchange, with monitoring results, a limited recent archive and supporting data, benchmark data archive, software and documentation. The NRT data flow at the end of the action (March 2004) is illustrated in Figure 5.1. This set up is assumed to continue in the ongoing TOUGH project.

All NRT data provided by the analysis centres (ACs) in COST-format files (COST-716 (2003a) and COST-716 (2003b)) is available to all project partners via the THORN FTP server. In addition, these files are copied to a local workstation, converted to the WMO BUFR format and passed to the Met Office's operational observations Meteorological Data Base (MetDB) and back to THORN. A sub-set of the BUFR data is also disseminated to users outside of the project via the Global Telecommunications System (GTS) — see below.

With significant increases in the amount of NRT observations (with ACRI, BKG and SGN processing centres more recently providing COST-format files), a 3-fold increase in the number of stations processed by GFZ, NKGS re-starting NRT processing, and "real-time" processing by SwissTopo (as LPTR), disk space quota on THORN has had to be raised several times during the three years of the demonstration phase of the project. Some 1.125 million observations of ZTD from 430 individual GPS sites (almost all in Europe) were uploaded to THORN during March 2004.

Files uploaded to the THORN server is also mirrored to a private FTP server for COST-716 data run by Delft University , which maintains a longer-term online archive of COST 716 files than is possible on THORN. ACRI-ST have set up a similar mirror site for the TOUGH project.

Due to the relocation of the Met Office to Exeter during 2003, disruption to the (non-operational) service provided by THORN was scheduled over the period of 5–17 December 2003. Temporary arrangements for data collection were put in place by diverting (most) data to the ACRI-ST server. When THORN was re-commissioned in Exeter (some days ahead of schedule), the files were recovered from ACRI-ST back onto THORN and then to the MetDB. Not all ACs used the ACRI-ST server, so there are some gaps in data coverage during this period. There was also a short break in passing NRT BUFR files to MetDB during October 2003 as a key workstation/file server was moved to Exeter. Since data continued to be uploaded to THORN, this resulted in no loss of data as the archive process caught up when the server was back in service. In February 2004, THORN's OpenVMS operating system was upgraded; unfortunately, FTP settings were set to inappropriate defaults, and ACRI-ST in particular could not upload files for several days until the problem was isolated and corrected. Again, no files were lost to the archive.

5.2.2 Data formats and software support

Before the demonstration phase began in test mode in January 2001, a data (file) format was developed by WGs 2 and 3 for easy exchange of data via THORN. The Met Office also provided software tools to read, write and manipulate files in this format. Application tools include a BUFR encoder.

At the first TOUGH semi-annual meeting in September 2003, some modifications to the details of the COST-format file specification were proposed. Changes included adding a project ID and the full name and country of the station, extending the precision of the station location and replacing height of antenna above the ground with antenna reference point (ARP) above the benchmark. The ZTD reference point was also clarified to be the ARP, not the benchmark. In liaison with ACRI-ST, an updated format document was issued in September 2003 COST-716 (2003a) and the V2 format is now in use by most ACs.

An updated software package, which includes support for the updated COST-format files COST-716 (2003a), the WMO-approved BUFR COST-716 (2003b) and the filtering has been released. The software is freely available to project partners via THORN; non-project users with a legitimate use may have the package upon request. To date the package has been supplied to Bundesamt für Kartographie und Geodäsie (BKG).

The Met Office also maintains a meta-data file on all the GPS stations ever uploaded to THORN. The updating of this file (copy on THORN) has now been fully automated as new stations are detected in the NRT data stream.

5.2.3 BUFR and data distribution

The BUFR proposal for GB-GPS data COST-716 (2003b), submitted in early 2003, was accepted by WMO and published in July 2003; data in this format could then in principle be disseminated via GTS/RMDCN from 5 November 2003. A COST-716 MC and TOUGH Project Data Access Policy was approved in late 2003, based on a Met Office proposal that a sub-set of data be provided in BUFR on GTS, via an “opt-in” list of GPS station and/or ACs. This strategy has been implemented as a filter to the BUFR encoder and shown to be a practical method.

After canvassing potential users world-wide, initially ECMWF, Météo-France, MeteoSwiss, and NCEP requested data via GTS and the necessary routing was set up. Final internal Met Office links were put in place in February 2004 and (after a brief test period) COST-716 data formally started to be disseminated in NRT via the GTS on 1 March 2004 (although this is not an operational service). The Japan Meteorological Agency (JMA) and the New Zealand Met Service have expressed an interest in these data but are not yet able to accept the BUFR messages over GTS.

The Met Office already had a policy to widely disseminate data from its own UK GPS stations and by the end of March 2004, almost all the COST-716 data were being disseminated via GTS. In some cases, only a sub-set “public” data from IGS/EUREF sites are provided as the necessary agreements with national network and individual site owners (required by the COST 716/TOUGH Data Policy) has not yet been reached.

Through the forum of the North America - Europe Data Exchange Group, ground-based GPS data have been formally requested from the US side. There has been contact with UCAR on the possibility of reciprocating the exchange of GPS data in the same WMO BUFR format.

5.3 User validation and feedback

NRT demonstration requirements of COST 716 were agreed between WGs 2 and 3 early in the project, and were subsequently included in the COST User Requirements Document COST-716 (2004). In summary:

- 75% of observations to arrive in MetDB within 1 hour and 45 minutes of observation time
- Delay to be computed daily and averaged over calendar months
- At least one month should meet delay criteria
- RMS error in ZTD to be better than 15 mm (target 10 mm)

The Met Office has continuously monitored NRT data feeds through THORN. This monitoring covers two aspects:

- Statistics of data volumes, number of stations and delivery delays as daily and monthly text reports and graphical plots, updated daily and monthly. These are available on THORN; the graphical versions are hosted on the COST 716 website at KNMI (`http://www.knmi.nl/samenw/cost716/stat/delays.html`).
- Statistics and graphical time series plots comparing observed and NWP-model derived ZTD values. Currently this comparison is limited to the Met Office’s UK-area Mesoscale model (12 km grid). These plots are also presented via the KNMI website. (`http://www.knmi.nl/samenw/cost716/NWPcomp/`). At the same web site a similar comparison is made between the operational NWP model of KNMI (HIRLAM) and retrieved NRT ZTD data. These ZTD data are converted into IWV and compared to radiosonde observations on a routine basis (`http://www.knmi.nl/samenw/cost716/ztd_iwv.html`).

Table 5.1: Number of GPS stations processed by each analysis centre during March 2004. (N.B. NKG were consistently providing ≈35k obs/month, but changed to the new COST-format in March; a formatting error resulted in NKG data not being recognized by the monitoring system.)

AC	ACRI	ASI	BKG	GFZ	GOPE	IEEC	LPT	LPTR	NKG	NKGS	SGN	Total
#Stns	35	42	64	214	52	29	61	38	20	109	55	719
#Obs ($\times$1000)	56	77	41	246	28	92	39	282	4	231	29	1125

5.3.1 Data flow monitoring

Key data flow parameters being monitored included: number of stations per AC, number of unique stations (as some stations are processed by more than one AC in overlapping networks) and timeliness (delivery delay).

Station numbers and observation volume statistics

During March 2004, 10 ACs (plus SwissTopo's real-time processing, LPTR) processed the number of sites and provided the number of observations shown in Table 5.1. Of the combined total of 719 sites, 430 were unique; 456 unique sites have been processed at some time in the NRT period see Figure 5.2. A peak total of over 1.125 million observations was provided during March 2004.

Station statistics are accumulated for calendar months. Month-by-month summary time-series plots covering the COST 716 NRT demonstration period are also produced (see Figure 5.3 and Figure 5.4 for plots of the number of stations and number of observations per month, respectively.

Delay statistics

Delays are defined as being the time difference between the observation time stamp for a ZTD sample in a COST-format file and the receipt time stamp of that sample in the MetDB. The average delay from a file arriving on THORN and the data going into the MetDB is about 5 minutes. On a daily basis, these two times are extracted from the MetDB for all data samples from the previous day and various statistics calculated. The results are plotted as histograms along with the summary statistics — a sample daily plot is shown at Figure 5.5. Similar plots are generated for each AC and repeated for 28-day accumulations. These plots are hosted on the KNMI public website (at URL noted above) and are updated daily.

As well as the rolling 28-day accumulations, similar statistics are accumulated for calendar months. Month-by-month summary time-series plots covering the COST 716 NRT demonstration period are also produced - Figure 5.6 shows the percentage of the observations arriving within 1 hour and 45 minutes and Figure 5.7 shows the time delay for which 75% of all the observations have arrived.

During the demonstration period, as the data volume has significantly increased, a number of tasks to support the monitoring have been fully-automated so that new sites and new ACs are processed as soon as they appear in the COST-format files.

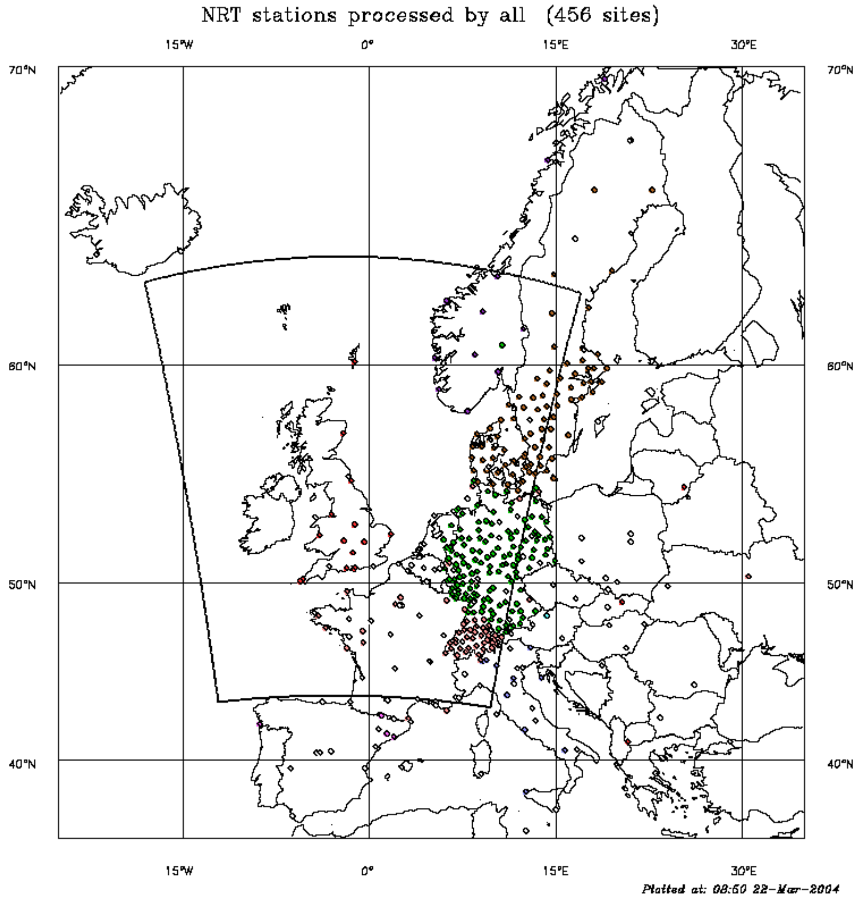


Figure 5.2: Map showing location of TOUGH NRT sites in Europe in March 2004. Not all sites are processed continuously, e.g. only 430 out of the 456 sites were processed that month. The area of the Met Office's Mesoscale model is shown by the solid lines around the UK and neighbouring mainland Europe.

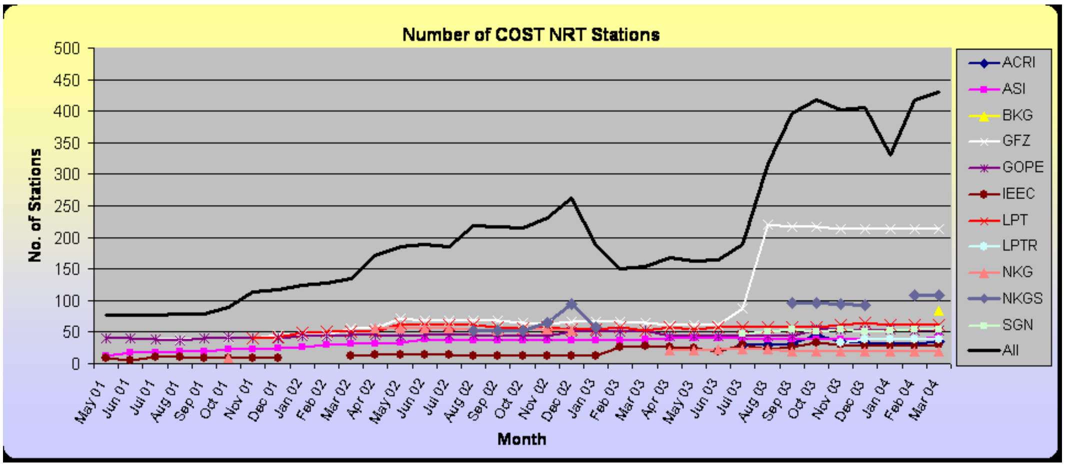


Figure 5.3: Monthly summary time series showing the number of stations processed by each AC and the total number of (unique) stations. The reduction in January 2004 was due to a temporary cessation of processing by NGKS (delivery recommenced on 1 February 2004).

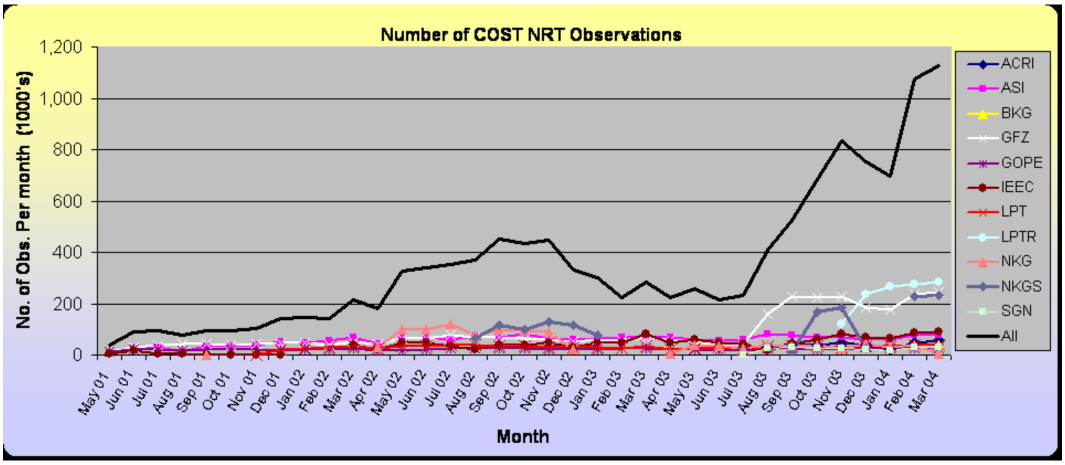


Figure 5.4: Monthly summary time series showing the number of observations delivered by each AC and the total. Reduction in numbers for January 2004 as for Figure 5.3.

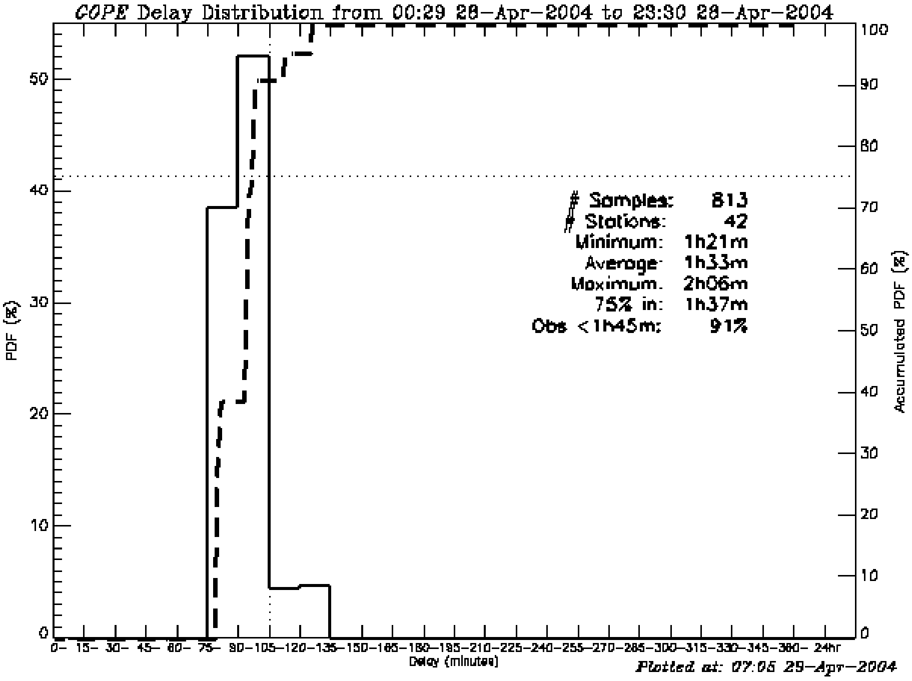


Figure 5.5: Example graphic summarizing delivery delays for GOPE for one day. Similar plots are generated covering the accumulated data over the previous 28 days and for all analysis centres individually. These plots are re-generated daily.

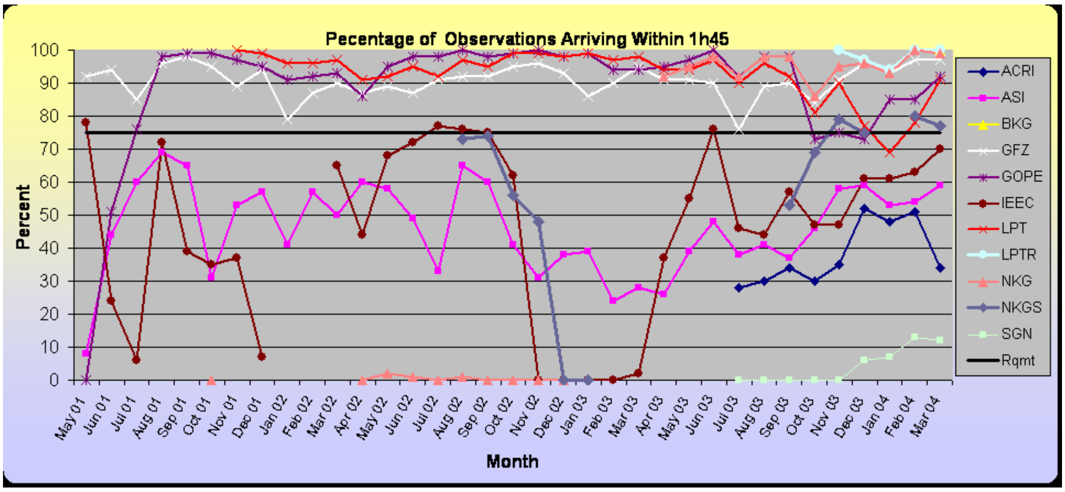


Figure 5.6: Monthly summary of percentage of observations arriving in MetDB within 1 hour and 45 minutes of observation time for each AC; the target is 75% or more. There was some apparent loss of performance in October and December 2003 due to the physical relocation of key Met Office computer systems from Bracknell to Exeter, and some loss in February due to THORN FTP system problems.

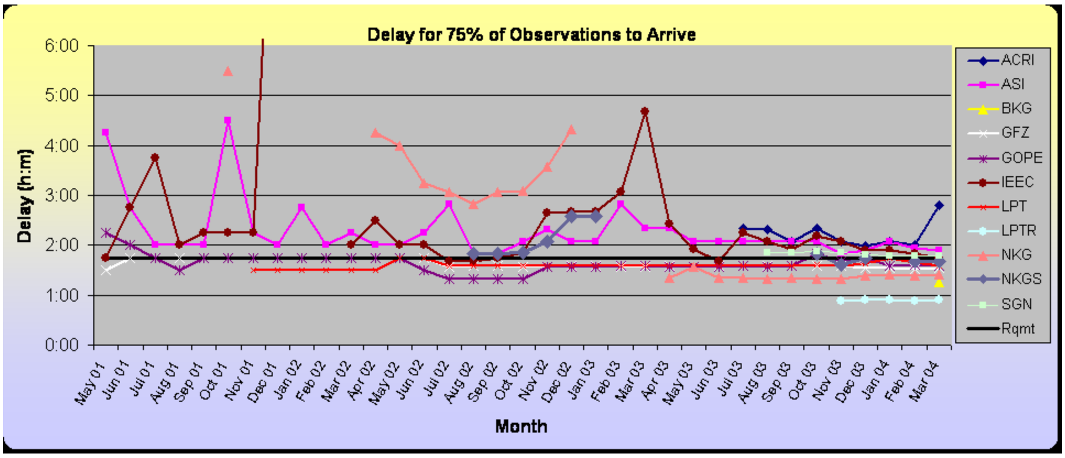


Figure 5.7: Monthly summary of time delay for 75% of observations to arrive in MetDB for each AC; the target is 1 hour and 45 minutes. From May 2003, all ACs have been delivering their NRT data within 2 hour and 30 minutes and from November 2003, within 2 hours and 5 minutes. SwissTopo's "real-time" (LPTR) products arrive in less than 1 hour.

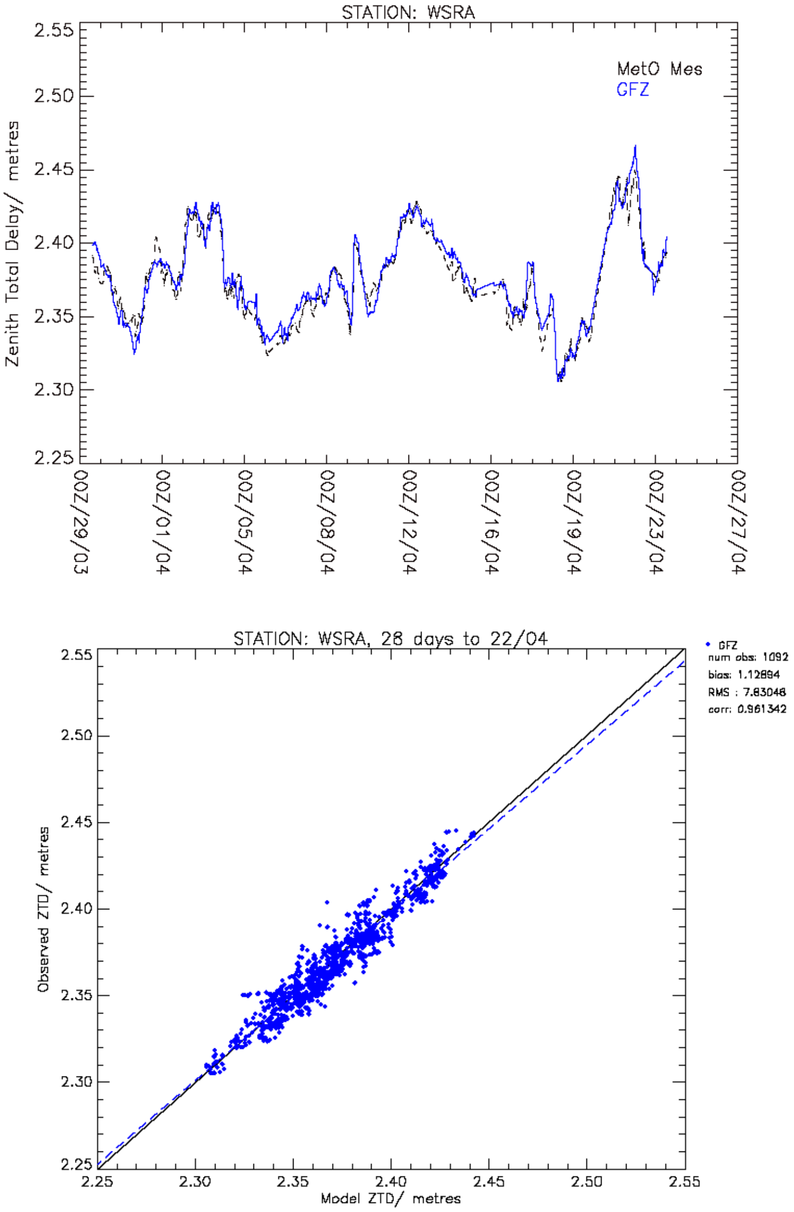


Figure 5.8: Example of a 28-day time series and a scatter plot of the observed ZTD (station WSRA processed by GFZ) vs. ZTD derived from the MES.

5.3.2 Data quality monitoring

COST-716 NRT ZTD data are compared with ZTD estimates derived from main and update run of the Met Office’s Mesoscale model (MES) 8 times daily (at 00, 03, 06, 09, 12, 15, 18 and 21 UTC). All GPS stations within the MES domain (shown in Figure 5.2) are monitored; European and Global model monitoring for stations outside the MES area is planned to be online shortly to allow comparisons with all NRT stations delivered to the MetDB via THORN. An example time series and scatter plot covering a 28-day period is shown in Figure 5.8.

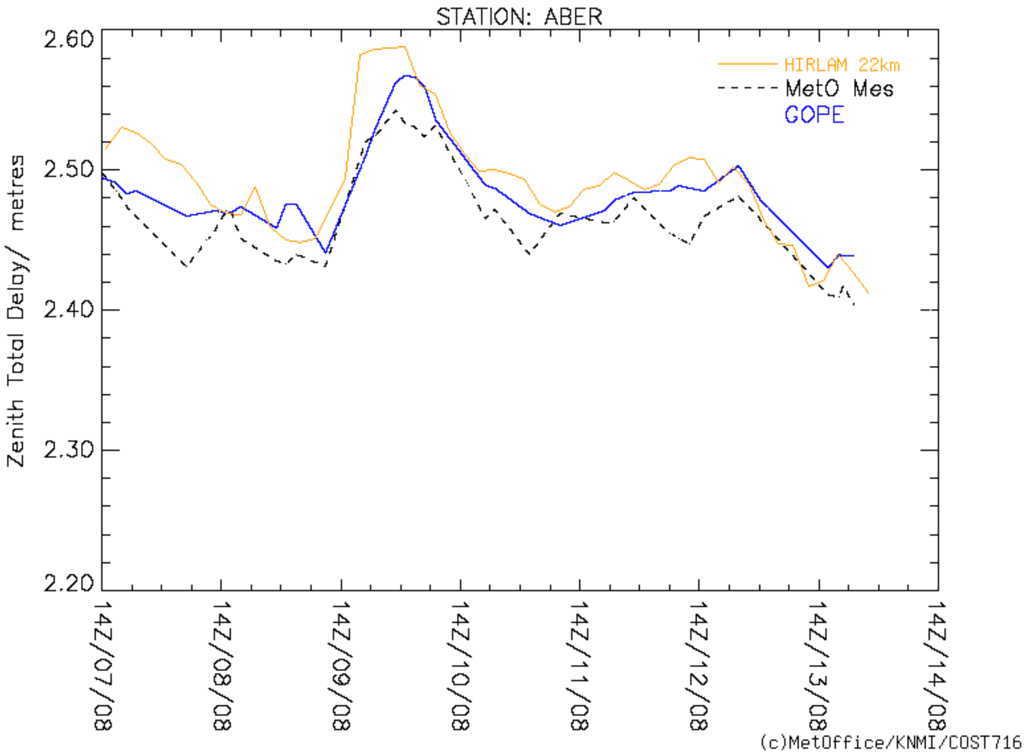


Figure 5.9: An example of a 1-week time series of ZTD data for station ABER compared with NWP equivalent values from the Met Office’s Mesoscale and KNMI’s HIRLAM models.

Monitoring plots and 28-day rolling statistics are uploaded to THORN once a day, where they are copied by KNMI and plotted together with HIRLAM ZTD equivalents. An example plot from the KNMI website is shown in Figure 5.9.

On occasion, we find various anomalous data points, which can be classed as:

- Transients
- Variable bias
- Consistent “low level” noise or inaccuracies
- Consistent “severe noise”
- Mixed quality of data for the same station; some processing strategies appear to give fewer or more problems.

Some examples of these problems—we leave to the reader to classify them—are shown in Figure 5.10. Where problems have been identified, the AC is informed so that the issue can be investigated and corrected.

These types of anomalous data points could have serious consequences for NWP assimilation. This issue is general for NWP assimilation, as the VAR method (as with others) in practice has to explicitly assume

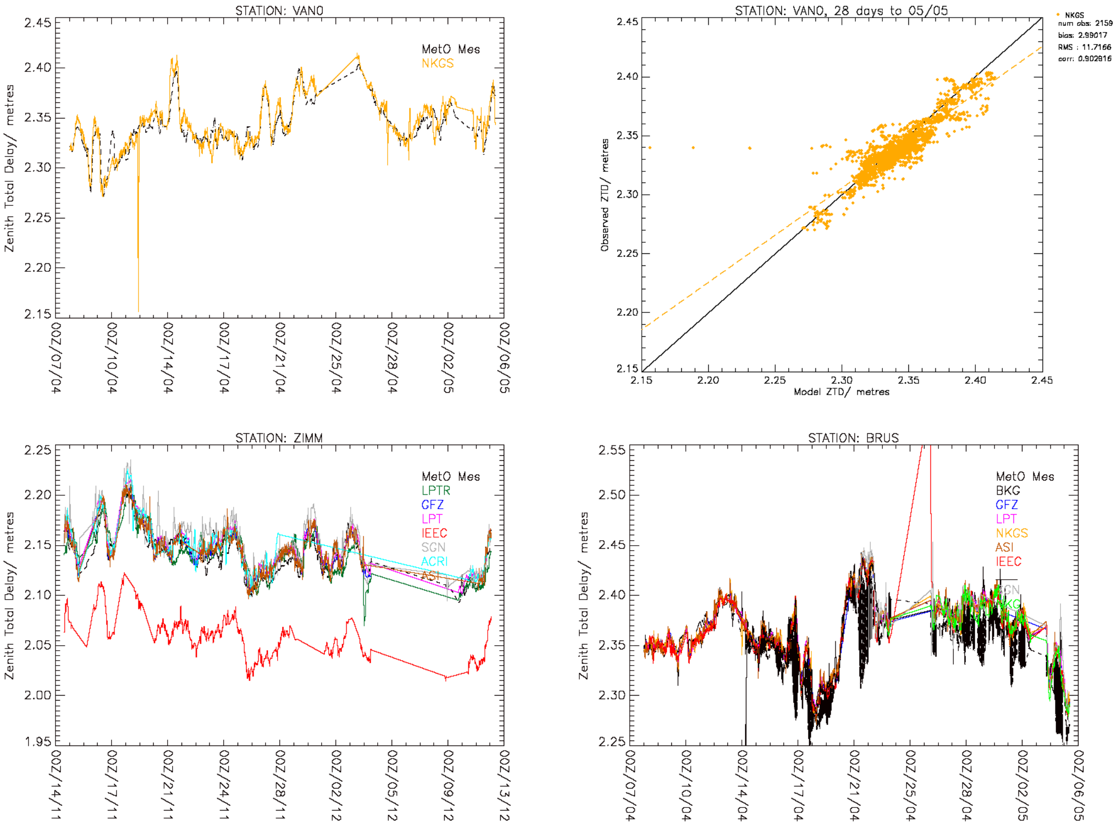


Figure 5.10: Examples of anomalous NRT data.

zero bias for all data types and that errors are distributed as Gaussian. We therefore have to quality control the observations prior to assimilation to meet this requirement, and this in turn implies an understanding of the error characteristics, and the flagging, corrections or elimination of errors (upstream, wherever possible).

This can be done within the assimilation system, but such gross errors should ideally be trapped at source. In some cases problems arise due to the processing strategy, as described in Chapter /refs-theory-accuracy (e.g. the use of hourly boundaries) and sometimes for external reasons (e.g. poor satellite orbits)

The formal error in ZTD value in the COST-format files is a basic quality control parameter required for direct use in assimilation. Unfortunately this is not currently a useful indicator of the sample quality. Research is continuing within TOUGH to provide a meaningful quality indicator that can be used to reject or down-weight individual observations in the assimilation process. Work under TOUGH will also investigate the causes of the biases and other data quality issues which are of importance when including observations in the assimilation process.

Chapter 6

Applications

Sylvia Barlag

6.1 Nowcasting applications

The quantitative use of GPS data for very-short-range meteorological forecasting, also called nowcasting, was added to the original objectives of the COST Action 716 at a later stage. At the workshop in Potsdam, February 2001, several interesting direct meteorological applications of the GPS water vapour data were shown. This led to a recommendation of the community to add the nowcasting subject to the list of applications to be studied.

The value of quantitative use of IWV data only became apparent once the real time data flow between the analysis centres and the ftp server set up by the Met Office was firmly established. Over the period of the action, more and more GPS analysis centres joined this effort, leading to a constantly improvement of the contents of the database and leading to a better coverage of the European domain by the GPS data. A real time comparison between IWV data and NWP data was set up by KNMI for validation and feedback purposes and was made available on a COST 716 NRT monitoring web site. A running comparison was shown between IWV from GPS reception stations, processed by the participating analysis centres, and the corresponding NWP value from the KNMI HIRLAM version. The fact that some GPS stations were processed by more than one analysis centre enabled these to assess differences between themselves. However, it also showed some interesting cases of differences between NWP and the real time GPS data. Due to the multiple processing for some stations, this could for some cases be directly attributed to the NWP data being in error. Furthermore, by studying not only the temporal pattern at some sites, but also the spatial pattern through combining the GPS data in a 2D spatial graph, NWP phase shifts could be seen. This led to the question how these data could be used to monitor the performance of NWP, and how they could serve the bench forecaster making very-short-term weather forecasts.

In the following sections several applications will be discussed in more detail. These are:

1. Time series comparison between IWV and NWP for detecting NWP phase errors
2. The use of 2D IWV fields and time series of these fields
3. The synergetic use of GPS-IWV and Meteosat imagery

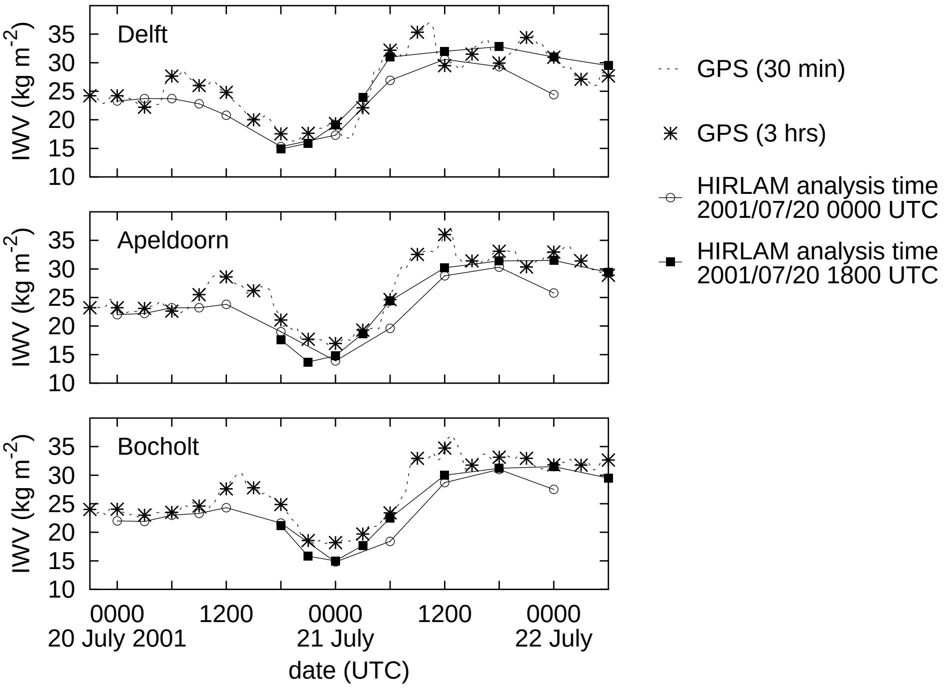


Figure 6.1: Times series of GPS IWV and two HIRLAM forecasts for three sites: Delft, Apeldoorn and Bocholt. The stars are GPS IWV observations plotted every three hours, the dashed lines shows GPS IWV observations on a 30 minute time interval. The open circle are HIRLAM IWV forecast started on July 20, 2001 at 0000 UTC and the solid squares are HIRLAM IWV forecast started on July 20, 2001 at 1800 UTC. See Figure 6.2 for the locations of the three sites.

6.1.1 Time series comparison

Siebren de Haan and Sylvia Barlag

The first example of the use of times series of GPS is shown in Figure 6.1. This figure depicts the time series of GPS and HIRLAM forecasts. Phase errors are not uncommon in numerical weather prediction models. Detecting these shifts can be crucial for a good timing of for instance a cold front passage. At what time a band with rain enters a region is very important when it concerns an extreme weather event. The occurrence of large phase shifts has already been noticed by Cucurull et al. (2000) and Guerova et al. (2003). Cucurull et al. (2000) showed that after a frontal passage the drop in NWP IWV was less abrupt than observed by GPS. Guerova et al. (2003) found that during a cold front passage the NWP IWV and GPS IWV had an offset of several hours. The case described here had no extreme weather but showed a bias and a phase shift when NWP forecasts and GPS are compared.

In Figure 6.1 the GPS IWV from three GPS sites are shown. GPS IWV observations at 30 minute and 3 hour intervals are shown. Also shown in these figures are two model forecast time series: one starting on July 20, 2001 at 0000 UTC and the other starting on July 20, 1800 UTC. Note that the forecast time series have data points every three hours up to the 12 hour forecast, hereafter every 6 hours. The actual observation frequency of GPS is 30 minutes but, in order to compare GPS IWV and HIRLAM IWV, GPS observations averaged over 3 hours are shown as symbols. The top panel shows IWV values for the site Delft, which lies close to the North Sea coast. The middle panel contains IWV values for the location Apeldoorn, which lies in the eastern part of the Netherlands and the time series shown in the bottom

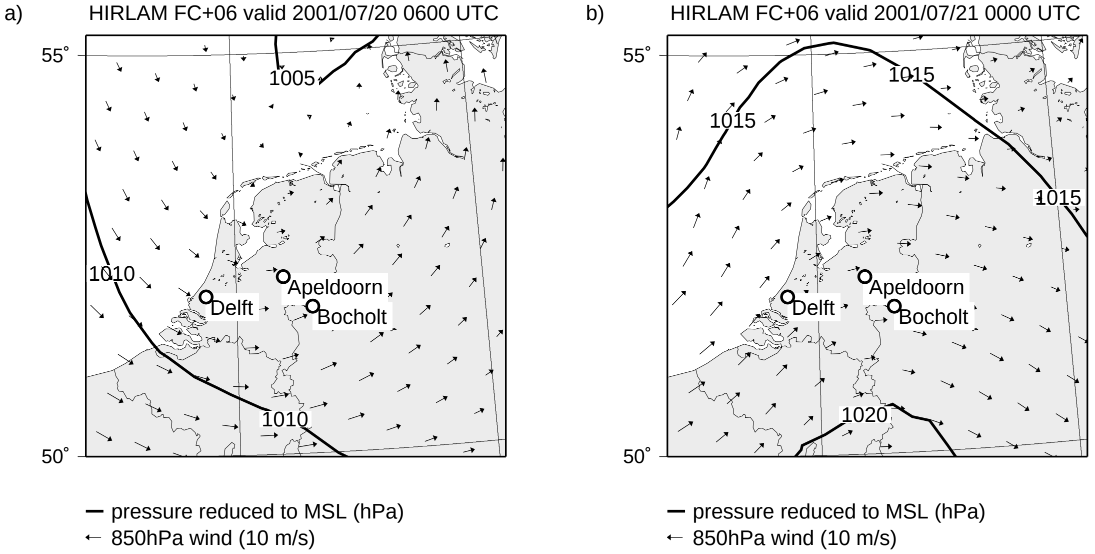


Figure 6.2: HIRLAM forecast 6 hours forecasts valid at a) 2001/07/20 0600 UTC and b) 2001/07/21 0000 UTC. Contoured is the pressure at mean sea level and the arrows indicate the wind speed and direction at 850 hPa.

panel are from the location Bocholt which lies in Germany close to the Dutch border. These locations are also depicted in Figure 6.2.

Note that the locations are roughly from west to east when the panels in Figure 6.1 are read from top to bottom. Figure 6.2(a) shows the pressure at mean sea level and the winds at 850 hPa for July 20, 0600 UTC. The flow at this time in the vicinity of the three GPS sites is from west to east. A low pressure systems moves northward in the coming hours resulting in a high pressure ridge 18 hours later, see Figure 6.2(b).

The HIRLAM forecast valid for Delft at July 20, 2001 0006 UTC (top panel Fig. 6.1) and starting at 0000 UTC does not show the increase of IWV visible in GPS during the first few hours. This bias is also present for the location Apeldoorn (just before 1200 UTC) and Bocholt (just after 1200 UTC). The fact that this bias has moved in the direction of the flow suggests that it could be caused by an artifact in the HIRLAM forecast. A signal of a phase problem occurs for the sites Delft and Apeldoorn for this forecast after July 21, 0000 UTC. At that time the forecast IWV and observed IWV are close to each other, but the increase of HIRLAM IWV is later than GPS for this forecast. The increase observed of GPS IWV at 0300 UTC in Delft is also observed in the forecast started at July 20, 1800 UTC. The maximum of GPS IWV at 1200 UTC in Apeldoorn and Bocholt is not visible in the IWV forecast. The 1800 UTC IWV forecast at times after 1500 UTC matches good with the observed GPS IWV.

By comparing these time series downstream of a front the timing of the model can be checked. Moreover local deviations can be detected and when these deviations are transported in the direction of the flow an adjustment to the forecast could be made. It may happen that this deviation in IWV triggers or prevents convection, depending on the magnitude of the deviation.

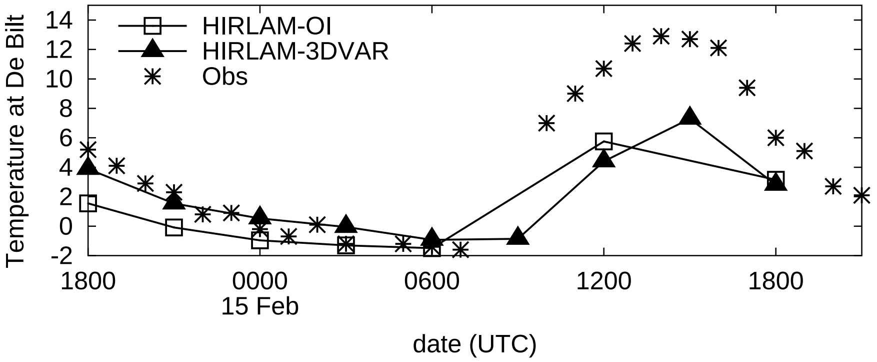


Figure 6.3: NWP temperature forecast and observations for De Bilt. HIRLAM-OI (open squares) is the output from the operational model run, started on February 14, 2001 at 1800 UTC; this analysis scheme used for this model is based on optimal interpolation. HIRLAM-3DVAR (solid triangles) is the output of a re-run of the model with a 3-dimensional variational analysis scheme. The hourly observations are denoted by stars.

6.1.2 2 metre temperature forecast

Siebren de Haan and Sylvia Barlag

The next example of the use of time series discusses a 24 hour NWP forecast of the maximum temperature at De Bilt of February 15, 2001, which was seriously underestimated. A difference between forecast and observed maximum temperature is not surprising, however the discrepancy that occurred was marked by the forecasters as too large. Normally a temperature difference within a few Kelvin is normal, due to parametrization and orographic modeling difficulties. The maximum difference on February 15 between the forecast and observed temperature was more than 6 K, see Figure 6.3.

This cannot be explained by modeling errors and therefore it must have a different origin. Two time series of NWP forecasts are shown in this figure: the model output labeled HIRLAM-OI is the operational model output as was used for the forecast; this version of the model uses an optimal interpolation analysis scheme. The model output labeled HIRLAM-3DVAR is a re-run of the model with a 3-dimensional variational analysis scheme. Note that, apart from the first 12 hours, the temperature forecast for both models are almost the same and that both are too low with respect to the observed temperature. The used analysis method did not cause the problems. All NWP data shown hereafter in this section is based on the operational model output, that is the HIRLAM-OI.

On February 14, 1800 UTC a high pressure system was situated around 55°N and 5°E, see Figure 6.4. In this figure the pressure at mean sea level and wind vectors at 850 hPa are shown. The NWP model forecast a movement of the high pressure system from the North Sea to northwest Germany, see Figure 6.5. The weather on February 15, 2001 was foggy in the morning, with temperatures around the freezing point. Later that day the fog cleared and it became a sunny day with temperatures around 14°C. The weather forecast said that the fog was to stay for the whole day.

In Figure 6.6 the observed and the forecast temperature and humidity profiles at February 15, 0600 UTC and 1800 UTC are shown. The top panel shows the 12-hour and 24-hour (valid at 0600 UTC and 1800 UTC, respectively) forecast profile from NWP and the bottom panel shows the observed profile from the radiosonde launches at De Bilt. At 0600 UTC the relative humidity from the two lowest observations indicate that the air at these heights was completely saturated. This layer was thin and extended from

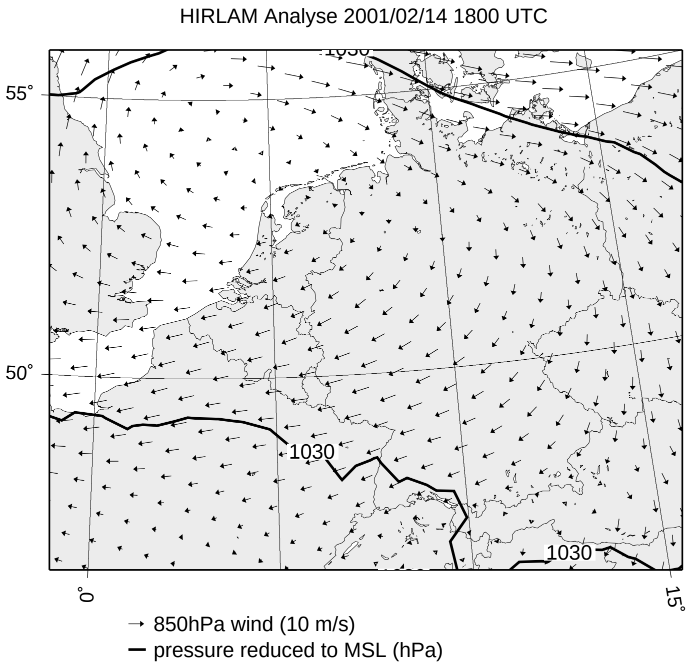


Figure 6.4: HIRLAM analysis of 2001/02/14 1800 UTC. Contoured is the pressure at the mean sea level; the arrows indicate the wind speed and direction at 850 hPa.

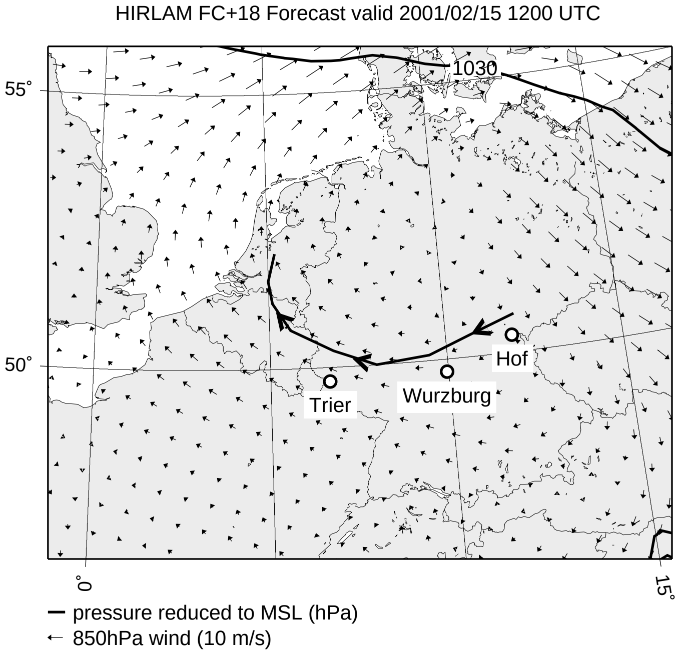


Figure 6.5: An 18 hour HIRLAM forecast valid at 2001/02/15 1200 UTC. Contoured is the pressure at the mean sea level; the arrows is the wind speed and direction at 850 hPa. The line indicates the trajectory of the airmass (in 24 hours), the arrows the direction of the flow along the line. The GPS sites close to this trajectory are indicate by a white circle.

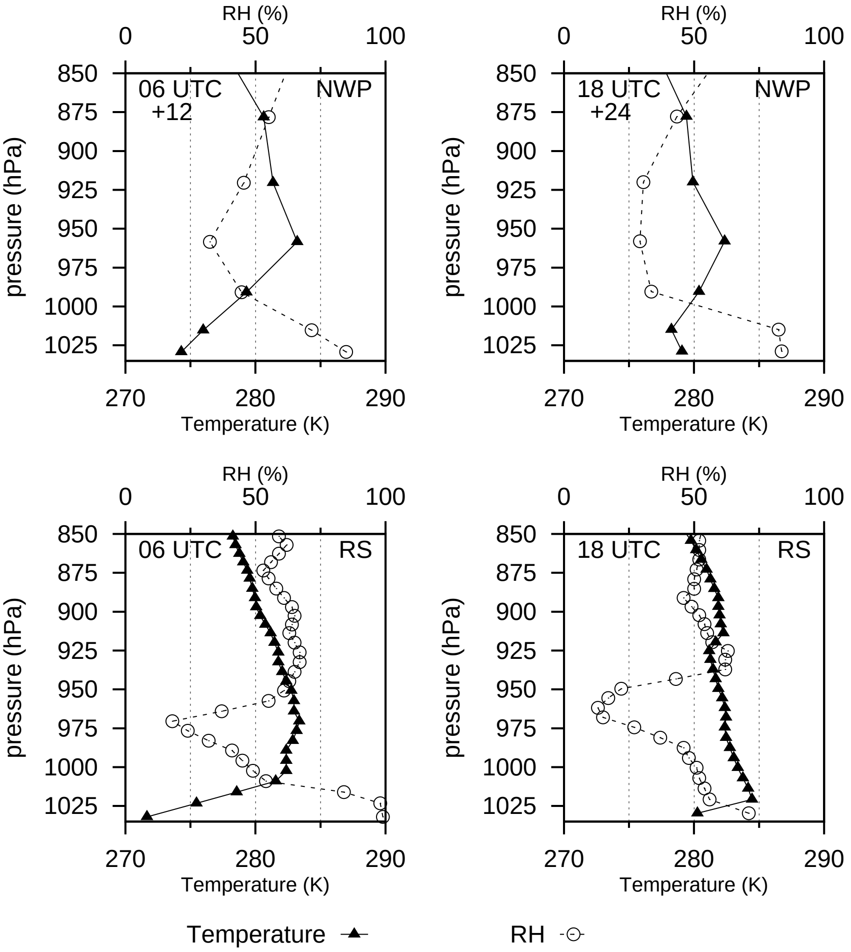


Figure 6.6: Temperature and humidity profiles for NWP forecast (top panels) and radiosonde launches at De Bilt (bottom panels) valid on February 15 at 0600 UTC (left panels) and 1800 UTC (right panels). Triangles represent temperature observations; Relative humidity (RH) is denoted by open circles.

the ground to a height of approximately 75 m. In the model profile this thin layer of fog is less clear, however it is present at the lowest model level. One should keep in mind that each model parameter (e.g. temperature, humidity) represents the mean of this parameter in the air volume described by the horizontal and vertical resolution of the model. This is the reason why the NWP profile is smoother than the observed profile. A relative humidity of over 80% is high for a level near the ground with a height of approximately 60 m; this indicates the presence of fog in the model.

At 1800 UTC the radiosonde profile showed the onset of the nocturnal boundary layer; the sunset was around 1630 UTC. No fog or low clouds were present because the relative humidity was below 75%. The NWP profile showed a fog/cloud layer (relative humidities over 80%) expanding over the two lowest layers. This fog/cloud layer cannot originate from the nocturnal boundary layer; it is too deep. The cause of the occurrence of this fog/cloud layer is investigated below. Insight is gained in the origin of humidity in the airmass over De Bilt at February 15, 1800 UTC by focusing on the trajectory of the airmass starting February 14, 1800 UTC and arriving in De Bilt 24 hours later.

An airmass at a height of 850 hPa starting in eastern Germany, near the Czech border follows a curved path and arrives 24 hours later in De Bilt. The path of this airmass is based on the NWP model forecast

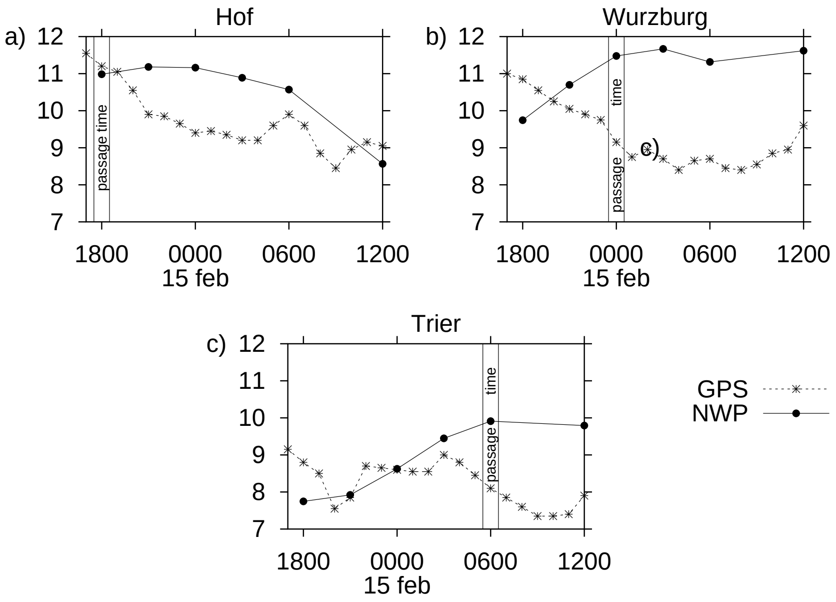


Figure 6.7: Integrated water vapour from GPS and NWP forecasts at (a) Hof, (b) Würzburg and (c) Trier. The passage time of the airmass is indicated by the vertical bar.

starting on February 14, 1800 UTC, and is determined by tracing the origin of airmass back in time, using model winds, see Figure 6.5.

The trajectory of the airmass passes close to the German GPS sites Hof, Würzburg, and Trier, see Figure 6.5. Only German GPS sites, processed by GFZ, were available in near real time on February 14, 2001. At February 14, 1800 UTC the airmass is near Hof. The IWV time series shown in Figure 6.7(a), show that at the time of passage the GPS IWV and NWP IWV correspond very well, although a few hours later large discrepancies occur: the GPS IWV decreases rapidly from 11.5 kg/m^2 to 9.5 kg/m^2 while NWP IWV stays more or less constant.

Moreover, the decrease of GPS IWV is already visible in the first hour after February 14, 1800 UTC. Six hours later, at February 15, 0000 UTC, the airmass has arrived in the neighborhood of Würzburg. Figure 6.7(b) shows that the differences, as well as the change with time in IWV for time series of GPS IWV and NWP IWV, are even larger. The absolute difference does not necessarily indicate that there is a forecast problem because orography and model resolution may introduce biases. However, the difference in the trends between GPS IWV and NWP IWV is remarkable and cannot be explained by biases. GPS IWV shows, again, a strong decrease of IWV with time, while NWP IWV shows even a small increase. At February 15, 0600 UTC when the airmass arrived in the neighborhood of Trier an almost identical signal as at Würzburg 6 hours earlier is observed, see Figure 6.7(c).

Along the trajectory, the NWP airmass gains humidity (NWP IWV is increasing), while GPS observations of IWV observed the opposite: a decrease in the total amount of water vapour. This implies that, compared to the GPS IWV, the airmass according to the model arriving at De Bilt was too humid. A large proportion of the energy from the sun is used for evaporation of the (at first) saturated model layers near the surface. If the airmass in the model would have been less humid the energy could have been used to heat the air and the result would have been a higher 2 metre temperature forecast. Amendment of the forecast for the observation that the model was too humid could have led to a better estimate of the maximum temperature.

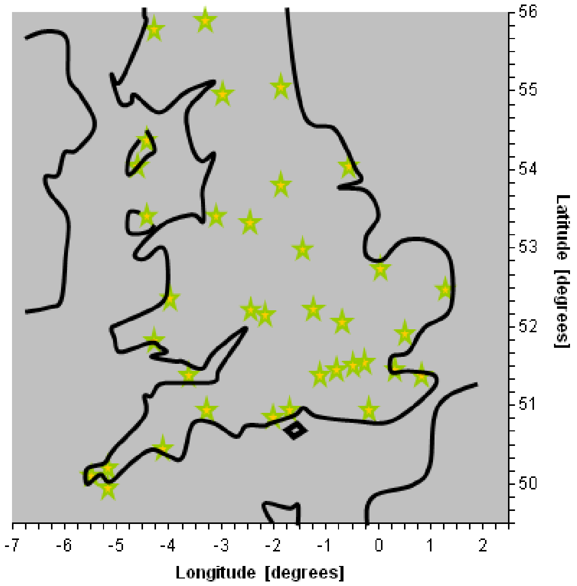


Figure 6.8: GPS sensor sites used in post processed analysis of GPS water vapour measurements over the UK. The sensors were owned by a variety of organizations, including Ordnance Survey, Trinity House, National Physical Laboratory, UK National GPS Site, Herstmonceux, IESSG, Nottingham University and the Met Office. Data were collected by IESSG, Nottingham University.

6.1.3 The use of 2D GPS-IWV fields

John Nash and Jonathan Jones

The use of two dimensional GPS water vapour fields allows the horizontal structure in the integrated water vapour to be identified by the user. Whilst in future, the water vapour observations may be integrated into an analysis incorporating other observation sources and NWP model background fields, there are a variety of users (including observing network planners) who would benefit from direct visualization of the GPS water vapour observations at this time. In summertime much of the smaller scale structure originates from convective precipitation. So, for this report the water vapour fields will also be superimposed on 2-dimensional precipitation fields measured by operational weather radar. Two sets of 2-D plots will be considered. Larger scale coverage will be taken from 10 July 2001, a day with widespread convection on different scales across the British Isles. A smaller scale study is concentrated close to London on 09 August 2001, when flooding occurred to the north east of London. These analyses were performed so users could judge whether real time GPS water vapour measurements would be useful in operational forecasting in the UK. The GPS sites used for the larger scale 2-dimensional analysis are shown in Figure 6.8.

The 2-dimensional water vapour fields shown in Figure 6.10-6.13 and Figure 6.15 were generated manually within the UK Met Office using time series of GPS measurements supplied by IESSG, Nottingham. Temporal resolution of the water vapour time series was 15 minutes. Each 2-D plot contains information from the nominal time, plus additional observations from the site mostly within 1 hour from the nominal time. An observation one hour earlier was placed downwind of the observing site, using the wind speed and direction at 2 km above the surface. The winds between, at 2 km on 10 July, were usually strong enough that observation from one hour earlier were located between 40 and 80 km downwind to the east northeast of the observing site. An observation from one hour after the nominal time was located a

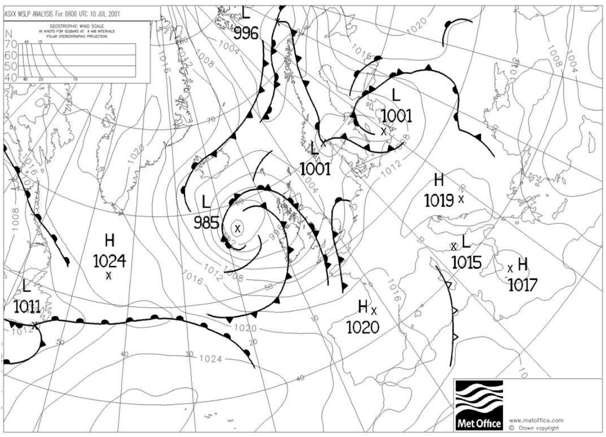


Figure 6.9: Surface analysis of weather conditions at 06 UTC on 10 July 2001, showing low pressure centred to the west of the British Isles, with several fronts across southern UK.

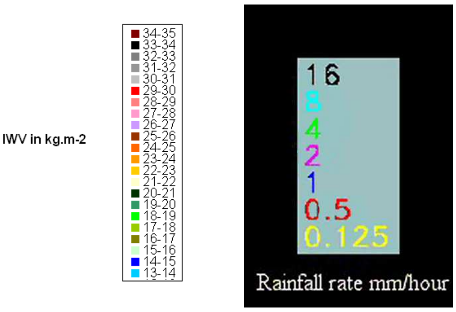


Figure 6.10: Colour keys for contours of IWV and for weather radar rainfall rates in the plots for 10 July 2001.

similar distance upwind of the site. Comparison with real time observations downwind indicated that the IWV fields could often modify significantly after 1 hour or travelling more than 100 km in the horizontal, so use of data at 2 hour time displacements was only considered when conditions appeared stable and advection in the horizontal was limited.

The errors in the GPS water vapour measurements used were expected to be less than 1 kg/m^2. It was discovered that the Trinity House [marine navigation] sensors needed a modified adjustment for phase change in the antenna. Otherwise systematic biases between the IWV from different sensor sites were estimated to be within the expected error.

On 10 July 2001, low pressure dominated the weather over the British Isles, as can be seen in the surface analysis at 0600 UTC, in Figure 6.9. Figure 6.10 shows the keys for the following 2-D plots of integrated water vapour and weather radar rainfall rate.

Figure 6.11 show 2-D plots of integrated water vapour at 3 hour intervals, with the position of the relevant fronts superimposed on the plots for 06.00, 12.00 and 18.00 UTC. In Figure 6.12 the same IWV data are superimposed on radar measurements of rainfall rate. IWV values above 26 kg/m^2 are shaded purple, values below 21 kg/m^2 are shaded green. Blue triangles show positions of wind profilers, Dunkeswell (51°N, 3.5°W) at 12.00, Wattisham (52°N, 1°E) at 18.00. Light blue circles indicate thunderstorm activity at 18.00. The weather fronts moved from west to east, taking between 6–9 hours to cross the UK.

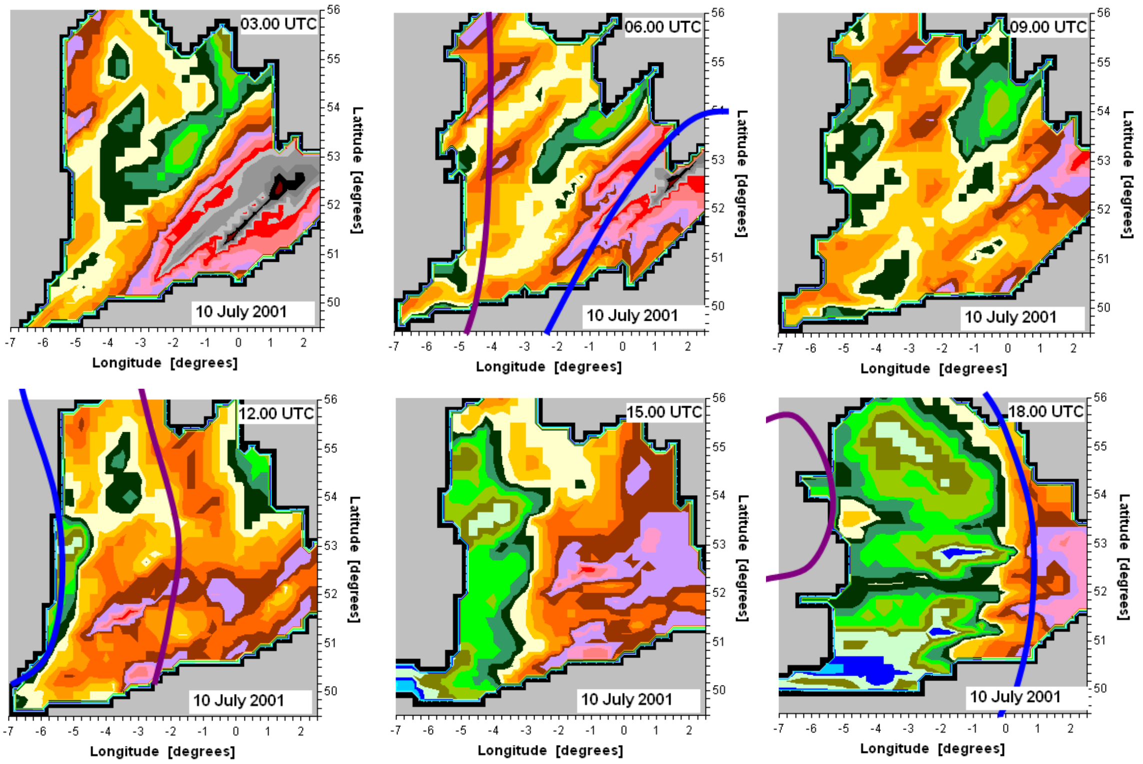


Figure 6.11: Integrated water vapour distribution over southern and central UK contoured at 1 kg/m^2 increments for 10 July 2001, from time series of post-processed observations,

The moistest air in Figure 6.11 was observed at 03.00 UTC, in advance of the first cold front. At this time the weather radar shows a band of moderate rain to the north west of the maximum values of IWV. The drop in IWV across the rain band is caused in part by a drop in the average temperature of the air across the cold front, since values as high as 34 kg/m^2 were not observed again on this day, even in the deepest rain. By 06.00 the moistest warm air had advected away from the British Isles across the North Sea.

Variations in IWV along the length of the occluded front (purple line) were judged to be significant and not he result of systematic bias between sensor sites. The plots from 06.00 through to 12.00 UTC, are each totally independent of the other plots, but the patterns persist over different parts of the country as the front moves east. Higher values were spaced about 100 km apart. At 12.00 highest values were downwind of persistent heavier rainfall near the Bristol Channel (51.5°N, 4°W) and also downwind of showers in the English Channel/southern England near the south coast (50.5°N, 3°W). The wind profiler at Dunkeswell was located in a region with slightly lower IWV between these two local maxima. The time series of GPS water vapour from Dunkeswell was superimposed on the wind profiler signal to noise from the same site see Figure 6.13. Wind profiler signals higher than 82 dB were produced by scattering from precipitation within showers. Thus, a line of showers (depth 0 to 3 km) passed the profiler just after 12.00. The winds near the top of these showers were stronger than at lower levels and were advecting moisture forward from the showers.

At 15.00 UTC the weather radar showed two bands of very heavy rainfall along the last cold front. The band in the north was centred at about 53.5°N, 2°W. This was ahead of a dry intrusion behind the cold front [local minimum in IWV, 3 kg/m^2 lower than the values to the north and south along the

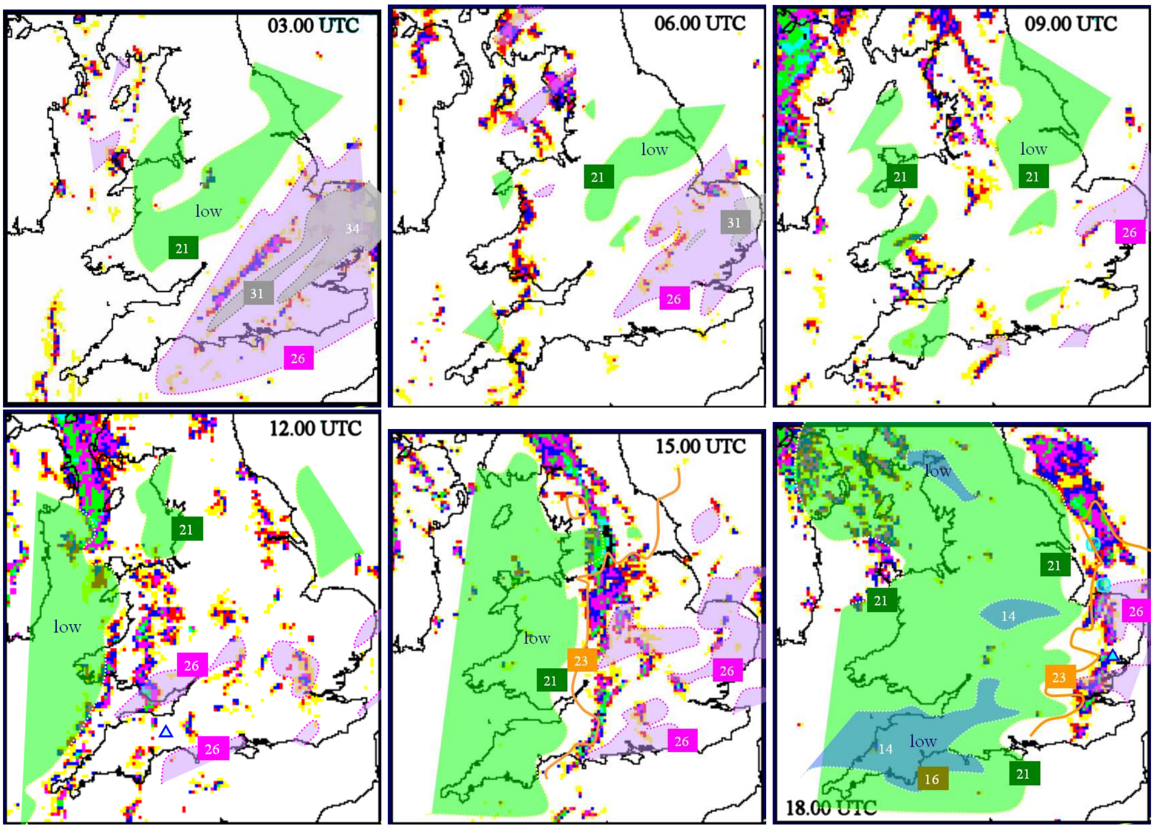


Figure 6.12: Integrated water vapour distribution over southern and central UK contoured at 5 kg/m^2 increments for 10 July 2001, superimposed on weather radar observations.

analysed front, see the 21 kg/m^2 contour]. The second band in southern England was centred at about 51°N,2°W, ahead of a second dry intrusion [local minimum in IWV, about 2 kg/m^2 lower than the values to north and south along the front, see the 23 kg/m^2 contour]. When this area of convection had passed over Dunkeswell around 14.00 UTC, it was not a single line, but was split into two parts. These merged to give the single line with the very high rainfall rates as the cold front moved east, as seen at 15.00 UTC. The decrease in Dunkeswell profiler signals at 5 km in advance of this convection suggests that drier air was present above 4 km. This very dry air descended with time after the rain bands had passed the site, as indicated by the dashed purple line on the signal to noise plot in Figure 6.13. This gave rise to the lower values of IWV seen in southwest England on the plots at 15.00 and 18.00 UTC.

When the southern band of rain passed over the Wattisham wind profiler, the line convection had split into smaller segments of heavier rain. However, a strong convective cell followed by a dry intrusion, crossed Wattisham, just after 18.00 UTC. During this event strongest winds were found at heights of about 2 to 3 km behind the convection.

Changes in IWV measurements and wind profiler signal structure were consistent with stronger winds feeding dry air into a region behind the convection where it was moistened and hence cooled by precipitation falling from heights between 3 and 4 km.

The analyses demonstrated that an operational GPS network needs to have a spatial resolution of at least 25 km if it is to resolve the more significant changes in water vapour associated with the organized convection seen in the weather radar measurements on this day. It is also vital that systematic biases

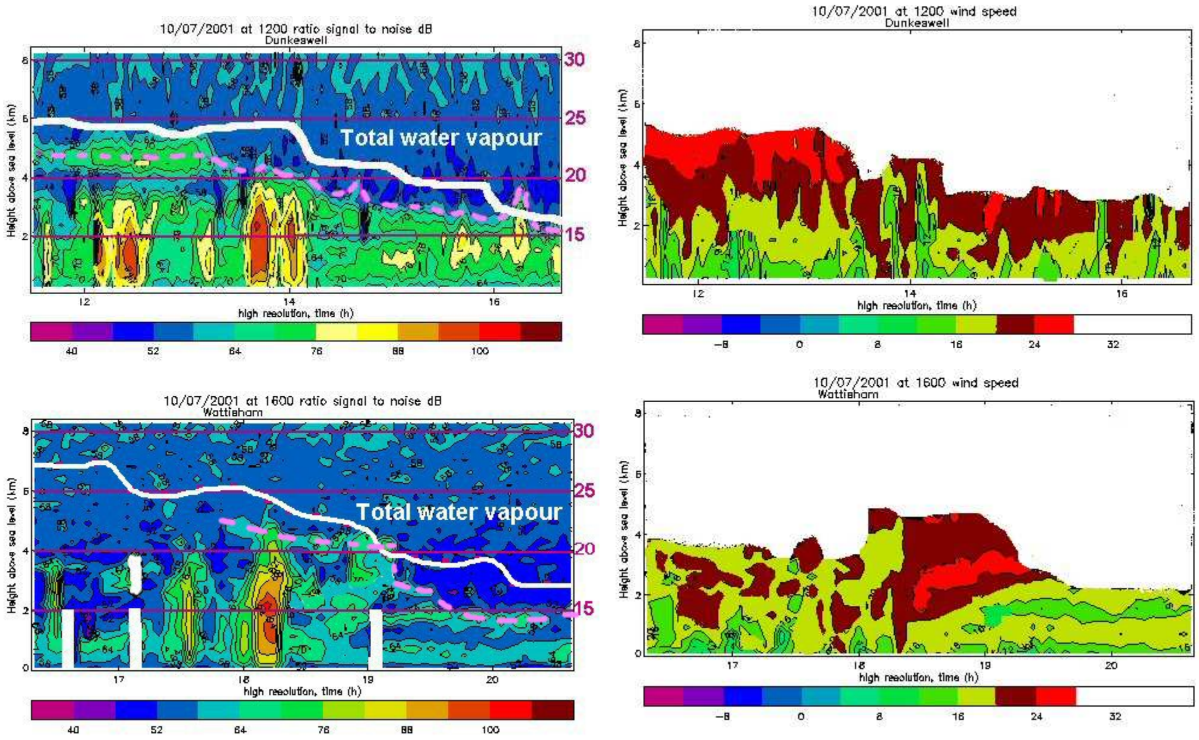


Figure 6.13: Time series of IWV [white lines] in kg/m^2 superimposed on 1.3 GHz wind profiler measurements of signal to noise from Dunkeswell and Wattisham. Associated wind speed measurements are also shown. The dashed purple line on signal to noise plots indicates the probable depth of the moist layer above the surface.

between sensor sites are as small as possible since the magnitude of the variations in IWV in the horizontal associated with dry intrusions along a front were relatively small, about 3 kg/m^2. The structure in the IWV associated with the convective activity in this case and others considered changed quite rapidly with time, so the users judged that the measurements would have to be delivered with a time delay of less than 1 hour if they were to be useful for short term forecasting/ nowcasting.

Combination of GPS water vapour measurements with information from weather radar and wind profilers to improve understanding of the vertical distribution of water vapour associated with organized convection, should lead to a better understanding of the atmospheric processes involved.

On the 10 July 2001, there were few thunderstorms over the UK during the period of the analysis, with just two short lived thunderstorms developing in eastern England (53.5°N, 0.5°E) at 18.00 UTC. The second case looks at thunderstorms developing near London as an upper trough moves eastwards towards London in relatively cold air. The surface analyses at 06.00 and 12.00 are shown in Figure 6.14.

Figure 6.15 IWV plots for 09 August 2001 for the southeast of England. Colour key for the IWV and weather radar plots as for Figure 6.10–6.13. Black pixels indicate the heaviest rainfall. Light blue dashed lines surround areas of thunderstorm activity on the left hand side IWV plots. Red stars indicate the position of the GPS sensor sites used in the analysis. As the leading trough line approached the southeast at 09.00 the highest IWV in advance of the trough increased by 2 kg/m^2 from 07.30 to 09.00. The weather radar shows heavy rain to the northwest of the highest IWV, but the high IWV sits in a ring of clear echo, with small but intense thunderstorms starting to initiate around the edges of the area

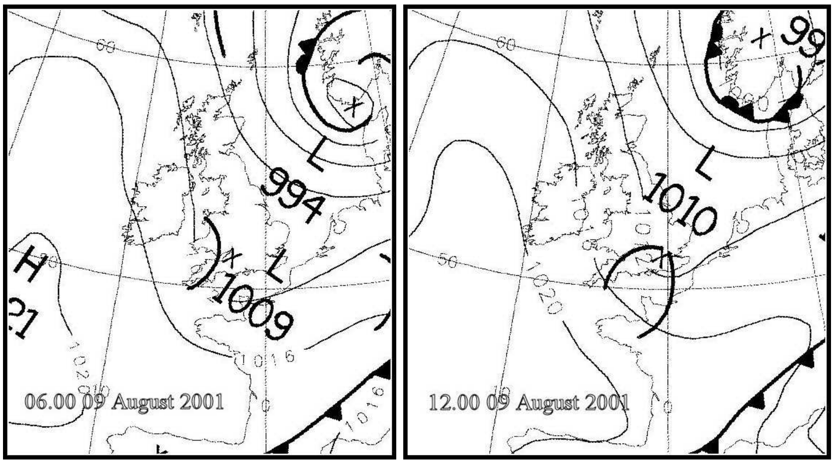


Figure 6.14: Surface analyses for 9 August 2001.

of higher IWV ahead of the trough. Earlier in the night there had been thunderstorm activity to the northeast of London, 52°N, 1.5°E, and this seems to have left a large gradient in IWV north to south to the east of London. By 10.30 the thunderstorms organized into a line to the north of the highest IWV, very close to the line of GPS sensor sites As time goes by the area of high IWV makes very little progress eastwards although the weather radar shows rain moving in this direction. The lower values to the east of London do not modify significantly when it starts to rain in this area later, so it is probable that the low values of IWV were associated with a significantly colder pool of air. By 12.00 the passing trough had triggered a line of small but severe thunderstorms, joining the two areas of activity at 10.30 and aligned approximately with the IWV gradient to the east of London. These small thunderstorms were slow moving and produced flooding in several parts of north east London.

This case (along with other case studies) indicated that knowledge of the 2-D structure of IWV fields is clearly one of the factors required for improving the prediction of some types of severe thunderstorm. Here, IWV fields were probably delineating the extent of warm and cold pools of air, since the air over southeast England was probably close to saturation at low levels.

This case study could not have been performed without a detailed knowledge of the winds near London. It is probable that improved wind observations need to be combined with improved water vapour knowledge from GPS water vapour if the optimum benefit to short term forecasting is to be obtained.

The IWV values to the north of the main line of sensor sites rely heavily on assumptions about the advection of earlier observations in the direction of the wind. As with the earlier case study a good target GPS sensor site density for operational measurements would seem to be about 25 km, if the integrated water vapour fields are to be adequately resolved.

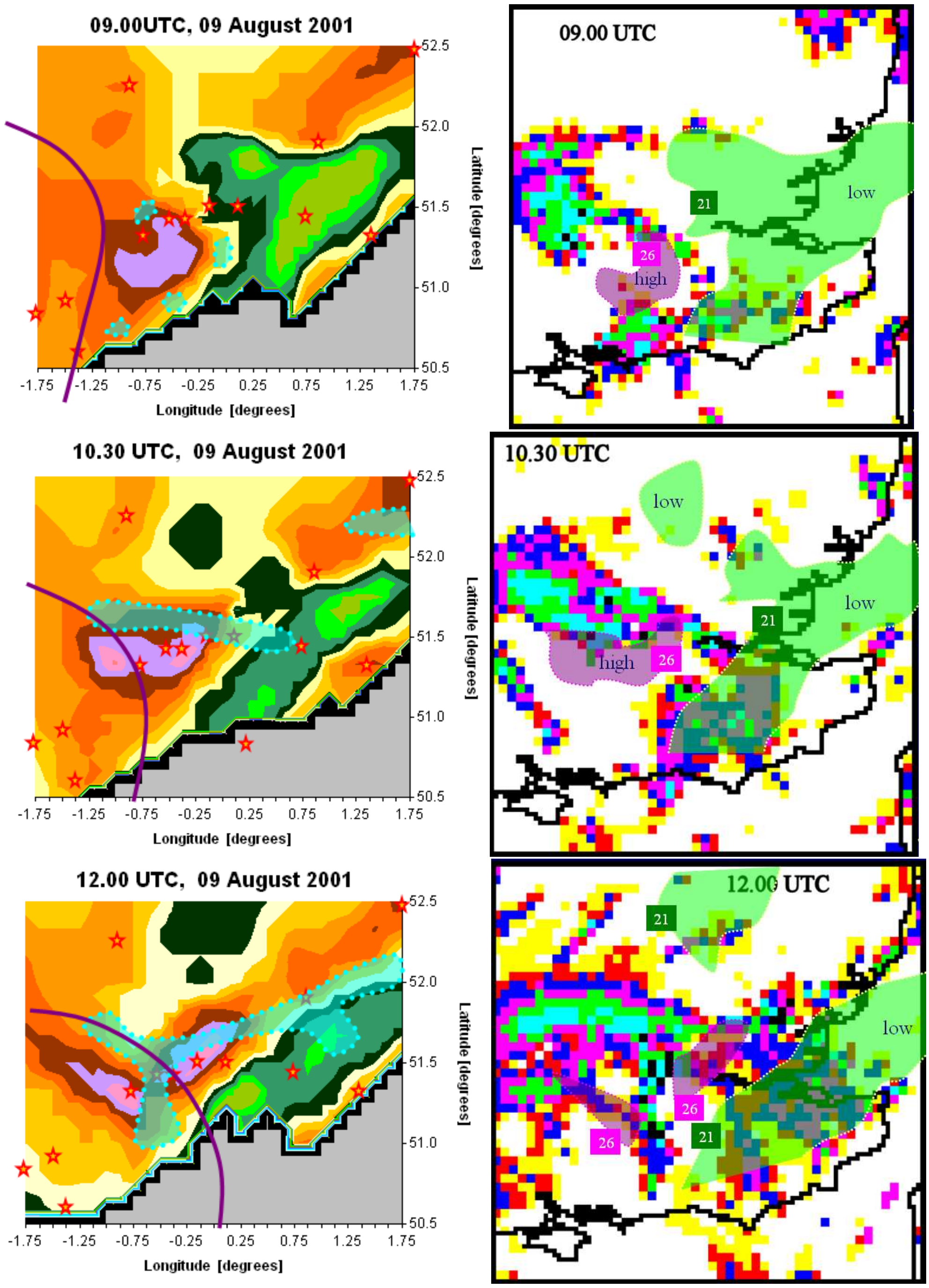


Figure 6.15: 2D IWV plots on a much higher spatial resolution than in Figure 6.10–6.13, exploiting in particular a line of GPS sensor sites near London which allow spatial resolution of about 10 km in one direction. These IWV plots are also superimposed on weather radar plots as in Figure 6.10–6.13.

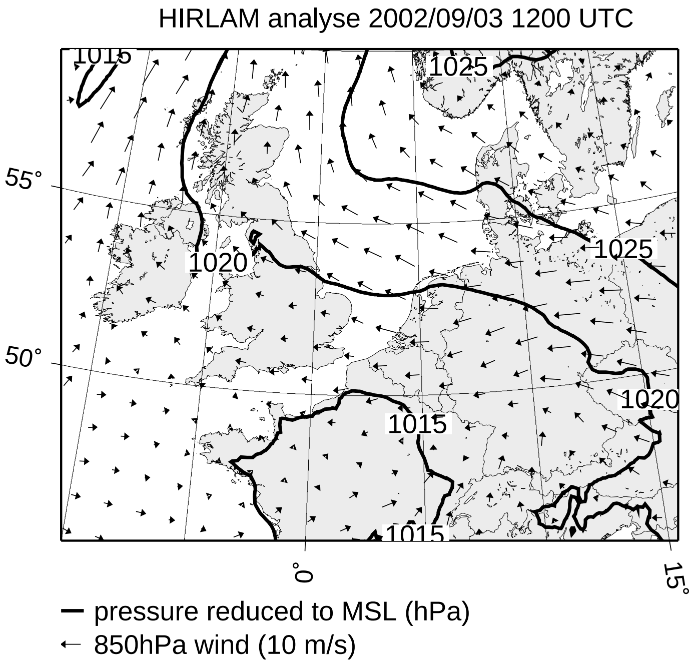


Figure 6.16: HIRLAM analysis of 2002/09/03 1200 UTC. Contoured is the pressure at the mean sea level; the arrows indicate the wind speed and direction at 850 hPa.

6.1.4 Synergetic use of (2D) GPS-IWV and Meteosat imagery

Siebren de Haan and Sylvia Barlag

To show that GPS IWV contains information on the possible development of deep convective clouds an overlay of 2-dimensional maps of GPS IWV and Meteosat WV images is made. The change of the humidity profile with time is estimated using this overlay.

On September 3, 2002 at 1400 UTC a system of deep convective clouds developed in mid-west Germany, close to the Dutch border and moved toward the Netherlands over the next hours. The development of this system was not forecast on the basis of the available operational observations and model data.

Figure 6.16 shows the pressure at mean sea level and 850 hPa winds for the HIRLAM analysis of September 3, at 1200 UTC. A high pressure system (over 1025 hPa) lies over the south of Norway and a low pressure region (around 1015 hPa) lies over France. In between these two pressure systems the flow at 850 hPa was (roughly) from east to west, see Fig. 6.16.

As stated before, Meteosat WV images contain information about the humidity in the upper troposphere. In Figure 6.17 the Meteosat WV image of 1200 UTC is shown together with a contour map of GPS IWV. Also shown in this figure are radiosonde wind observations at 500 hPa and 850 hPa. The area with high brightness temperatures (dark) is an area with very low upper tropospheric humidity, that is dry above 600 hPa. Underneath this dark area, GPS IWV increases from the west, with IWV values around 16 kg/m^2, to the east with values around 22 kg/m^2. Note that to the north and south of this area the IWV values are lower; the GPS IWV in the vicinity of the dark area can be regarded as a ridge of high IWV. The wind observations at 850 hPa, and the model analysis, at 1200 UTC indicate that this ridge is

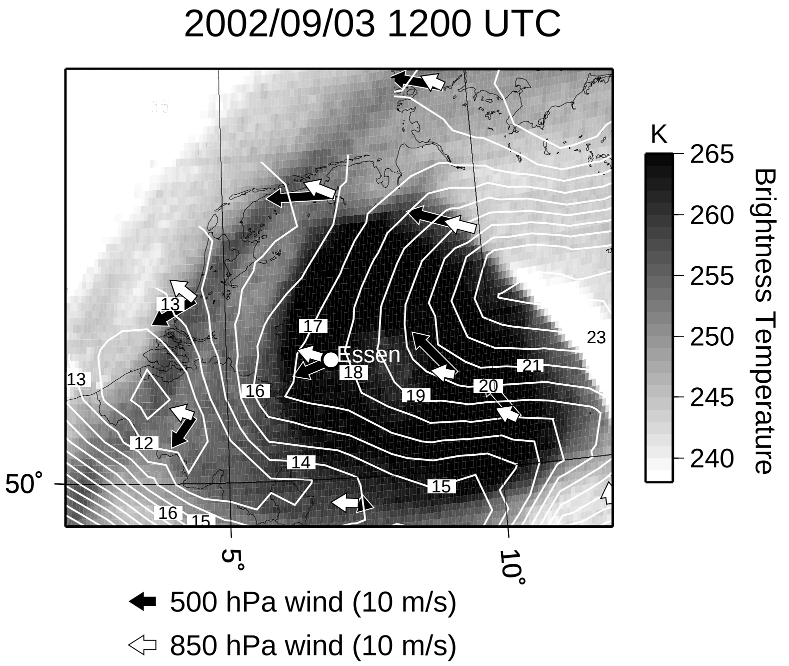


Figure 6.17: Contour map of GPS IWV distribution for 1200 UTC. The Meteosat WV image of 1200 UTC is shown in grey scales. At the locations of radiosonde launches wind speed and direction at 850 hPa (white arrows) and 500 hPa (black arrows) are shown.

transported westward toward the Netherlands. Moreover, the dry region higher in the atmosphere (above 600 hPa) is transported in nearly the same direction with on the east and north side of the region a greater speed than lower in the atmosphere.

In Figure 6.18 the virtual potential temperature is shown for the radiosonde launch of 1200 UTC at Essen (Germany) located in the mid-west of Germany not far from the Dutch border, marked in Figure 6.17 by a white circle. The virtual potential temperature is define as, according to Stull (1988),

$$\theta_v = T(p_{ref}/p)^{R/c_p}(1 + 0.61r), \qquad (6.1)$$

where p_{ref} is a reference pressure (usually 1000 hPa), T is the observed temperature at pressure p, r is the water vapour mixing ratio at pressure p, R is the gas constant of dry air and c_p is the specific heat of dry air at constant pressure. The definition of virtual potential temperature is chosen such that it removes the temperature variation caused by changes in height of an air parcel, hence the term potential and it incorporates the moisture of an air parcel into the temperature, giving rise to the term virtual.

The static stability of a profile is related to the increase/decrease of θ_v with height, see Stull (1988) for an extensive discussion. In Figure 6.18, the part of the profile starting at the surface up to the height where θ_v is equal to its value at the surface is unstable, when no condensation takes place during the ascent. When condensation occurs the θ_v will not be constant but increases with height. implying that the unstable part becomes larger. At 1200 UTC clouds maybe formed but the cloud tops remain below 800 hPa, and therefore are not visible on the Meteosat WV images.

In Figure 6.19 the Meteosat WV and GPS IWV contour map for 1300 UTC are depicted. Both the ridge and the black area have moved to the west. Figure 6.20 shows Meteosat WV and GPS IWV distributions at 1400 UTC. The grey arrow points to the location where deep convective clouds developed. Dry air

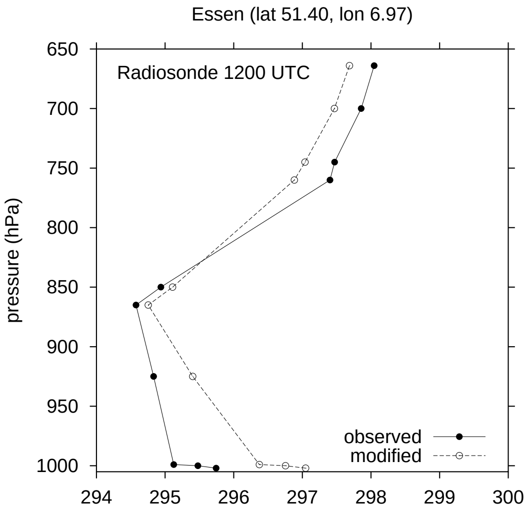


Figure 6.18: Virtual potential temperature profile from the radiosonde launch at Essen (Germany, see Fig. 6.17 for the location). The solid circles are form the observed profile, open circles correspond to the modified profile, see text.

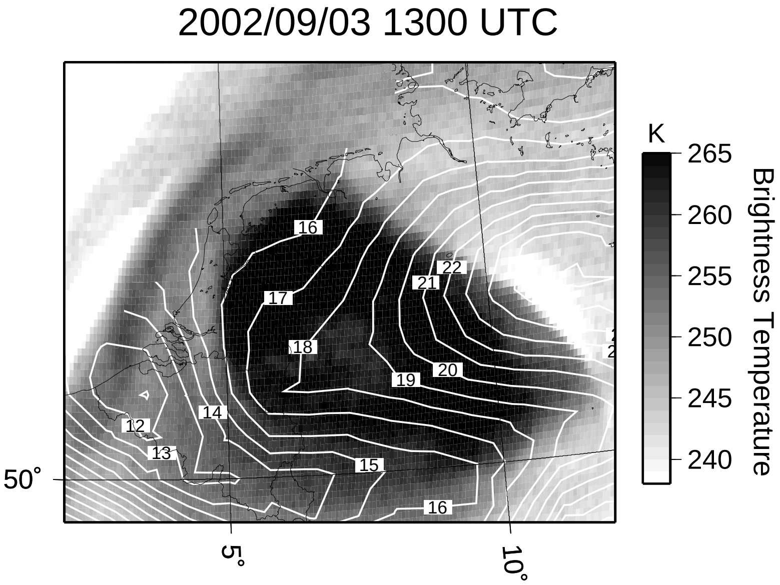


Figure 6.19: Contour map of the 2-dimensional GPS IWV distribution for 1300 UTC. The Meteosat WV image of 1300 UTC is shown in grey scales.

in the upper troposphere has moved over the indicated region, while the total amount of water vapour increases. This results in a change in the θ_v profile: θ_v in the lower part (around 850 hPa) increases and the air becomes more humid, while in the upper part of the profile the θ_v decreases. As a result of this change in θ_v-profile with time a larger part of the profile becomes unstable, that is the top of the unstable layer becomes higher; air parcels reach heights above 650 hPa. In Figure 6.18 this modification is visualized by the open circles. This profile is constructed by increasing the humidity below 800 hPa and decreasing the humidity above 800 hPa. East of these deep convective clouds no development is observed. This is due to the fact that the virtual potential temperature profile at Fritzlar (lat. 51.08°,

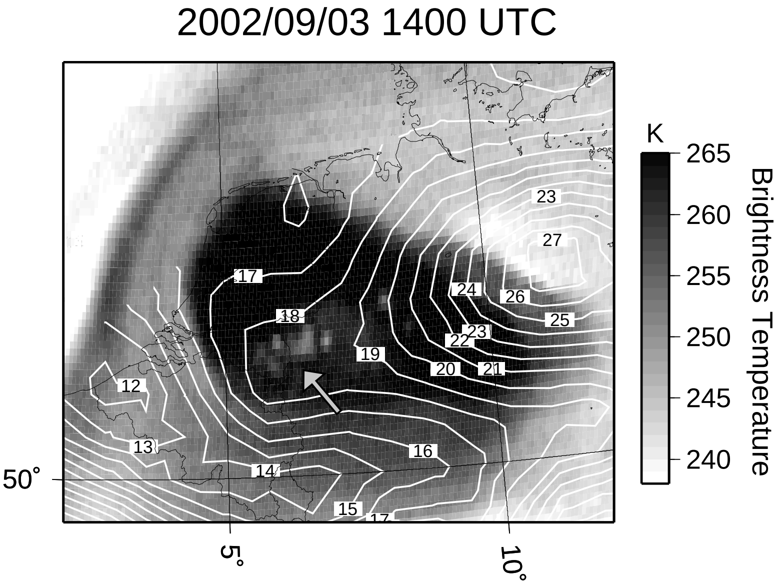


Figure 6.20: Contour map of GPS IWV distribution for 1400 UTC. The Meteosat WV image of 1400 UTC is shown in grey scales. The grey arrow points to the location where deep convection occurred.

long. 9.17°) on 1200 UTC is more stable in the top part of the atmosphere than the profile of Essen. Moreover, the increase of IWV is less. The local increase of IWV (i.e. the ridge) caused the virtual temperature profile to change and resulted in deep convective cloud.

The combination of Meteosat WV, GPS IWV and radiosonde profile information is useful for signaling a possible occurrence of deep convective cloud development. The signal was already present in the IWV contour one hour prior to the occurrence of the deep convection. The strength of using GPS IWV contour maps lies in the fact that they can be updated frequently (currently every hour) and that the horizontal resolution over land is at least 100 km, depending on the locations of GPS sites. Moreover, this case showed that the additional information based on time series of GPS IWV contour maps could have been used to forecast the deep convection.

6.2 Impact on numerical weather prediction

Numerical Weather Prediction (NWP) techniques are essential for the current practice of weather forecasting. NWP techniques, which have evolved extremely during the last decade, is basically a forward integration (following the general laws of physics) of an initial state of the atmosphere. The quality of the initial state is of crucial importance to the quality of the forecast. This initial state is determined from a time history of observations and previous model runs. The most important observations are surface pressure, wind temperature and humidity.

Upper air observations are sparse; from all conventional methods of observation, only radiosonde observations provide an atmospheric moisture profile. Remote sensing observations in combination with modern data assimilation methods have the potential of fill the lack of upper air humidity observations and improve the forecast with respect to for example rainfall.

In the next sections, different forecast models with different data assimilation techniques are explained. First, the different data assimilation methods used here are briefly described. Hereafter the results of assimilation of GPS data are presented in different sections for each operational NWP model. Each section contains a short description of the forecast model, the data used and the results. The last section is dedicated to the overall conclusions.

6.2.1 Data assimilation methods

In order to produce a forecast using an NWP model a “first guess” or analysis of the atmospheric state over the entire model domain must be made. Since the number of meteorological observations falling within the model domain will typically be an order of magnitude smaller than the number of degrees of freedom of the model, the problem of estimating the initial model state is mathematically underdetermined. The process known as data assimilation attempts to combine information available from both the model and meteorological measurements by using observations to adjust an existing atmospheric state provided by the model itself. There are several methods of using observational data to initialize a numerical model, two of which are outlined below.

Nudging

The basic concept of the Nudging method is to relax the model prognostic variables towards the observed ones without significantly disturbing the dynamic balance of the model. A relaxation term is introduced in the prognostic equation so that, assuming a single observation, the tendency of the prognostic variable $\psi(\mathbf{x}, t)$ is given by:

$$\frac{\partial}{\partial t}\psi(\mathbf{x}, t) = F(\psi, \mathbf{x}, t) + G\left[\psi^{obs} - \psi(\mathbf{x}^{obs}, t)\right] \tag{6.2}$$

The first term F denotes the dynamical and physical model. The second term consists of the observation increment (i.e. the difference between the observation ψ^{obs} and the corresponding model value $(\mathbf{x}^{obs}, t)$ multiplied by a weight G which depends on the constant nudging coefficient and the spatial and temporal distance between the observation and the time-space model grid point (for more details see Schraff (1996)). Note that the nudging technique can exploit the high time resolution of the GPS. The nudging technique has been employed by DWD and MeteoSwiss for assimilation of ground- based GPS data.

Three and four dimensional variational data assimilation (3D/4D-Var)

Three-dimensional variational data assimilation (3D-Var) has been used for assimilation of GPS data at SMHI/DMI and the Met Office. 3D-Var is based on the minimization of a cost function J, which consists of two terms; J_b, which measures the distance between the resulting analysis and a background field (or a-priori) and J_o, which measures the distance between the analysis and the observations (e.g. Lorenc et al. (2000) or Gustafsson et al. (2001)).

$$J = J_b + J_o = \frac{1}{2}(\mathbf{x} - \mathbf{x}_b)^T \mathbf{B}^{-1} (\mathbf{x} - \mathbf{x}_b) + \frac{1}{2}(H\mathbf{x} - \mathbf{x}_b)^T \mathbf{R}^{-1} (H\mathbf{x} - \mathbf{x}_b), \tag{6.3}$$

where $\mathbf{x}$ is the model state vector to be determined by the minimization, $\mathbf{x_b}$ is a model background state (e.g. a short range forecast derived from a previous analysis), and y is the observation vector. H is the observation operator which transforms the NWP model variables into the observed quantities. The matrices $\mathbf{B}$ and $\mathbf{R}$ represent the error covariances of the background field and observations respectively. A general difficulty in the formulation of 3D-Var algorithms is the large dimension of the $\mathbf{B}$ matrix and the required inversion of this matrix. In many 3D-Var schemes, this has been solved by introducing simplifying assumptions regarding the covariance of forecast errors (e.g. horizontal homogeneity) and by transformation of the model state vector to an assimilation control vector whose error covariance matrix can be assumed to be diagonal. A general advantage of the variational data assimilation approach is the ability to use a non-linear observation operator and the resulting freedom to use any observed quantities as input to the data assimilation system instead of being compelled to use the data mapped into model variable space by means of some form of retrieval procedure. This makes it possible, for example, to directly assimilate satellite radiances or GPS zenith total delay (ZTD) observations in the variational data assimilation scheme, instead of retrieved products such as temperature or humidity profiles.

One weakness of 3D-Var is that the time evolution of the data over the analysis cycle is not properly taken into account. The solution to this problem is four-dimensional variational data assimilation (4D-Var). A 4D-Var scheme is being developed within the HIRLAM community (Huang et al. (2002)), but this is not yet available for experimentation with GPS ZTD data. The Met Office has a working 4D-Var system, but this requires further testing and optimization before 4D-Var GPS assimilation trials can be performed. It is expected that the assimilation of GPS ZTD data will have a greater impact using 4D-Var due to its ability to utilize the very high temporal resolution of the observations.

In 3D-Var there is a method to partially compensate for the lack of a time Dimension by using a method known as first guess at appropriate time (FGAT). In this case we do not only have a first guess that is a 6 hour forecast, but several forecasts at different lengths. If we, for example, use observations from plus/minus three hours around the analysis time, we use forecasts with lengths between 3 and 9 hours as first guesses and the observations are compared to the forecast closest in time to the observation time. This approach has been used in the ZTD assimilation trials at SMHI.

6.2.2 Assimilation trial results: DWD

Maria Tomassini

Forecast Model and assimilation system used

At DWD, the current version of the Local Model (LM) was used for GPS assimilation experiments. LM is a non-hydrostatic regional model for central and western Europe, with a spatial grid resolution of approximately 7 km and 35 levels in the vertical. The assimilation scheme of LM is based on nudging towards observations. In the present operational implementation, the LM uses data from surface and aerological reports and computes observation increments once every 6 advection time steps of 40 s. A systematic difference between GPS and LM exists which varies with season; during summer GPS indicates a higher humidity content in the atmosphere than LM, in winter almost the same or sometimes a smaller one. This variability reflects the seasonal changes in PW and it is mostly due to disagreements between GPS and LM in the diurnal cycle of humidity.

The operational LM scheme is designed to use observations at several levels of the atmosphere such as upper-level observations from radiosondes and aircraft. The whole procedure can be regarded as drawing the model IWV towards observed IWV by preserving its vertical structure. The use of an integrated quantity such as the IWV from GPS requires a pre-processing step which allows the spread of the information over the model vertical layers.

The nudging of GPS IWV has been implemented following Kuo et al. (1993). A ”pseudo- observed” profile of specific humidity q_v^{obs} is obtained scaling iteratively the model humidity profile q_v^{mod} with the ratio of observed to model PW, i.e. at each single model level k and for one iteration:

$$q_v^{obs}(k) = \frac{PW^{obs}}{PW^{mod}} q_v^{mod}(k) \tag{6.4}$$

Model pressure and temperature interpolated to the GPS station height are used to derive PW from ZTD. The mismatch between GPS sensors height and LM model orography for the GFZ GPS network it is generally not so large. Some exceptions are the station JENA which is 80 m below the lowest model level, and some stations close to the Alps, e.g. GARM which is 280 m above the lowest model level. Since no systematic correlations were found between the height differences and the PW errors, the approximation of pressure and temperature at the GPS station with the model derived ones seems acceptable.

Having performed the retrieval, the retrieved profile of specific humidity is then nudged into the model. A vertical quality weight function W(k) proportional to the specific humidity at saturation and to the thickness of the level k is introduced in the G term for GPS. Thus the GPS humidity profile is given larger weight at those levels which can contribute more to the integrated value PW, normally between 700 hPa and 800 hPa, and less at other levels. Moreover, the GPS profile is always neglected above 500 hPa because these levels contributes very little to the integrated value of water vapour. Given the dense network of GPS stations available, it was decided to introduce a radius of influence of approximately 50 km (for the radiosonde this radius is approximately 130 km). A threshold quality control has been also introduced for GPS, but it was found to reject very few observations.

Assimilation experiments

Several numerical experiments have been run to investigate the impact of assimilating ground- based GPS data, with trial periods run for February, May and August 2001. Initially, LM assimilation cycles for a single day were examined to test and tune the code modifications introduced for nudging the new data. Once the code had been validated, LM was run over longer periods to investigate and potentially

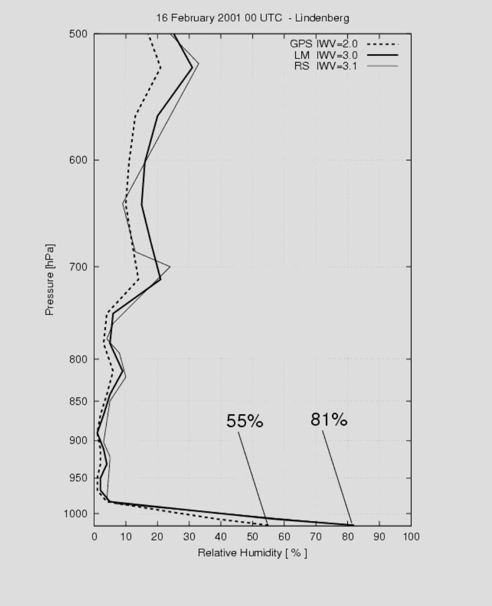


Figure 6.21: Relative humidity vertical profiles at station Lindenberg on 16 February 2001 at 00 UTC: profile from the vertical sounding corresponding to 3.1 kg/m^2 (thin line), profile from the operational LM corresponding to 3.0 kg/m^2 (thick line) and the profile retrieved from the operational LM profile and the GPS observation of 2.0 kg/m^2 (dashed line).

improve the forecast impact of GPS data. Periods characterized by intense weather events (convective mesoscale storms, abundant precipitation etc.) and/or by a poor performance of the LM operational forecast system were selected for the study. More than 80 days of analysis and forecast fields were produced in experimental modus. These fields were compared with the operational ones and verified against observations such as the GPS IWV itself, upper-level measurements from radiosonde data, synop and radar precipitation, and satellite cloud cover images. The main results emerging from this work are summarized below.

Case 1: Low GPS IWV in winter. During a winter time experiment (16 February 2001), problems occurred due to low GPS IWV values (see Figure 6.21). The bias of GPS IWV with respect to LM IWV is generally positive, except in very cold and dry conditions such as those of the experiment. In this low-level inversion case, the nudging of IWV values $\approx$1 kg/m^2 below the initial model fields produced an excessive and unrealistic drying of the LM analysis. The not very satisfying performance of the experiment might be also related to the relative random error (stddev/mean) of GPS IWV in winter, which is higher than in other periods. For example, comparison between the IWV from GPS and radiosondes at the station Lindenberg showed that this error varies from approximately 8–9% in December–February to 4–5% during the summer months. As a preliminary measure, a minimum threshold of 2 kg/m^2 has been introduced in the IWV nudging code. The impact of GPS IWV in winter remains an open issue and requires further investigation.

Case 2: 3rd May 2001. The 3rd May 2001 experiment including all GPS IWV data improved the analysis of a strong rainfall event in Northern Germany, however, it produced also excessive rain over the Black Forest region when verified against rain gauge. This was caused by nudging of data from two stations (Freiburg and Karlsruhe), which observed higher values than the model during daytime. On average, the sequences of hourly GPS data reveal a diurnal cycle quite different from that of the

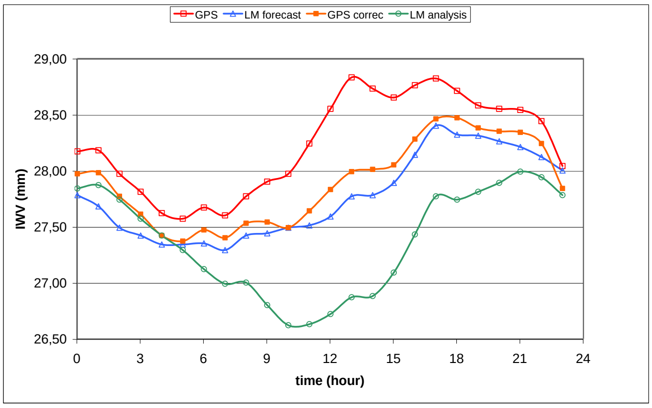


Figure 6.22: . Mean of diurnal variation of IWV in the GPS data (red line), in the LM forecast started at 18 UTC (blue line), in the GPS data with bias correction (orange line), and in the LM analysis (green line) for 103 stations during August 2002.

model (Figure 6.22): GPS IWV starts increasing after 6 UTC (8 local time), reaches a maximum around 12 UTC, and decreases after 18 UTC. The behavior of the model (LM analysis in the figure), tends to be the opposite, with a small decreases of humidity content during the morning and an increase in the afternoon. (It is interesting to note that the cycle of the free model run or LM forecast is closer to the GPS cycle, suggesting that radiosondes might be responsible for the diurnal drying out effect in the analysis). The extra moisture around noon and in afternoon of GPS IWV data, even if correct, erroneously triggers the convective parameterization of the model. The results is that GPS nudging introduces systematically higher precipitation rate in the daytime analysis and in the forecast started at 12 UTC. The solution of this would be, of course, to correct the model climate by improving the model itself. Since this was not possible in the time frame of the project, it was decided to adjust the observation values to the model climate by means of a diurnal bias correction applied during the nudging of the data (GPS corrected data in Figure 6.22). This approach has been tested during the two week experiment of August 2002 and it resulted in slightly better results than when no bias correction is applied to the data.

Case 3: August 2001. An impact study using GPS data in LM was also conducted for a 10 day period from 16th to 25th August 2001. During the first four days of the period an intense south-west circulation produced unstable and stormy weather conditions over Central Europe. Afterwards, a Scandinavian high pressure system brought more stable weather conditions. This period was selected because of the poor performance of the operational LM forecast, especially with respect to precipitation.

Two assimilation experiments were run, a control (CNT) (the same as the routine LM), and a GPS trial run including half-hourly GPS data from 76 stations in Germany and surrounding countries. Unfortunately, at the time of the experiments, no data from French GPS stations were available. The 24 hour forecasts started from the assimilation fields of 00 UTC and 12 UTC of each experiment and were verified against GPS, radiosonde observations, and synoptic and radar precipitation observations.

Figure 6.23 shows verification of the experiment forecasts started at 00 UTC against GPS observations. The RMS error of the difference observed minus forecast IWV for the forecasts of CNT and GPS are averaged over 9 cases and plotted as function of the forecast range. At forecast step T+0 (analysis) the fit of GPS to the observations is approximately 1 mm against the value of 2.5 mm of CNT. In the forecast

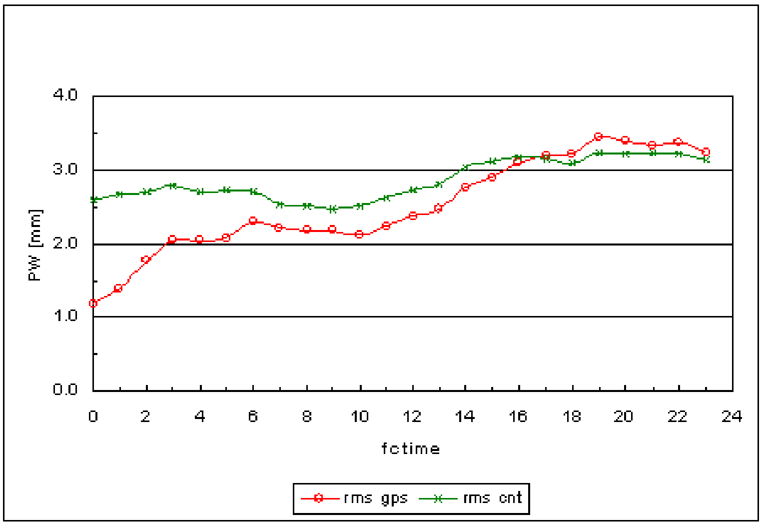


Figure 6.23: IWV Root Mean Square (RMS) error computed against the GPS observations of the 24 hour forecast started at 00 UTC as function of forecast hour: RMS of the GPS forecast (circles), RMS of the CNT forecast (crosses). Mean over 9 cases, from 17 to 25 August 2001.

range up to T+12 the error of the GPS experiment remains smaller than that of the CNT, but after T+12 the RMS of the two runs are almost the same, implying that the impact of the GPS data has become negligible after 12 hours.

The upper-air verifications against radiosonde data demonstrate a clear positive impact of the GPS IWV data (Figure 6.24). The relative humidity, temperature and wind RMS errors of the 12 hour forecast of the GPS experiment are smaller than those of the CNT experiment at all levels. The most marked improvement is in the relative humidity between 800 hPa and 600 hPa, with an error reduction of the order of 10%. The same verification but for the 24 hour range gave very similar results for GPS and CNT, confirming the neutral impact of GPS data at longer forecast times.

A subjective evaluation of 6-and 12-hour precipitation patterns from the LM assimilation and forecasts against precipitation analysis derived from SYNOP observations and against radar images suggests that GPS has a mixed impact on precipitation. For example, the GPS 0–6 hour forecast started from the 12 UTC of 18 August enhances the erroneous excessive rainfall of CNT all over central Germany (Figure 6.25). In general, the 12 UTC forecast of the GPS experiment generates more rain than the corresponding CNT forecast. This can be attributed to the positive bias of GPS IWV with respect to LM during daytime which has been seen in the monitoring results. In another case, the 0–6 hour forecast started from the 00 UTC of 21 August, the GPS data correctly reduces the rain of CNT over the south-west and eastwards of Germany (Figure 6.26).

A quantitative evaluation of the precipitation forecast for the federal state Baden-Württemberg in the south-west of Germany has been also performed (Figure 6.27). A precipitation analysis based on hourly measurements from more than 100 ombrometers spread over this area is particularly useful for validation of short-range NWP forecasts. (The very dense rain gauge network of Germany as a whole delivers only 24 hour precipitation accumulations.) Unfortunately there are only 2 GFZ GPS stations in Baden-Württemberg (FREI and KARL) and no stations to the west over France (upwind during the experiment). However, the verification demonstrates a small positive impact, especially in the 0–6 hour forecast started at 00 UTC (two forecasts are clearly improved). The impact in the forecast range T+6 to T+18 is on av-

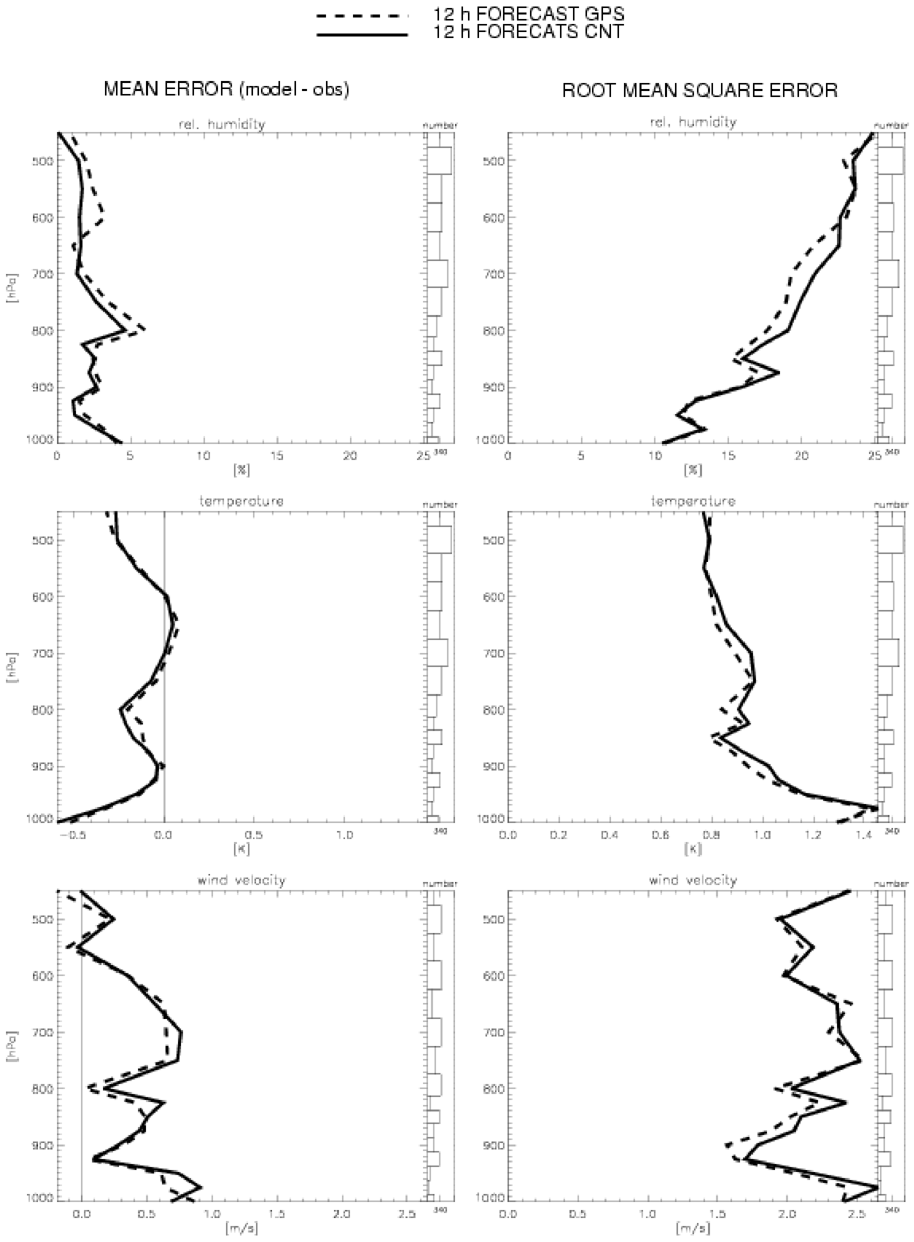


Figure 6.24: Forecast mean error (left) and root mean square error (right) of the experiment of August 2001 with GPS data (dashed curves) and of the control (solid curves) for relative humidity (top), temperature (middle), and wind velocity (bottom). Average over 15 cases (00 UTC and 12 UTC forecasts) using radiosondes in Germany and surrounding countries.

erage neutral, the only difference being in two forecasts started from 12 UTC, when the GPS experiment produces more rain than CNT.

Case 4: 1–14 August 2002. During the first two weeks of August 2002, extremely large amounts of rain fell in many parts of Central Europe, giving rise to overflowing rivers and causing severe damage. In two experiments covering the period of 1–14 August 2002, GPS IWV data were introduced into the nudging-based data assimilation cycle, and 30-hour forecasts from the analyses were started daily at 00, 12, and

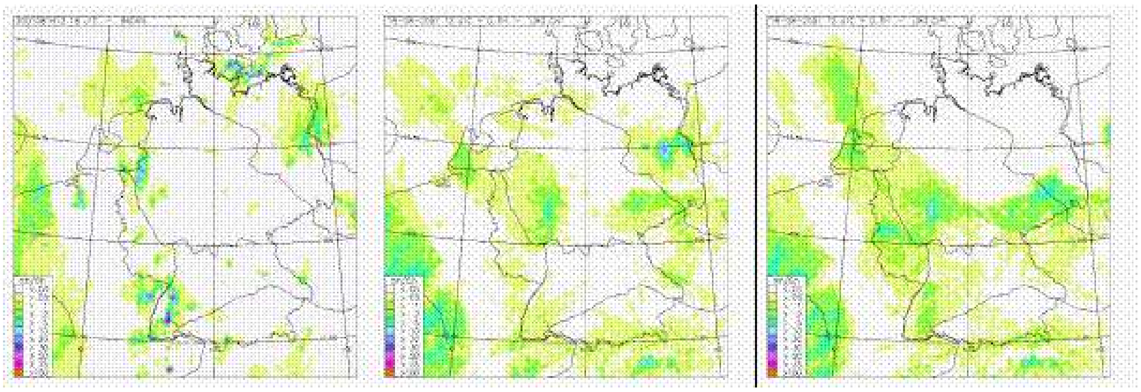


Figure 6.25: Accumulated precipitation from 12 to 18 UTC on 18 August 2001 as observed by radar observation (left), and from the 0–6 hour 12 UTC forecast of the control run (centre) and of the GPS experiment (right)

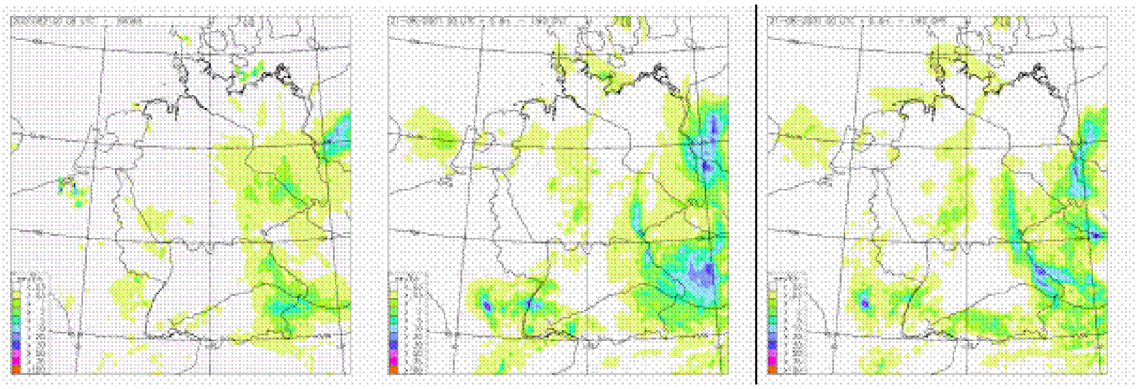


Figure 6.26: As Figure 6.25 but from 0 to 6 UTC on 21 August (left) and from 0–6 hour 00 UTC forecast (centre and right).

18 UTC. In the first experiment “gps”, the data were used without correction, and in the second one “gpsbc”, a time-dependent bias correction was also applied previously to the GPS data. This correction reduces the GPS IWV values mainly during daytime to fit them better to the model (forecast) climatology. The output of the experiments is compared to that of the operational runs “opr”. A visual evaluation of precipitation patterns from both experiments and operational forecasts against analyses derived from SYNOP observations indicates a positive impact of the GPS data on average. The bias correction has very limited impact in most cases, although in some cases, it does moderately reduce the precipitation amounts. Compared to previous experiments for August 2001, there are fewer cases of spurious rain, but more importantly, some improvements occur in critical weather situations. The forecasts from the experiments with GPS data appear to be more accurate in position and strength of some rain patterns. In the gps 18-hour forecast of 12-hourly precipitation valid for 8 August, 18 UTC (Figure 6.28), the intense cell of rain is closer to the Ore Mountains (at the plotted German - Czech border) than in the operational one. The same cell became too weak in the gpsbc experiment, though. It can also be seen that GPS IWV correctly enhances the rainy patterns in the Hamburg area.

Summary of DWD results

The NWP experimental forecasts of upper-level variables have been verified using GPS and radiosonde data giving the following results:

- The forecast impact of the assimilation of GPS IWV is largest at forecast ranges up to 12 hours.

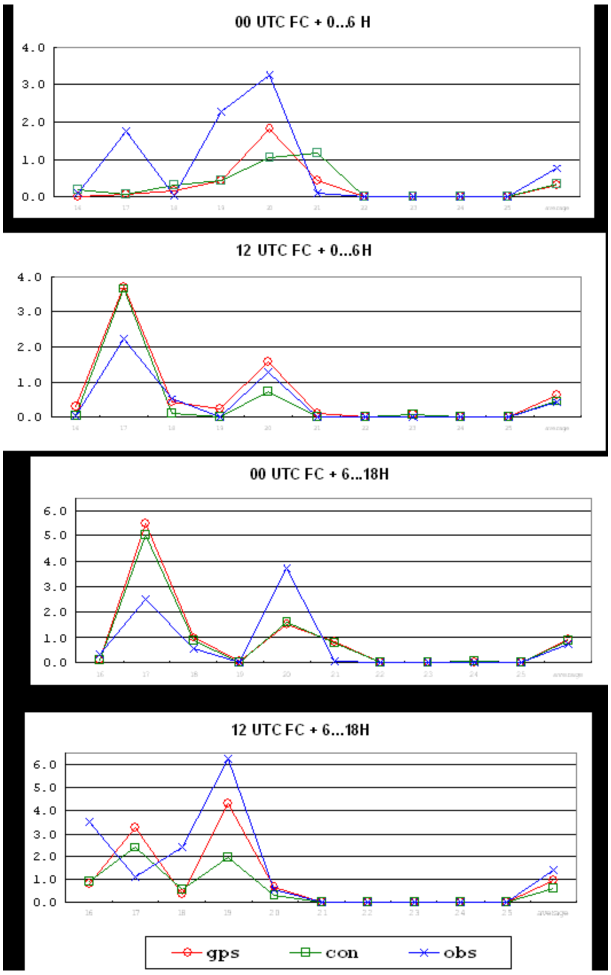


Figure 6.27: Precipitation verification for Baden-Württemberg: mean precipitation for the area observed (crosses), forecasted by the GPS experiment (circles), and by the control experiment (squares).

- In a 10 day experiment in August 2001 the assimilation of GPS IWV improves the 12 hour forecast of humidity, temperature and wind, e.g. the RMS error of relative humidity decreases at certain levels up to 10% (Figure 6.24).
- In a 2 week period in August 2002, GPS IWV have an overall neutral impact on forecasts and slightly variable with the forecast range, i.e. positive on the 6 hour, neutral on the 12 hour and negative on the 24 hour range.

The precipitation results have been verified comparing the forecasts fields to synop analyses and radar pictures, and indicate:

- The forecast precipitation is sensitive to GPS data at forecast ranges of up to 24 hours, although most of the impact is seen in the 6–12 hour range.
- The nudging of GPS IWV does not substantially modify the model performance; in most of the cases precipitation patterns are moved or corrected but the structure is not completely altered.

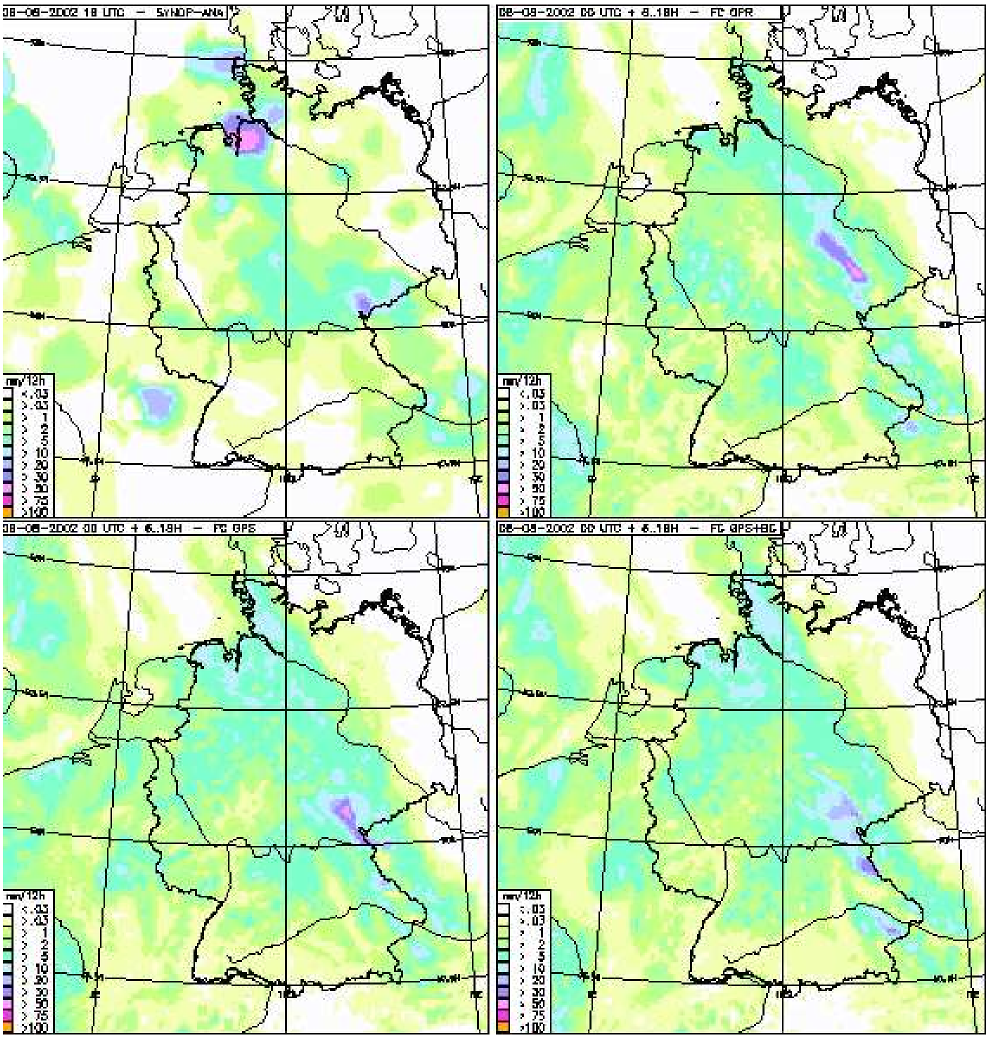


Figure 6.28: Accumulated 12 hour precipitation 8 August 2002, 18 UTC, as analysed from synop observations (top left), as forecasted with a forecast lead time of 6–18 hours by control run opr without GPS data (top right), by experiment gps with GPS data (bottom left), and by experiment gpsbc with GPS data and bias correction (bottom right).

- In a 10 day experiment in August 2001 GPS has a mixed impact on the forecasts of precipitation, with the forecasts started from the 12 UTC analysis with GPS data systematically overestimating the precipitation, while those started at 00 UTC showing positive impact at 0–6h forecast ranges.
- In a 14 day experiment in August 2002 with intense precipitation the impact of GPS data is overall slightly positive, in particular in the precipitation forecasts started from the 18 UTC analysis (few radiosondes are reporting at this time, thus GPS data are likely to provide missing information).

6.2.3 Assimilation trial results: MeteoSwiss

Guergana Guerova

Forecast Model and assimilation system used

Since April 2001 MeteoSwiss has employed the aLpine Model (aLMo) for operational NWP. ALMo is the Swiss configuration of the COSMO (COnsortium for Small-Scale MOdelling) non-hydrostatic limited area Local Model (LM) developed by the National Weather Services of Germany (lead partner), Switzerland, Italy, Poland and Greece. The Swiss implementation of LM has a horizontal resolution of about 7 km, and the domain extends from 35.11°N to 57.03°N and from -9.33°E to 23.42°E (Figure 6.29), covering most of western Europe. A terrain following vertical coordinate system is used, with 45 vertical layers with about 100 m vertical resolution in the lowest 2 km of the atmosphere and the model top at 20 hPa.

At MeteoSwiss two 48-hour operational forecasts are run daily at 00 and 12 UTC, i^{th} initial conditions obtained from a continuous data assimilation cycle. The assimilation cycle is based on a Newtonian relaxation technique, nudging model fields towards direct observations. In the nudging all standard meteorological observations are used (synop, temp, buoy, aircraft wind and temperature) but no satellite data are assimilated.

The ZTD derived from GPS measurements is assimilated in aLMo using the procedure developed at DWD and described in Section 6.2.2. For the observing system experiments (OSEs) aLMo is nested in the ECMWF global model.

Data used

GPS data provided by the COST-716 NRT campaign was used for four OSEs using aLMo. ZTD data from about 100 GPS stations (red dots in Figure 6.29) processed by three processing centres (LPT, GOP and GFZ) was used. The selection of processing centres was based on optimal domain coverage, data quality and availability. For the period May 2001 - December 2002 the three centres delivered more then 90% of the data within the selected time window of 1 hour and 45 minutes. As seen in Figure 6.29 the overall GPS coverage over Switzerland and north of Switzerland is very good, but is poor in the southern part of the aLMo domain.

Meteorological situation

For the first OSE the period 9 to 23 September 2001 was selected, which was characterized by intense atmospheric circulation, front passages and cyclogenesis in the Gulf of Genoa.
The second OSE was for a shorter period from 9 to 13 September 2001. The atmospheric circulation was driven by a cyclone located over the Baltic Sea and a cold front moving slowly eastward, passing over Switzerland on September 9 and initiating cyclogenesis in the Gulf of Genoa on the night of September 10.

The five days period between 10 and 14 of January 2002, selected for the third OSE, was characterized by low stratus cloud over the Swiss Plateau and Southern Bavaria, induced by an anticyclone with weak pressure gradients located over Hungary—a typical winter situation.

The forth OSE, from the 18th to 24th of June 2002, was a very active period with intense precipitation events and front passages.

Results

Analyses and two daily 30 hour forecasts were calculated with and without GPS data assimilation. The results from the first OSE can be summarized as follows: through assimilation of GPS data a modification of the model IWV field is obtained primarily in the southern part of the model domain, with up to

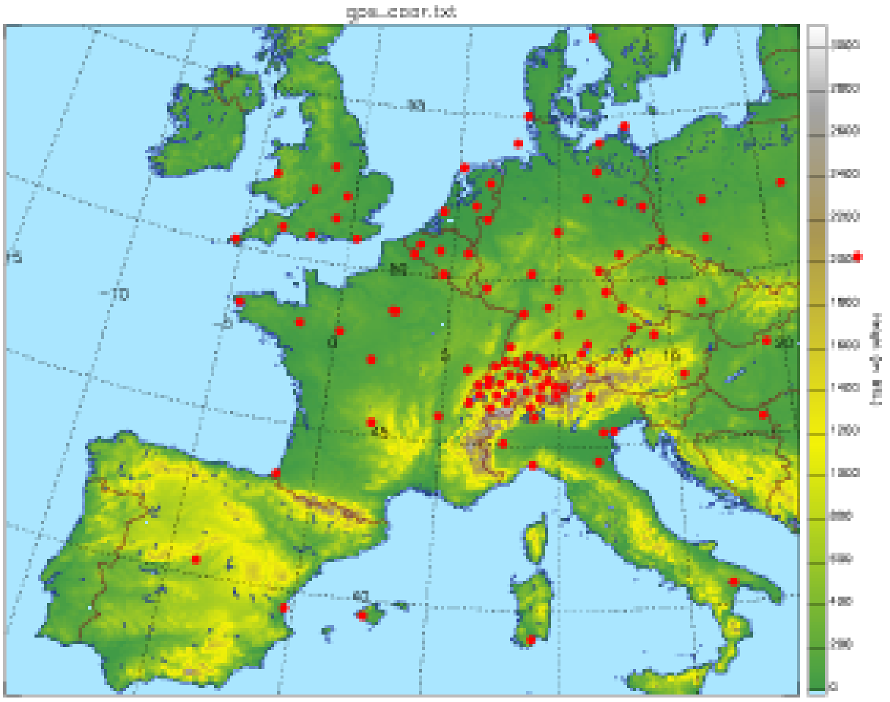
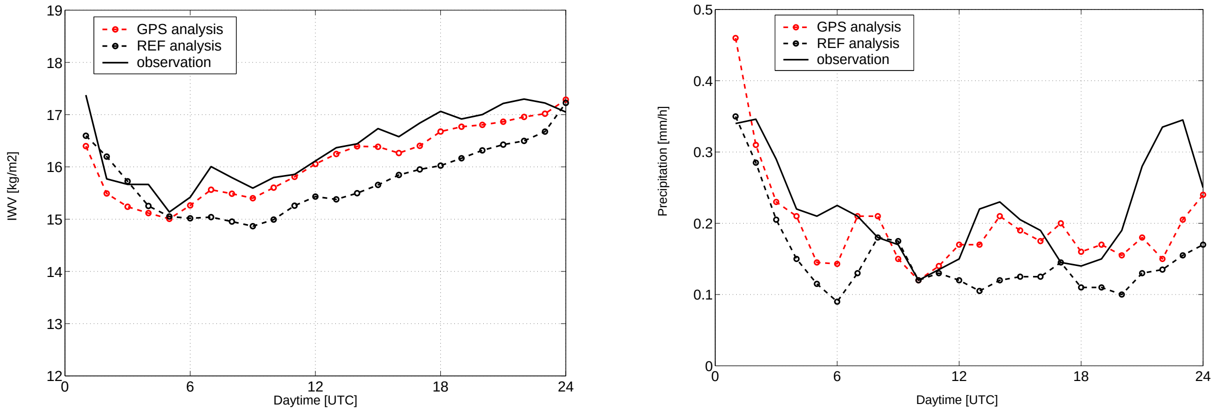


Figure 6.29: ALMo domain and the location of GPS sites (red dots) used in OSEs. The colour scale represents the orography and the thin red lines national boundaries.

a 30% relative change observed. By visual inspection of the overall daily impact one observes a tendency to increase IWV in the daytime. The results of precipitation verification over Switzerland are commented here. Figure 6.30a shows the diurnal cycle of IWV for the period 9^{th} to 23^{rd} of September 2001 for the GPS analysis (red dashed line), reference analysis (black dashed line) and the GPS observations (black solid line). While the GPS analysis compares well with the observations the reference analysis generally underestimates the IWV. This indicates a negative bias of the reference analysis and successful assimilation of the ZTD in the GPS analysis run. Figure 6.30b presents the diurnal cycle of precipitation for the same period. It can be seen that the reference analysis tends to underestimate the overall precipitation amount measured by the synop stations (black dashed line), while the GPS analysis (red dashed line) improves the precipitation diurnal cycle, especially in the hours between 12 and 17 UTC.

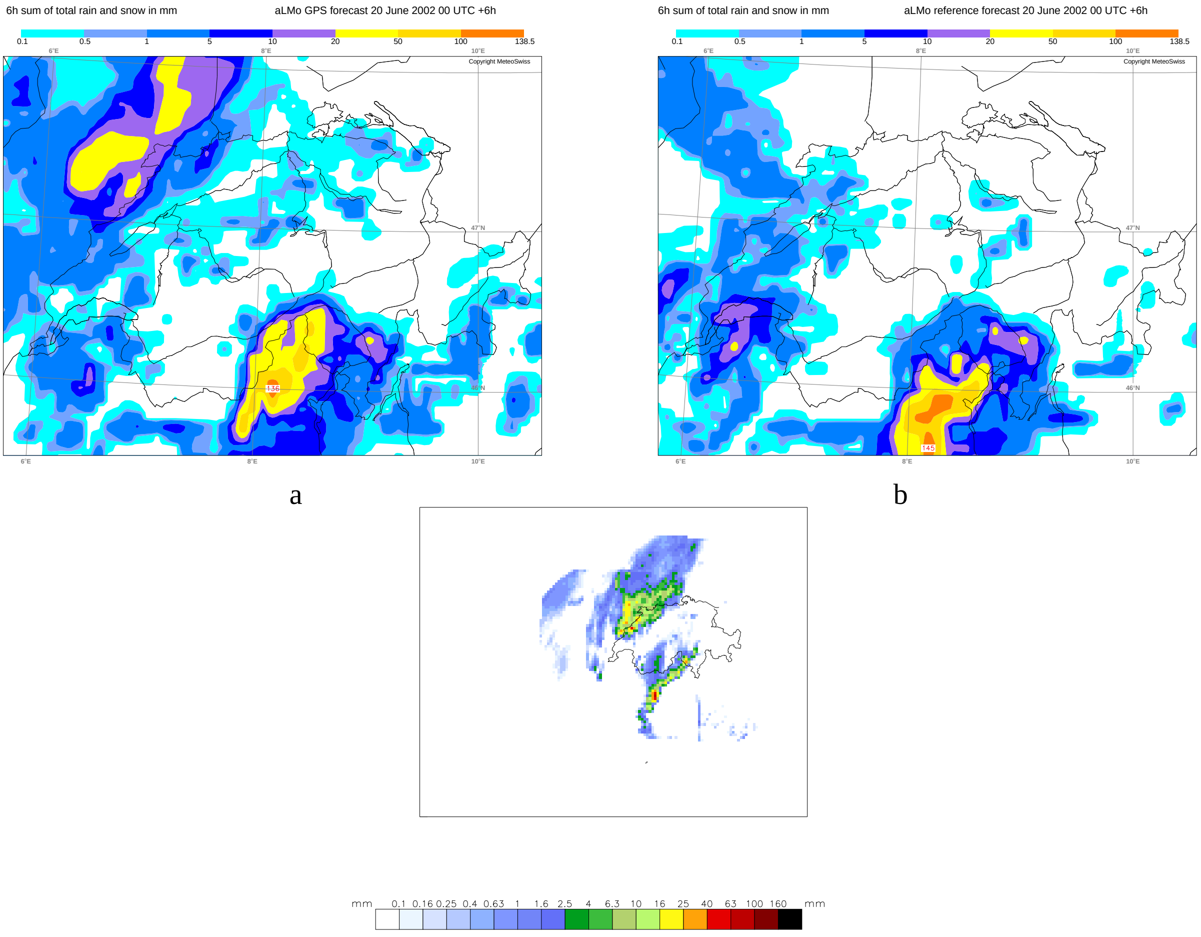
For the follow up OSEs pressure, temperature and dew point temperature at 2 m were verified against approximately 1000 surface stations from the synop network. In the second and fourth OSEs the overall temperature and dew point temperature biases were moderately improved; impact of GPS on the standard deviation shows the same trend, but with a much smaller magnitude. In the second OSE, the improvements in 2 m temperature and dew point temperature bias is 7% and 13% respectively. In the forth OSE the dew point temperature bias is improved by around 0.1 K, or about 14%, and the 2 m temperature is improved by around 25%.

In the second OSE performed for September 2001, the GPS impact on the precipitation field is moderate to small with isolated cases of improvements in forecast maximum precipitation. During the fourth OSE, performed for June 2002, intense precipitation events (above 20 mm/6 hr) are reported on the 20–21 and 23–24 June. The first case is the 00 UTC forecast on 20th June 2002 and is presented in Figure 6.31. The intense precipitation event over the Jura region (Northwest of Switzerland) seen in the GPS forecast



a b

Figure 6.30: a. Diurnal IWV cycle for the first OSE. IWV observations (black solid line), reference analysis (black dashed line) and GPS analysis (red dashed line). b. Diurnal precipitation cycle for the first OSE. ANETZ observations (black solid line), reference analysis (black dashed line) and GPS analysis (red dashed line).



a b

c

Figure 6.31: An accumulated precipitation 20 June 2002 from: a. GPS forecast, b. reference forecast and c. radar observations. The forecast intense precipitation pattern over the Jura region (north-western Switzerland) in the GPS forecast is confirmed in the radar observation.

(Figure 6.31a) is completely missing in the reference forecast (Figure 6.31b). In comparison the radar data (Figure 6.31c) shows intense precipitation over the same area. Through assimilation of GPS data the moisture deficiency of up to 8 kg/m^2 present at 00 UTC reference forecast west of Switzerland has been corrected and this resulted in the significant improvement in the precipitation forecast. This is a case which demonstrates that GPS data can provide important information at the right time and place, thus improving the forecast. One case with deterioration of the analysis occurred on 23^{rd}–24^{th} of June between 18 and 06 UTC. The GPS assimilation resulted in a substantial increase of large- scale precipitation in southern Switzerland with a maximum higher than 200 mm/6 hr, tripling the reference analysis value. The observed by the radar precipitation is in good agreement with the reference analysis. The reason for the significant overestimation of precipitation was found to be the continuous feeding of the model with water vapour through assimilation of the Italian GPS site Torino.

From the experiments performed with aLMo we conclude that the impact of GPS data on precipitation forecast is limited to the first 6 hours and to intense precipitation events.

The third OSE, January 2002, was focused on low stratus cloud cover. However, due to inconsistent usage of humidity correction scheme of the model the results from this OSE are inconclusive.

6.2.4 Assimilation trial results: Met Office

Adrian Jupp

Forecast Model and assimilation system used

During August 2002, the Met Office implemented a completely new operational version of its Unified Model (UM versions 5.2 and above, often referred to as the “New Dynamics” with a vertical and horizontal new grid structure and significant improvements to the model physics. The Met Office operational NWP data assimilation system has used 3D-Var since 1999; our approach to assimilating ground-based GPS data involves direct assimilation of ZTD estimates rather than assimilating IWV or humidity profiles derived from ZTD data, as these require further assumptions to be made which will introduce further errors. The Met Office runs two configurations of the UM for NWP purposes, the Global and Mesoscale models. The latter was used for these initial assimilation trials. The Met Office Mesoscale model has a horizontal resolution of around 11 km, with analyses and forecasts run out to 36 hours produced 4 times daily at 0Z, 06Z, 12Z and 18Z, with intermediate analyses and 3 hr forecasts produced at 03Z, 09Z, 15Z and 21Z providing boundary conditions for the next main forecast runs out to 36 hr, resulting in a total of 8 assimilation cycles per day each assimilating data 1.5 hr either side of analysis time. The operational Mesoscale model assimilated surface, radiosonde, and aircraft observations at the time of the assimilation trial. More recent configurations of the Mesoscale model also assimilate radiances from the AMSU-B instruments and scatterometer winds data.

The ZTD assimilation trial results discussed below were performed using the old version of the UM, which employed a hybrid pressure- level based vertical grid. The new model employs a height- based staggered vertical grid, such that specific humidity and potential temperature are stored on one set of levels and pressure on the alternate levels. Since performing the initial assimilation trial described here we have reformulated the ZTD forward model to take into account the new vertical level structure and to attempt better corrections for differences in height between the GPS antenna and model orography. We have also built in the capability for a bias correction scheme should this turn out to be necessary. This forward model has since undergone extensive and routine comparison with COST 716 GPS ZTD data in order to assess both the quality of the data and of the forward model itself (see Chapter 5). Generally we see RMS ZTD differences of between 10 and 15 mm in lowland sites within the UK Mesoscale model

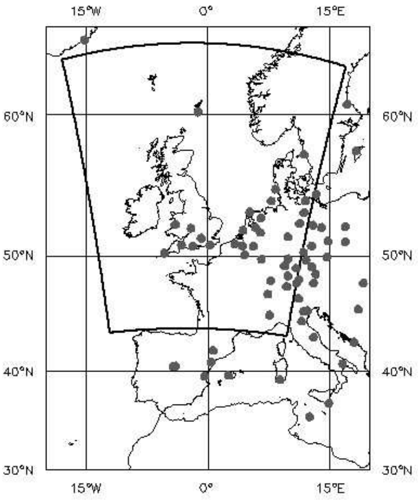


Figure 6.32: Extent of COST-716 near real time network in July 2001, also showing the boundaries of the Met Office Mesoscale model.

domain. The quality control system has been modified in the light of this monitoring, which has highlighted the nature of the problems with some of the GPS data; in particular abrupt, unphysical changes in ZTD estimates which could have severely detrimental effects on NWP forecasts. We have observed systematic biases between model estimates and ZTD data in some cases. These biases have appeared to be reasonably stable over relatively long periods and are not present in comparisons between GPS and other NWP models, suggesting a systematic problem with the ZTD forward model and/or model representivity. We are currently investigating a more satisfactory solution to this problem before we embark on further assimilation trials using the new system.

Data used

All available GPS ZTD data falling within the Mesoscale Model boundary (see Figure 6.32) was extracted for assimilation. 3D-Var cannot make use of the time- dependence of a series of observations, and as such for each GPS station the observation closest to analysis time should ideally have be used. In this case, however, all observations falling within the assimilation time window were presented to the assimilation scheme. Since this time we have included a temporal thinning routine within the GOS ZTD assimilation scheme which will also be of use for 4D-Var, when we will require an improved understanding of the time correlation of the data. Note the the Aberystwyth receiver is West Wales (52.424°N, 355.996°E) was not operational for the period covered by the trial.

The assimilation trial was started at 0000Z on 1^{st} July 2001; here we concentrate on results from 3^{rd} July, by which time the model will have had time to spin up with the inclusion of GPS in 16 assimilation cycles.

Error covariances

Due to our current level of understanding of GPS ZTD observation error covariances it was assumed for the purposes of the trial that the observation errors were uncorrelated, despite the fact that this is unlikely to be the case. Due to the lack of reliable ZTD data quality indicators or statistics at the time of the trial, we assumed RMS ZTD observation errors to be constant at 6 mm for all stations assimilated.

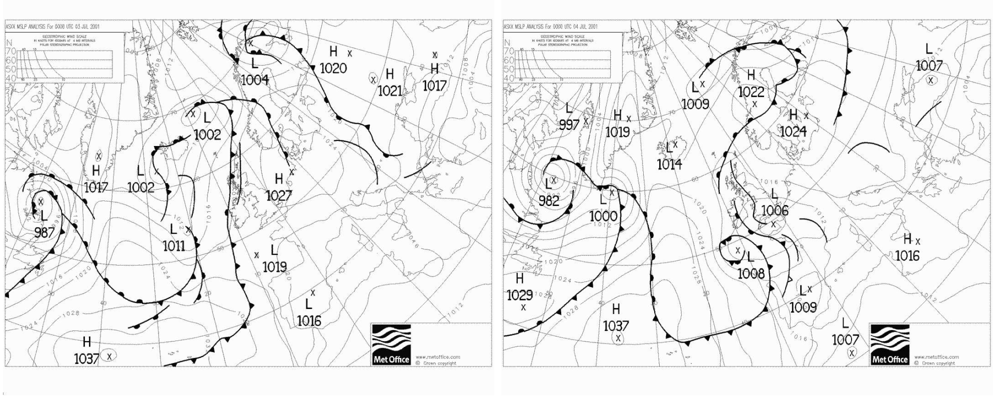


Figure 6.33: Analysis for the 3^{rd} and 4^{th} of July 2001.

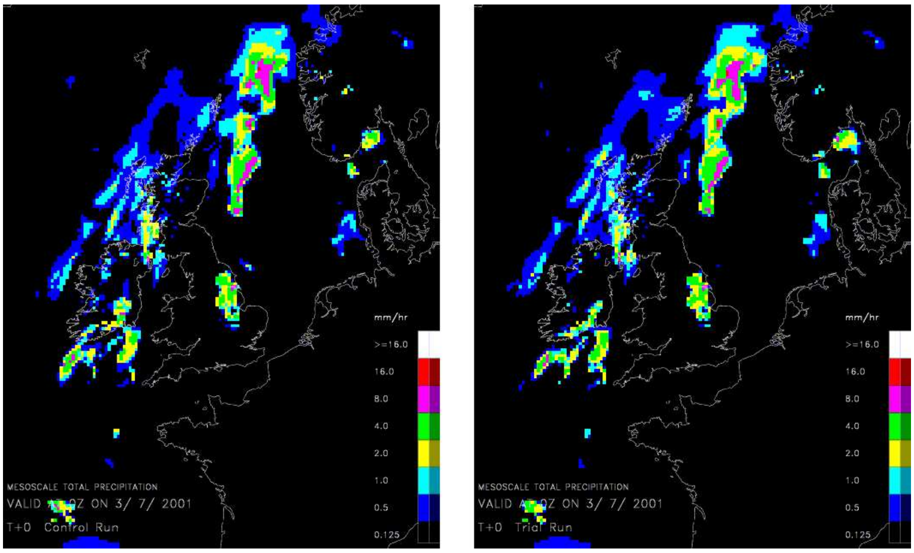


Figure 6.34: Control and trial Met Office Mesoscale Model analysed precipitation fields for 0Z, 3^{rd} July 2001

Meteorological situation

The meteorological situation at the time under consideration was a complex one, with a high pressure centre over the eastern UK drifting north- eastwards towards Scandinavia to be replaced by a slack low pressure area, with a series of fronts and troughs passing over western and northern areas of the British Isles. (see Figure 6.33).

Results

Here we perform a subjective analysis of the modification of model precipitation fields which results from the assimilation of GPS ZTD data.

T+0

Some changes to the precipitation structure around the Lerwick site in Shetland (60.13°N, 358.815°E) can be observed in the forecast run. At this time the airflow from Shetland is in a northeasterly direction

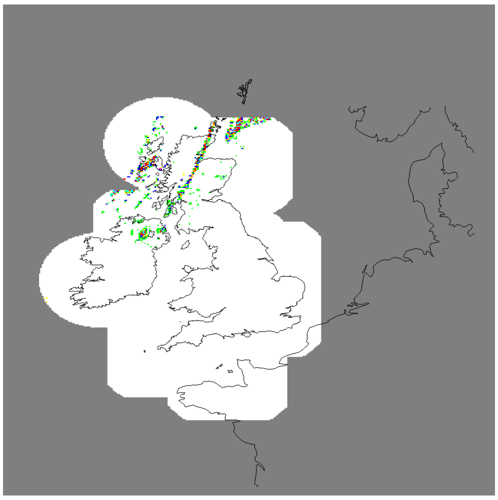


Figure 6.35: UK radar image for 2200Z, 2^{nd} July 2001

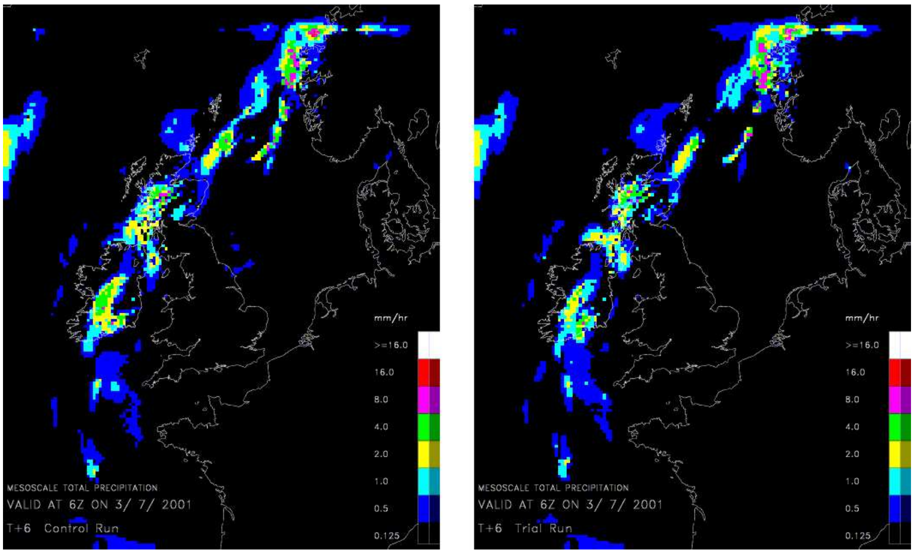


Figure 6.36: Control and trial Met Office Mesoscale Model 6 hour forecast precipitation fields valid at 06Z, 3rd July 2001

towards Norway. Changes to the precipitation fields over South- West Ireland may result from advection of upstream information from the Cambourne site in Cornwall from previous assimilation cycles, given the east- southeasterly airflow at this time. Unfortunately radar data was not available for 0000Z; here we show data for the closest available time of See Figure 6.34. Note that the model appears to have produced a spurious area of rainfall over eastern England in both the control and trial experiments, which is perhaps not surprising given that the nearest available GPS sensors were more than 100 km away.

T+6

Alteration of precipitation fields to the North-East of Shetland appear to have persisted, consistent with downstream advection of information from the Lerwick GPS station. (See Figure 6.36).

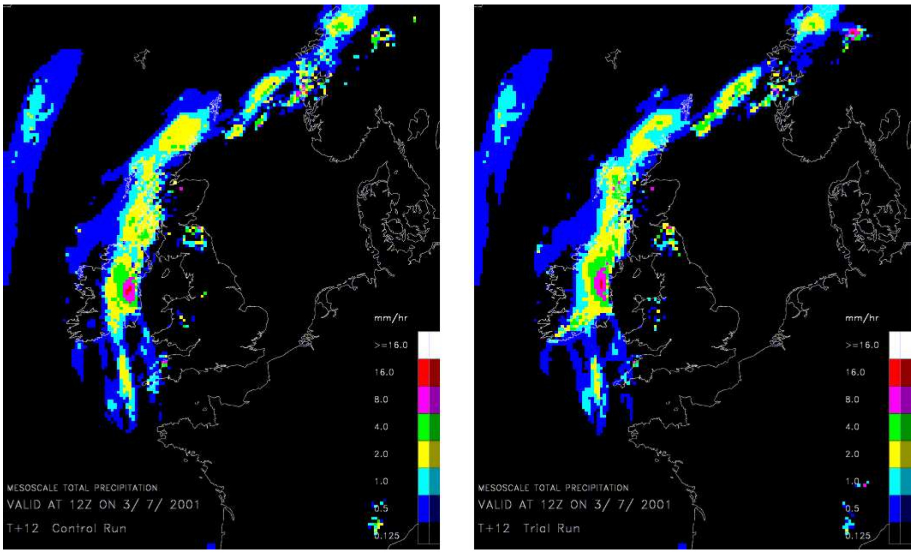


Figure 6.37: Control and trial Met Office Mesoscale Model 6 hour forecast precipitation fields valid at 12Z, 3rd July 2001

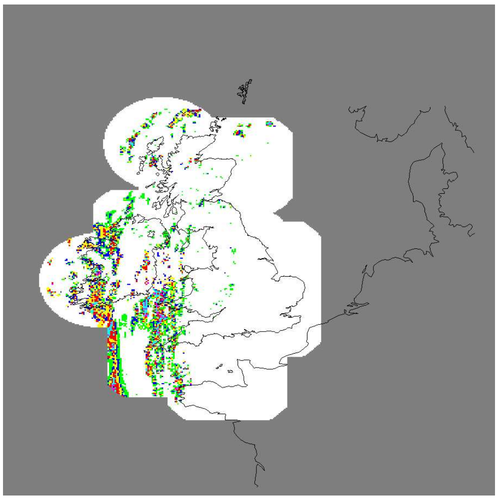


Figure 6.38: UK radar image for 1200Z, 3^{rd} July 2001

T+12

The most significant differences in precipitation structure are again downstream of Lerwick, with apparent drying over some coastal areas of Norway and intensification of forecast rainfall further inland (see Figure 6.37). Elsewhere few differences in precipitation patterns are noticeable.

T+24

Again we observe significant differences over Norway and to the north of Scotland. See Figure 6.39.

Conclusions

The results from this experiment show a broadly neutral impact on model precipitation, although some

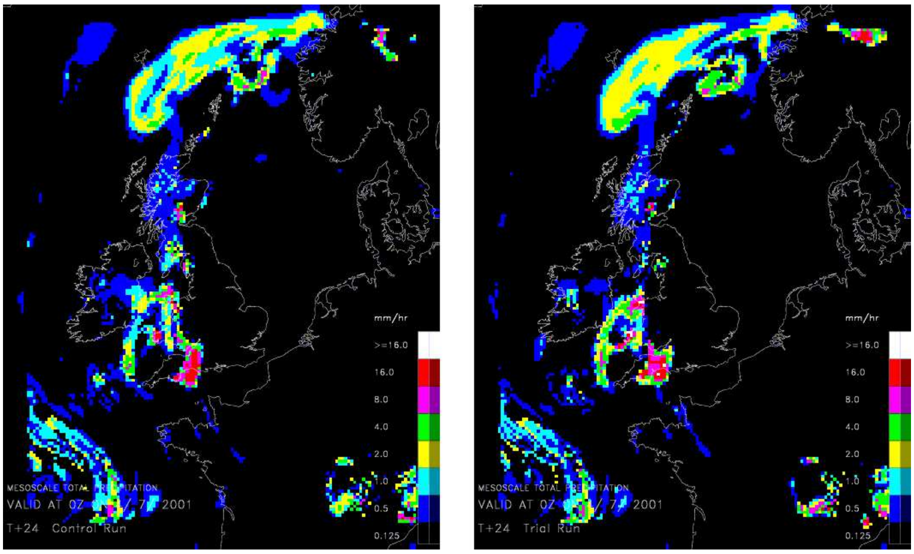


Figure 6.39: Control and trial Met Office Mesoscale Model 24 hour forecast precipitation fields valid at 0Z, 4th July 2001

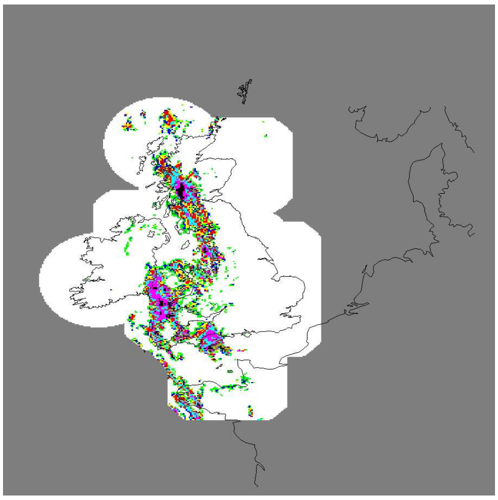


Figure 6.40: UK radar image for 0000Z, 4^{th} July 2001

significant changes occurred downstream of the Lerwick GPS site which we were unfortunately unable to verify.

Due to the high time resolution of GPS observations (often 1 or more observations per hour), more than one observation per GPS station per analysis cycle may have been assimilated in the 3D-Var scheme for this experiment. Since 3D-Var can make no use of the temporal information in the data this may have led to an averaging out of increments and a smaller impact than might have been the case were just the observation closest to analysis time used. The current scheme assimilates only the observation closest to analysis time, in common with other surface observations.

The number of GPS stations available for assimilation both over the UK and Europe as a whole has increased dramatically since the time of the experiment, and so the potential for significant forecast impacts must now be increased. It would, for example, have been interesting to see whether GPS data which is now available over eastern England would have improved the erroneous diagnosis of rainfall in the 0000Z analysis on 4th July.

6.2.5 Assimilation trial results: SMHI

Martin Ridal

Forecast Model and assimilation system used

Details of the SMHI assimilation scheme and observation handling are described by Gustafsson et al. (2001) and Lindskog et al. (2001). The experiments used a similar set up to the operational version of the HIRLAM model used at SMHI but with different resolution; all experiments were run with a resolution of 0.3° ($\approx$ 33 km) and 40 vertical levels. From each analysis 24 hour forecasts were run and FGAT was used in the analysis.

We assimilate the zenith total delay (ZTD). In the assimilation, the observation operator calculates a model ZTD from the model variables at the latitude and longitude of the measurements by calculating the zenith hydrostatic delay (ZHD) and zenith wet delay (ZWD). The ZTD is then simply the sum of the two delays.

The reason why ZTD is preferred in the assimilation to more derived products (e.g. IWV) is that the surface pressure and surface temperature or a temperature profile is required to derive IWV from ZTD (see e.g., Davis et al. (1985) or Bevis et al. (1992). Since there is no simultaneous ground pressure measurement at most GPS sites the pressure needs to be taken either from climatology or from surface observations at synop stations, which will give either less accurate values or a risk of “circular” use of surface observations which are already assimilated into the model.

The orographic height of the HIRLAM grid box in which a measurement is made is not the same as the height of the GPS receiver. To account for this, the model profile is shifted up or down during the assimilation to match the height of the GPS receiver. The moving of profiles is performed using a rather complex algorithm in order to preserve the boundary layer structure (Majewski, 1985).

A quality control (data screening) prior to the assimilation is performed in order to remove data with either very large errors or stations that differ significantly compared to the surrounding stations. A quality control during the variational assimilation is also included.

Error covariances

For the assimilation of the GPS observations it is also necessary to specify the covariance of the observation error, the $\mathbf{R}$ matrix in Equation 6.3. In the absence of any further information, we have assumed the observation errors of individual observations to be uncorrelated. It is likely, however, that this approach is over-simplistic since nearby stations often see the same satellites (Stoew et al., 2001; Jarlemark et al., 2001).

With regard to the observation error standard deviations, formal values are provided by the GPS data processing centres. These formal values, however, only represent the errors in the processing and not the full observation errors. Error sources that are not taken into account are, for example, satellite positions, clock errors and errors caused by the mapping function. In addition, the applied observation error standard deviations need to be considered in relation to the assumed forecast error standard deviations and the assumed errors of other observation types (e.g. radiosonde data). The assumed ZTD forecast error standard deviation is of the order 15 mm ZTD, and this corresponds roughly to the assumed error of

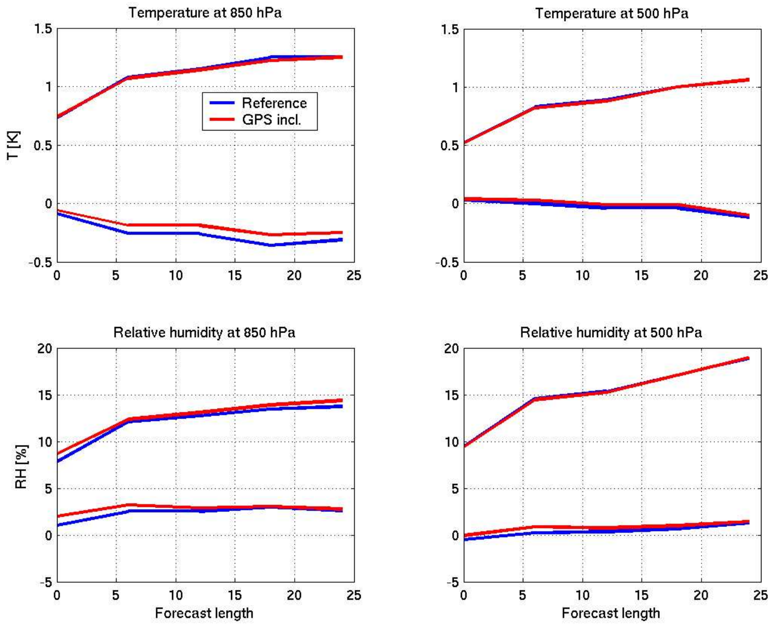


Figure 6.41: Verification scores for assimilation experiment from 1–15 July 2002. Blue lines are the reference case and red lines include GPS derived moisture. See text for details.

radiosonde data. In order to prevent the GPS data will from dominating the few radiosonde observations available, we decided to multiply the formal standard deviations provided by the GPS processing centres by a factor of 3 and to apply a minimum standard deviation of 15 mm for the ZTD measurements.

Results

Assimilation experiments were run for a two week period in July 2002 and another two week period in June 2003, which were very active periods with low pressure systems and convective storms passing over Scandinavia as well as over central Europe.

Two experiments were run for each period, each including all the conventional observations such as data from synop stations and radiosoundings. The second experiment is the same but GPS ZTD is included as an additional observation, where we use ZTD data from ±2 hours from the analysis time.

The standard means of verifying a forecast is to examine verification scores. This means that the forecast is compared to observations from sites that are regarded as reliable. In our case we use a list of such stations (radiosonde and SYNOP) established by the European Working Group on Limited Area Models (EWGLAM) (Hall, 1987).

For the experiments run, inclusion of GPS showed very little impact on the verification scores. Figure 6.41 shows examples of the verification for temperature and relative humidity where the upper two panels show the temperature for 850 hPa (left) and 500 hPa (right) and the lower panels show the relative humidity for the same altitudes. The blue curve represents the reference case and the red curve the experiment with GPS moisture included.

The relatively small impact on the verification scores is however expected since these scores show an average over the entire area and over the whole period. A larger impact might be expected for isolated cases of strong precipitation, primarily convective precipitation where a small change in moisture can be of importance.

We therefore looked at the accumulated precipitation between the 6 and 18 hour forecasts to see if there were any cases with differences between the runs. Several such cases were found; one example is illustrated in Figure 6.42. These graphs show the reference run (Figure 6.42a), the assimilation run with GPS data included (Figure 6.42b), and a radar image showing the accumulated precipitation for the same 12 hour period (Figure 6.42c). In this case the starting time for the forecast was 1800 UTC on the 9^{th} of July. The radar is taken as truth, although in reality it will also contain errors (Koistinen & Michelson, 2002).

We can see in this example that the precipitation over southern Norway seems to be too intense in the reference case as compared to the radar. Over northern Norway and Sweden however the precipitation is fairly weak. For the model run including GPS data however, the northern part is slightly more intense and, the precipitation over southern Norway is decreased and more similar to the radar image. There is thus a positive effect in this case when we include the GPS ZTD as an additional observation.

Several other examples with positive effect can be shown and even though these positive effects dominate there are cases with neutral or even a slightly negative impact on the precipitation when including the GPS ZTD data.

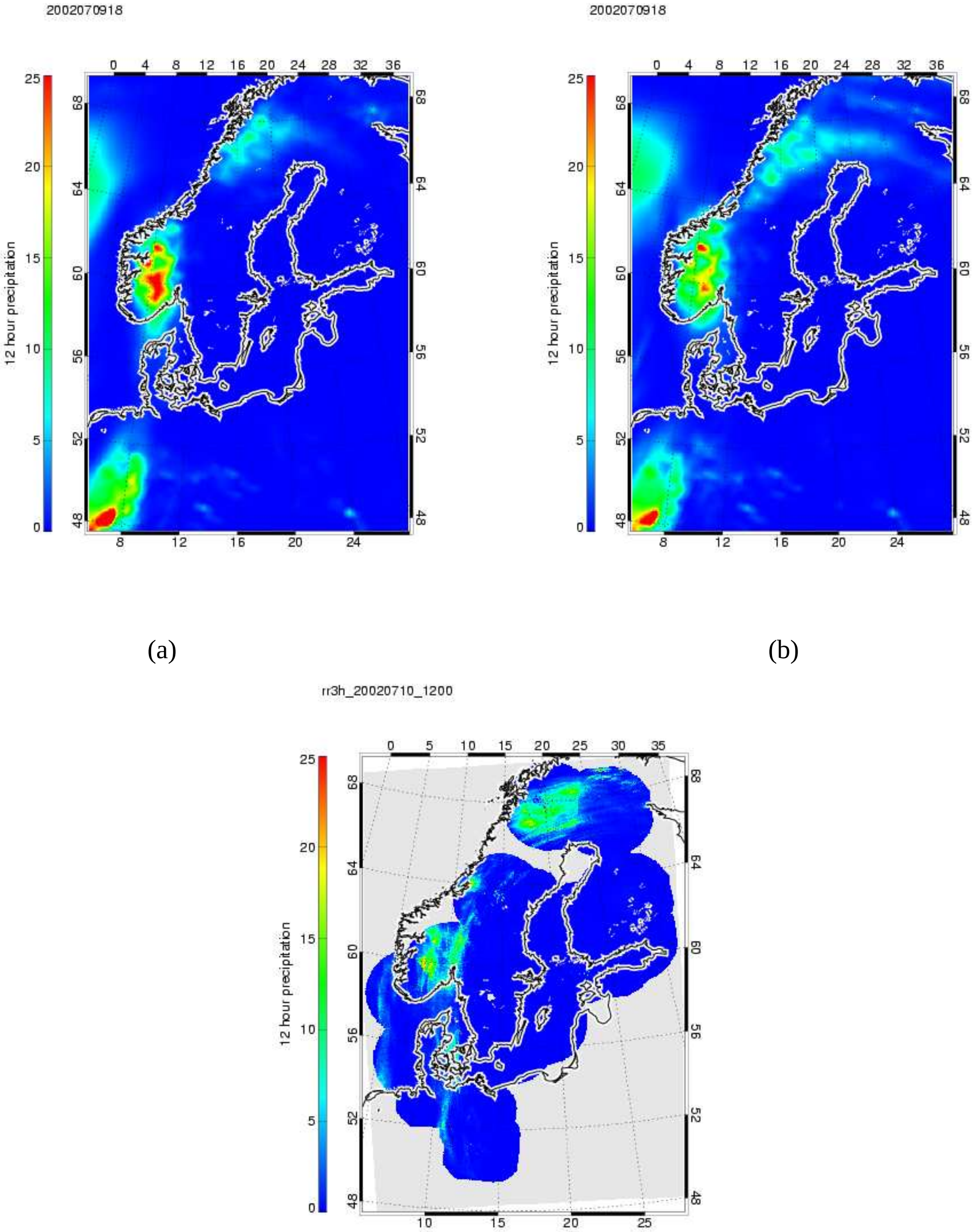
A new moisture control variable

From the experiments described above we have seen that the impact of the new moisture information is rather limited on the forecast fields. One reason for this is that the assimilation scheme used at SMHI is not yet designed to optimally handle the moisture information which ground based GPS data provides. Until now the only moisture observations available have been radiosondes. These are very sparse both in time and space which have lead to an improper initialization of the moisture field.

To solve this problem and to improve the impact, work has started to develop a new control variable for moisture assimilation. The control variable is the variable used in the minimization of the cost function described above instead of the observed quantity or the model variables. The most important property of the control variable is that its error covariance matrix should be a unity matrix. This is necessary in order to perform the inversion of this matrix, and for an efficient pre-conditioning of the minimization problem. Another desirable feature is a error distribution. A detailed description of how the cost function is minimized can be found in Gustafsson et al. (2001).

Within HIRLAM work is now underway to implement a new control variable for moisture following the approach of ECMWF, which has shown positive results (Holm et al., 2002). The introduction of this new control variable for moisture will make better use of the new measurements, not only GPS derived moisture but also measurements from other satellite instruments and radar data.

The other obvious solution is to switch from 3D-Var to a 4D-Var assimilation scheme. In a 4D-Var scheme the moisture is better handled, for example better initialized and with feedback to the dynamical variables. We expect to run the first tests with 4D-Var during 2004.



(a)

(b)

(c)

Figure 6.42: (a): 12 hour accumulated precipitation between 6 and 18 hour forecast. Reference case. (b): Same as (a) but with GPS ZTD included as an additional observation. (c): Radar image for the same 12 hour period as in (a) and (b).

6.2.6 Assimilation trial results: DMI

Henrik Vedel

Forecast Model and assimilation system used

Software for assimilation of ground based GPS data has been made for the 3- and 4D-Var data assimilation system HIRVDA for the HIRLAM model, driven by SMHI with additions from DMI. The system is capable of utilizing ZTD, ZWD, or IWV. Here ZTD is used , because it does not rely on auxiliary data which could degrade its quality. If auxiliary data exist, e.g. local pressure, assimilation of ZTD and local pressure would be preferred , not the assimilation of ZWD or IWV.

The ZTD of the model, which is during the data assimilation compared to the observed GPS ZTD, is calculated as $ZTD = ZHD + ZWD$, where ZHD is calculated using the Saastamoinen formula and

$$ZWD = \frac{R_d}{\epsilon g_s(\theta)} \sum_{i=1}^{N} q_i(k' + \frac{k_3}{T_i})(p_{i+1/2} - p_{i-1/2}). \tag{6.5}$$

Here q and T are specific humidity and temperature of the 'full' model levels, p is the pressure of the 'half' model levels. R_d is the gas constant for dry air, g_s the local gravitational acceleration. Prior to calculation of the model ZTD the model profile of temperature and humidity, and the surface pressure, is determined for the GPS site in question. This is done firstly by linear interpolation horizontally, secondly a vertical transformation of the profile is made to the altitude of the GPS site using the method of Majewski (1985), after first calculating the altitude of the GPS site in the HIRLAM height reference system.

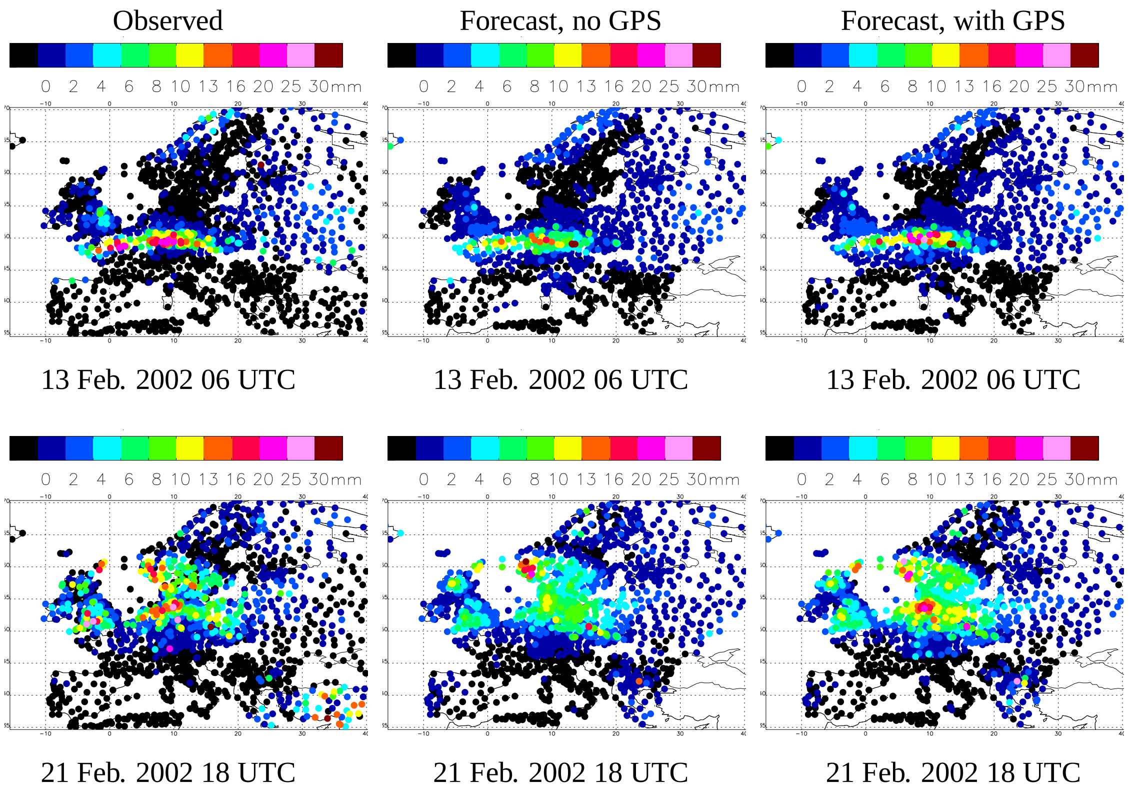
Data used

Since the year 2000 a number of impact experiments have been performed with GPS ZTD data. The GPS data come from the MAGIC and COST 716 (thorn server) projects. The experiments have been made as parallel runs. In these the outcome of an ordinary, operational-like assimilation and forecast cycles was compared to the outcome of a similar cycles in which GPS ZTDs were added on top of the other meteorological observations.

Here, the result is presented for the run which covered the month February, 2002.

Prior to assimilation the observation error must be specified. This must include both the error of the observations themselves and the error of representativeness. The latter represents the fact a measured property can vary significant within a NWP model grid-box and is not well represented by a single, local observation. Humidity is a highly variable quantity both in space and time. The standard way of assessing the GPS ZTD observation errors for NWP does not work because the errors of the GPS data are correlated. We have considered instead the standard deviations of the ZTD offsets between GPS and RS sites with separations smaller than about a grid-box size. This will include both the observation errors of the GPS and RS measurements and the error of representativeness on the relevant scales. From this one has to substitute an estimate of the instrumental error of the RS ZTD. We estimate, based on the above verification study, that the combined measurement and representativeness error of GPS ZTD is of the order 10 mm for our model setup. For the period under consideration, the formal errors from the GPS processing centres were multiplied with a constant, yielding values which were on average of the order 10 mm.

Such studies should be redone when more data become available. Theoretically we expect the GPS ZTD observation error to vary with geographical location and season (humidity is very strongly dependent on temperature, proximity to water, prevailing atmospheric flow). This is confirmed by the seasonal and



13 Feb. 2002 06 UTC 13 Feb. 2002 06 UTC 13 Feb. 2002 06 UTC

21 Feb. 2002 18 UTC 21 Feb. 2002 18 UTC 21 Feb. 2002 18 UTC

Figure 6.43: Comparison of observed and predicted 12 hour precipitation.

regional variation of the magnitude of ZTD offsets in the MAGIC data sample (Haase et al., 2003, 2002). Proper representation of this in data assimilation is a problem of the future.

Conclusions

The general findings are:

- Statistical observational verification of pressure, temperature, geopotential height, wind, and relative humidity are largely neutral. In exp. 2 geopotential heights were systematically improved, though. The verification is done a six hour intervals, this prevents us from testing whether there is an improvement of model humidity on even shorter time scales, as reported by some other groups.

- Contingency tables and threat scores indicate that the forecast of 12 hour precipitation above 5 mm is improved with GPS data in short range forecasts. There is a slight increase in the already existing over prediction of light precipitation. It has been demonstrated that this is not just a simple bias resulting in a constant “lift” of the precipitation amounts when including GPS data.

- By eye inspection of precipitation maps consistently indicates that when there is a large discrepancy between 12 hour precipitation forecasts with and without GPS data in connection which significant precipitation, the GPS forecasts are superior.

Figure 6.43 gives a few examples, more assimilation results in can be found in Vedel & Huang (2004).

6.2.7 Overview and intercomparison of results from the different centres, potential for NWP

Overall we see a mixed picture with regards the impact of GPS data on NWP forecasts. Many of the forecast impact experiments run thus far used a sparser station network than is currently available (March 2004), and in addition assimilation schemes have yet to be tuned to use GPS data in an optimal fashion. The initial experiments performed and the ongoing ZTD data monitoring have been useful for informing such considerations as quality control and tuning. For example, in some cases GPS ZTD data from this early period was prone to abrupt changes which bore no relation to the atmospheric state. These problems sometimes still occur, but improved observation processing quality control should now mean that poor quality observations are less likely to be presented to the various assimilation systems. Error covariances for GPS data are currently poorly understood, and the assumptions made thus far in 3D-Var trials (uncorrelated errors) mean that the GPS data is being used sub- optimally.

A greater impact (positive and negative) has tended to be observed for assimilation trials using the nudging technique in comparison to 3D-Var. This is likely to be due to the fact that nudging can use the high time resolution of GPS observations. It will be interesting to see whether 4D-Var impacts will be significantly greater in magnitude than those seen for 3D-Var.

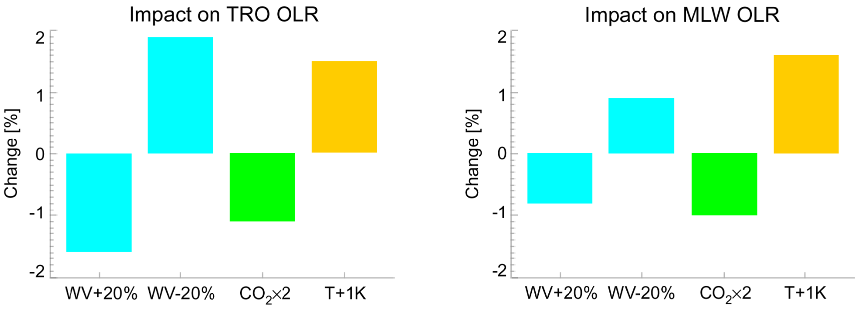


Figure 6.44: Outgoing Long Wave Radiation (von Engeln et al., 2004).

6.3 Climate applications

Sylvia Barlag and Siebren de Haan

The use of GPS meteorology data for climate investigations has been advertised for several years now. In the early stages of development of the GPS system it was already recognized that the measurement of the GPS signal delays could be performed very accurately. The signal processing technique is very mature, and calibration is therefore not necessary. Also, the improvements made in separating the various sources contributing to the atmospheric delay gave rise to a firm believe that the GPS data are a unique and reliable long term source of consistent atmospheric water vapour values.

The increases in tropospheric water vapour over the last 25 years are described by the Intergovernmental Panel on Climate Change (see Houghton et al. (2001)) as qualitatively consistent with increases in tropospheric temperatures and with an enhanced hydrologic cycle, with more extreme and heavier precipitation events occurring. A problem, still to be fully understood and modelled, is the feedback caused by water vapour in an atmosphere with increasing levels of anthropogenic gases. An example is given in Figure 6.44 where the large differences in feedback expected from a 20% increase or decrease in water vapour in the free troposphere are shown. This graph shows that there is ample reason to monitor and study the water vapour content of the atmosphere. Given the above considerations about GPS as a source of water vapour data their value for the detection, attribution and understanding of climate change should be investigated.

6.3.1 On the climate observing systems

In its Second Report on the Adequacy of the Global Observing Systems for Climate in support of the UNFCCC (see GCOS-82 (2003)), the Parties involved make several recommendations aimed at improvement of these system. First of all it is important to note that humidity is marked as one of the key atmospheric variables required for climate. The surface observing networks of the World Weather Watch (WWW) Global Observing System (GOS) provide the basis for a comprehensive network for surface parameters, among which humidity. However, while observations of surface humidity are essential for the monitoring of what we perceive as climate, detailed information on the three-dimensional state of the atmosphere is necessary to ensure that climate can be understood and predicted on all scales. The specific variables of interest are upper-air temperature, wind, humidity, clouds and the earth radiation budget. The adequacy report states about humidity in particular that:

> *"upper air humidity and related quantities such as precipitable water in layers must be measured accurately to validate models of hydrologic processes, to calibrate satellite and other remote sensing water vapour retrieval methods, to determine the radiative forcing due to water vapour and the nature of the water vapour feedback as greenhouse gases increase, and to increase knowledge of atmospheric chemistry processes in the ozone layer."*

Although the adequacy report recognizes the radiosonde network of the WWW/GOS as the basis of a comprehensive network for these variables, an extensive assessment of the upper troposphere and lower stratosphere water vapour by the SPARC project of the WCRP (see SPARC (2000)) concludes that:

> *"the operational radiosonde network does not produce water vapour data that can be used for either analyses of long-term change, process studies in the upper troposphere, or for validation of UTH measurements. However, emerging data sets from improved quality, quasi-operational aircraft and ground-based instrumentation show promise and should be used more extensively for process studies, climate analyses and validation of satellite data."*

Also the adequacy reports recognizes that radiosonde-based climate trends are questionable due to instrument discontinuities. Differences of more than 10% between instrument types have caused global instrument-caused drying by an average of 4% between 1973 and 1996 (using preliminary adjustments). A global average tropospheric warming of around 0.4 K with unchanged relative humidity would raise total atmospheric water vapour content by nearly 3%. Therefore, global water vapour trends are not reliably detected using unadjusted radiosonde data.

With respect to global satellite data the adequacy report concludes that several long-term projects are now developing climate data sets by reprocessing long satellite records with consistent algorithms. However, the problem of correcting for biases and instrument drift when combining several data sources is not always addressed and may lead to global averages still containing the biases of the individual sources.

Finally, the report recognizes that that ground-based GPS receivers show considerable promise for obtaining total column water vapour observations over land and attributes priority global exploitation of this promise through international coordination.

6.3.2 Some preliminary results

In order to be able to estimate any trend in water vapour content it is essential that the data used in the processing are homogeneous in space and time. Because water vapour is the most abundant gaseous species in the atmosphere, and moreover, is highly variable on a daily as well as on a seasonal time scale, a clear distinction between signal and systematic measurement error is required. The discussion in the previous section shows that the expected increase in water vapour on the decadal to centennial scale is a few percent of the natural background. To distinguish between a possible climate trend and a drift of the observing system, or in other words, a drift of the systematic error of this system, a very stable observation system is required. Changes in for example site, network or satellite configuration, which influence the behaviour of the systematic error, should be avoided or at least be characterized. This long term stability requirement (see Chapter 3) seems a challenging goal even for the GPS (or Galileo) system.

Since the emergence of GPS as a possible source for studying climate several investigations into the value of the GPS data have been made with the help of data from local stations and international networks. These possibilities all assume the use of GPS data as an independent source for observing climate trends.

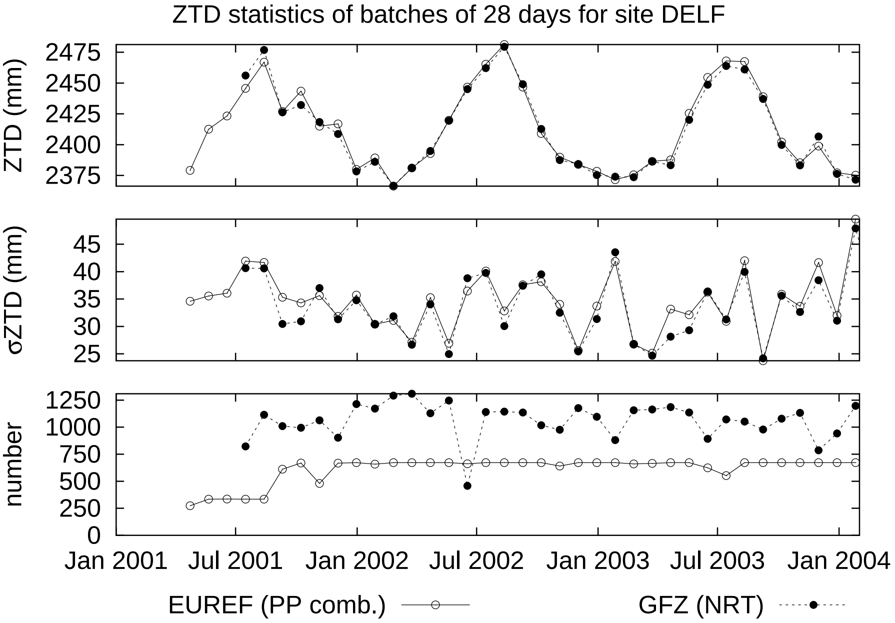


Figure 6.45: 28 day batch ZTD statistics for the GPS site DELF of two processing methods: GFZ (precise point positioning in NRT) and EUREF (combination of post-processed solutions). Top panel: mean of ZTD in each 28 day batch; middle panel standard deviation and bottom panel number of observations in each batch.

Table 6.1: Statistics of the comparison ZTD estimates from EUREF and GFZ for DELF.

EUREF - GFZ	num	bias	std.dev.
Δtime $\leq$ 30 min.	16850	2.16	36.04
1 day batch	861	1.14	28.97
7 day batch	138	1.67	9.69
28 day batch	34	1.00	4.60

In the framework of the IAG and the EUREF commission a post-processed solution is determined, see Chapter 4. A comparison has been made between the EUREF weekly combined solutions and the NRT solutions as estimated by GFZ for the GPS site DELF. The 28-day mean of these two time series is shown in Figure 6.45. The top panel shows the mean of 28 day batches; the middle panel the standard deviation and the bottom panel the number of observations in each 28 day batch. The batches are not overlapping. The top panel shows that the means of both time series are very close. Furthermore, the standard deviation in 28 days is also similar, although the total number of observations in a batch is different. From this figure we may conclude that the errors due to, for example predicted orbits in stead of precise orbits, are smoothed out when a signal is averaged over a longer period. This can also be seen from Table 6.1, where the statistics for different batch lengths is shown. Apart from the first row in this table, the statistics are based on a batch size of 1 day, 7 day or 28 days. The first row is the result of the comparison between the actual observations which are within 30 minutes of each other. The standard deviation between the two types of ZTD estimate decreases when larger batch sizes are used.

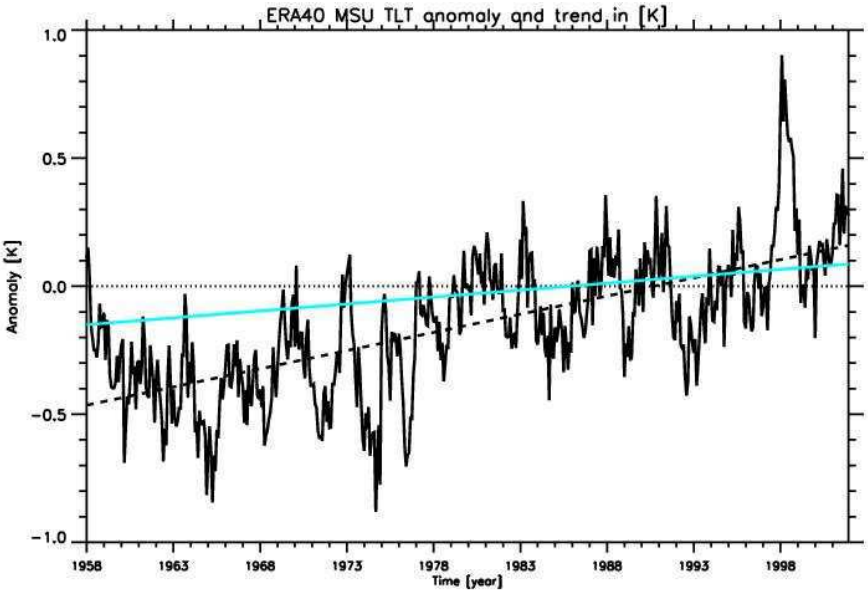


Figure 6.46: Vertically integrated water vapor, IWV, of ERA40 for the period 1958–2001. The dashed line shows an increasing trend. The full line indicates a corrected trend obtained by adding a factor to the data for the period 1958–1972 obtained from the difference between ERA40 and the NO SAT experiment, and by excluding data for the years 1972–1978 (from Bengtsson et al. (2004)).

GPS data have also been used to quality check the results of the ERA-40 re-analysis data set, as long as GPS data is not analyzed. The ERA-40 experiment is an attempt to reconstruct a homogeneous record of the atmospheric state over the years 1958–2001 by using a single atmospheric analysis model for the whole period, here the ECMWF model, while using all available observations for that period (see Simmons & Gibson (2000)). The advantages of using a three-dimensional atmospheric state model are that the gaps left by any single observing systems are either filled by other observing systems or by the model itself in a physically consistent manner. Other important advantages are that systematic modelling errors are consistent over the analysed period and that gross observing errors can be detected. All together re-analysis data may reveal climate trends over the considered period. Nevertheless, it should be kept in mind that the data may represent the best estimate but are still not the truth, and that dominant observing systems will transmit their systematic error to the results. An example of this is given above, where the dominance of systematic error in the radiosonde system was discussed. An analysis of the ERA-40 data in terms of temperature and water vapour trends was made by Bengtsson et al. (2004). Figure 6.46 shows the water vapour trend seen in the ERA-40 data with and without correction for dominant satellite sounding errors. This analysis and that made by Hagemann et al. (2003) use GPS observations series from several GPS stations around the world to test the quality of climate time series. They conclude that GPS observations and (corrected) trends are in line. The benefit of the use of GPS observations in these studies is that they are an independent source of information. It is from Bengtsson et al. (2004) that the requirement for the stability of the GPS system as a stand-alone observing system was deduced.

GPS data may also be used to test results from climate prediction models. Vedel & Stendel (2004) discusses a 110 year model climate simulation by comparing the first and last ten years of the simulation. The model used is the ECHAM model (see Roeckner et al. (1996)) driven with a specific emission scenario (for more details see Vedel & Stendel (2004)). The main focus of their work is on climate

Table 6.2: Behaviour of 10 year global means of ZTD, ZWD, ZHD and IWV (from Vedel & Stendel (2004)).

	Current	Future	Evolution	Unit
ZTD	2324	2358	34	mm
ZWD	123	157	34	mm
ZHD	2202	2201	-1	mm
IWV	19.71	25.47	5.76	kg/m^2

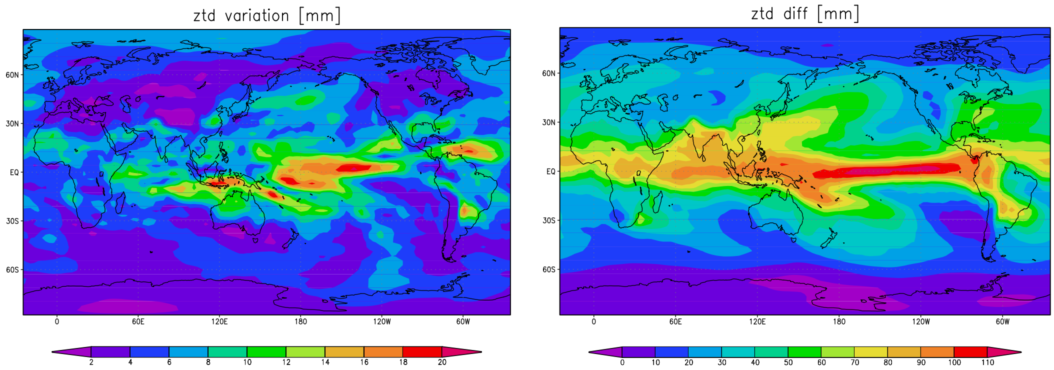


Figure 6.47: Climate induced a) interannual variation of ZTD; b) evolution of ZTD. (from Vedel & Stendel (2004))

monitoring and in particular how to optimally use GPS observations for climate monitoring. From the model simulations the expected trends, both for ground-based and space-based GPS measurements, are extracted. For ground-based GPS, the results show that most of the change should be observed in the wet component of the GPS delay. However, the study also emphasizes the use of the raw GPS data in stead of IWV. Auxiliary meteorological data could contribute their own systematic error to the trend (see the derivation models for ZWD and IWV in Chapter 2). The GPS observable itself is the total atmospheric delay data. In Table 6.2 the results of this study are shown. An evolution of 34 mm in ZTD is observed, and this is completely due to the increase in ZWD. This increment is determined by comparing the 10 year global mean of the first 10 years (years 0–10) with the global mean of the last 10 years (years 100–110). An increment in ZWD will result in an increase in total water vapour. In Figure 6.47 the interannual variation of ZTD and of the expected change in ZTD due to climate change are shown. The conclusion of Vedel & Stendel (2004) is that: a) 'raw' GPS data are as sensitive to climate change as traditional data; b) consequently the data should be used in a "raw" form, because it renders them independent of data from other observing systems, thereby independent of the eventual biases and problems of those systems.

Finally, the Swedish GPS network, which has produced data since 1993, was used to assess the stability of estimated linear trends in the IWV (Gradinarsky et al. (2002)), both as a stand-alone technique and in combination with other data sources. The estimated trends are as expected very small. In fact the largest trend is seen at the Onsala site on the Swedish west coast. For this site there are also Water Vapour Radiometer (WVR) data, geodetic Very-Long-Baseline Interferometry (VLBI) data, and nearby radiosonde (RS) launches, from the same time period. All these methods result in an estimated trend in the IWV of about 0.2 mm/yr for the time period 1993–2002. Each one of these four techniques, has its individual

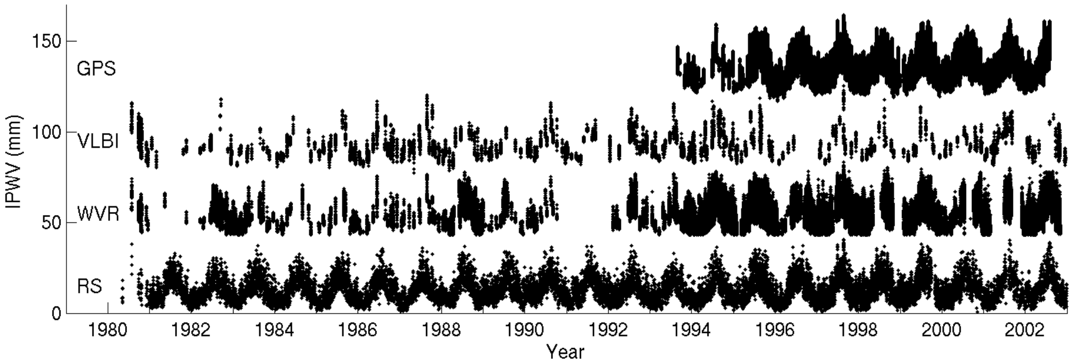


Figure 6.48: Combined time series of IPWV from four different techniques over 23 years. Shown are the original data sets, i.e. VLBI (V) without offset, WVR (W) offset by +40 mm, GPS (G) offset by +80 mm, RS (R) offset by +120 mm.

advantages and disadvantages, e.g. in terms of sampling and time coverage, and a combination of the results may provide a more robust estimate of long-term changes in IWV than each individual technique by itself. Figure 6.48 shows the IWV measured by VLBI, GPS and WVR at Onsala, and by RS at a 37 km distance at the Göteborg-Landvetter Airport (Haas et al., 2003). The four independent techniques also show a similar spectral content for the IWV, i.e. an annual signal, seasonal signals, and long periodic signals. The best estimate for a linear trend in the IWV for 1980–2003 is +0.06±0.01 kg/m^2/yr.

All these examples show comparable expectations for the water vapour trend in a warming climate of approximately 0.05 kg/m^2/yr.

Chapter 7

Planning for the Operational Phase

7.1 Introduction

John Nash and Hans-Peter Plag

The material provided in this chapter is based on the work of Working Group 4 (WG 4) of COST 716—"Planning for the operational phase", which started its work in mid 2001. At this time, the COST 716 Demonstration Network Experiment was beginning to deliver large amounts of total zenith delays in the timely fashion requested by the meteorological users.

This chapter summarizes the situation at the end of the COST Action 716 with respect to

- the physical network of observing sites including data and analysis centres, information on running costs,
- the application networks that have developed during the lifetime of the COST action, including the demonstration project of WG 2,
- the institutional and organizational networks that are in place or developing, including the boundary conditions for future organizational alternatives on a European level

and ellucidates organizational alternatives for an operational phase that would give mutual benefits to both the geodetic and the meteorological communities. In this sense, the chapter describes the strategy needed for a successful exploitation of the growing ground-based GPS infrastructure (and also future GNSS infrastructure) for meteorological and climatological applications.

The chapter is separated into two parts, with the first part (Sections 7.2 to 7.4) giving the necessary background information which set the boundary conditions for any operational activity in the field and the second part (Sections 7.5 to 7.7) discussing in detail the alternatives and associated costs for an operational phase.

The rapid progress in the development of the supply of observations by the Demonstration Network (van der Marel & et al., 2002) (and Chapter 4) clearly necessitated the development of a strategy for follow-on activities if the progress achieved by COST Action 716 was not to be lost with the conclusion of the project in 2004. Thus, WG 4 was requested to develop and assess options for the implementation of an operational phase of a GPS network following the completion of COST Action 716. To this end, existing national solutions to running a network and processing the results were reviewed to form the basis of the proposals (Section 7.2).

Section 7.3 reviews the requirements for NWP and climate applications as they were specified by WG3 and this sets the background for the observational network and data processing required for the operational phase. In Section 7.4, the current state of the art for use of GPS-derived tropospheric information and the limitations identified during the COST Action are discussed.

WG 4 was also expected to assess the optimal density for the network and the probable impact on the current observing system. This would then lead to a cost/benefit analysis. In practice, estimates of the probable development of the GPS network applicable for water vapour determination in the foreseeable future were evaluated. The options for future implementation for an operational application of GPS-derived tropospheric parameters for NWP and climate discussed in Sections 7.5 and 7.6, respectively, were then based on the existing national experiences taking into account the probable development of the GPS network available for meteorology. The cost implications were quantified on the basis of the current costs identified in the demonstration network and these costs were summarized in Section 7.7.

Finally, a number of recommended strategies for international operational work within Europe were proposed and these are found in Section 7.8. The recommended strategies had to take into account that in many countries the supply of the observations has outstripped the capabilities of meteorologists involved in numerical weather prediction to develop optimized assimilation procedures.

Here, it is worth mentioning that operational numerical weather prediction models are the result of a compromise between accurate scientific representation and approximations necessary to make the models work as best as possible with a less than adequate density of available observations. One of the main advantages of GPS total water vapour measurements is the good temporal resolution and continuity of observation that can be achieved. In most countries the data assimilation techniques that can benefit most from this data coverage are under development but are not yet ready for operational exploitation.

The available water vapour observations in current numerical forecast models are not sufficient to specify the effects of all the scales of motion that need to be represented in mesoscale weather forecasting (200 km down to less than 50 km). For instance, in many countries, cloud cover forecasting is critical for customers affecting the surface temperatures and hence national power supply requirements. Thus, the horizontal structure in relative humidity fields in the forecast model is added on the basis of an assumed relationship between surface observations of cloud and the vertical distribution of relative humidity. In the future, merging estimated profiles of relative humidity with the real total water vapour measurements from GPS may not be straightforward. If the relationship between cloudiness and relative humidity distribution that has been assumed in the numerical weather prediction model is actually in error, significant changes may be required to model parameterizations if both data sources are to be used.

It follows that, demonstrating GPS total water vapour measurements improve the occasional precipitation forecast is not an adequate test in some countries of the operational usefulness or suitability of the GPS measurements. It must also be shown that the assimilation of the observations does not disrupt the cloudiness forecasts and forecasts of associated meteorological variables such as surface temperature. Precise answers as to how useful total water vapour measurements will be in future will not be apparent for some time.

Experts developing the use of water vapour measurements in numerical weather forecasts agree that water vapour is best represented with a model variable similar to relative humidity, rather than by absolute humidity. The numerical model needs to forecast upper cloud as well as low cloud. Total water vapour needs to be transformed into this type of parameter without introducing false values of the relative humidity parameter at heights where total water vapour measurements are insensitive to the true relative humidity. The most reliable methods of achieving this have yet to be identified. It is recommended that the usefulness of GPS water vapour measurements should be improved by integrating the GPS network with other upper air observations (laser ceilometer, cloud radar, weather radar, wind profiler and radiosonde) to provide a basis for the distribution of relative humidity in the vertical. This would involve some collocation of the GPS water vapour network sites with upper air or surface meteorological networks.

Finally, it has to be taken into account that most meteorological services in Europe are currently under pressure to reduce the cost of conventional observing networks. Even small additional expenditure may be difficult to find. Thus, the proposals must allow for the different national GPS networks to be developed at a rate that is suited to the financial circumstances of the meteorological community in the individual countries. They must also allow for the rate at which the country can generate the necessary evidence of benefit from observing system experiments to justify the expenditure.

7.2 Presently available semi-operational solutions

7.2.1 Introduction

In the frame of the COST Action 716, in several countries the exploitation of GPS-derived tropospheric parameters for NWP applications developed into a semi-operational state. Particularly the demonstration project run by WG2 stimulated a high level of interaction between the geodetic communities traditionally responsible for the national GPS networks and the meteorological communities interested in using the new observational data in NWP. In the following sections, examples selected to illustrated the diversity in the national solutions are reported briefly. Most of these reports reflect the status in 2003 or early 2004. Focus is on the semi-operational implementations with particular emphasis on the status, plan and ownership of the physical GPS network, the semi-operational processing of the GPS data and the data flow to centres, as well as the application of the products through assimilation in NWP. The sections complement the information given in the final report of WG1 (which gives an overview of the GPS networks in the European countries, see Pesec, 2001) and the material provided in Chapter 4.

7.2.2 Sweden

Jan Johansson and Gunnar Elgered

The GPS network SWEPOS

Sweden has a continuously operating ground-based GPS network called SWEPOS. In March 2004, it consisted of 57 sites reasonably well spread over the country (see Figure 7.1). In total, 22 of these sites are of geodetic quality, meaning that the GPS antennas are on stable mounts in solid rock. The other 35 sites have antennas on buildings but this still means that they are useful for making atmospheric estimates as long as the actual position is continuously estimated from the GPS data. During 2004, the SWEPOS network will be further extended and include more than 70 stations.

SWEPOS was designed and established in collaboration between the National Land Survey of Sweden (NLS) and the Onsala Space Observatory at Chalmers University of Technology. Data have been obtained from the first twenty established sites since August 1993. NLS has the operational responsibility for the network including data archiving.

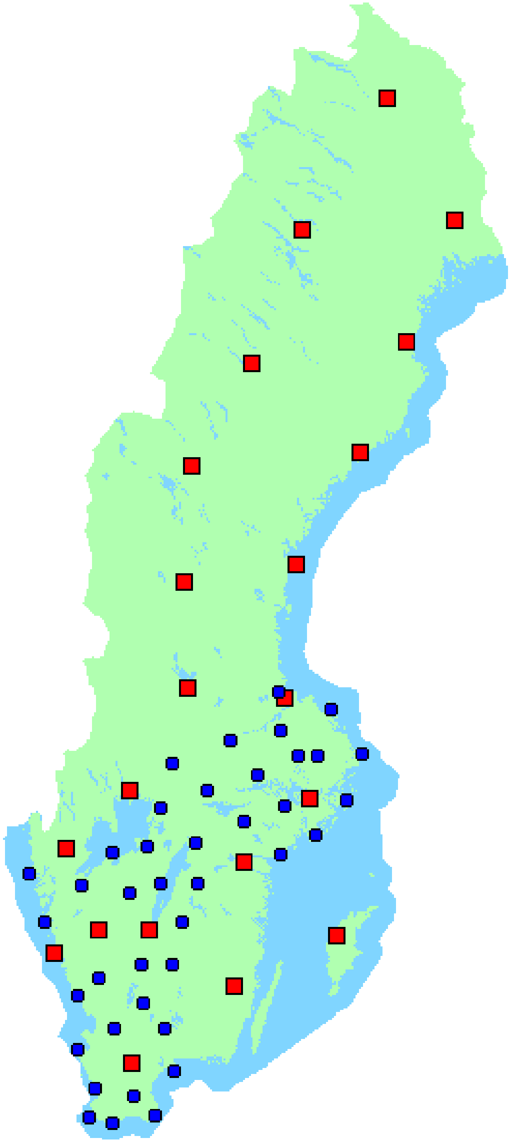


Figure 7.1: The Swedish network of GPS sites as of March 2004. The red squares indicate the original geodetic network with antenna pillars on bedrock. The blue rounded squares show the more recent sites for RTK applications.

The stations are equipped with 1 or 2 Ashtech high-quality geodetic receivers and in addition some stations have a Javad Legacy receiver. Some stations also have Ashtech or Javad receivers for tracking of both GPS and GLONASS satellites. All stations have the Dorne-Margolin choke-ring antennas commonly used in the International GPS Service and other permanent networks. All receivers at the same site are connected to the same antenna using a power splitting device. The antennas are protected by hemispheric radomes.

The 22 geodetic stations have the antenna mounted on a 3 m high concrete pillar which is well insulted and temperature controlled. The other stations have the antennas mounted on roof tops. All stations also have a low horizon mask (lower than 10° elevation angle).

Other equipment at the stations are: Uninteruptable Power Supply (UPS), remote power control, air condition and temperature regulation, TCP/IP connections for real-time monitoring and data retrieval, and telephone lines/modems for redundancy.

The data sampling rate is 1 s and standard data files contain 1 or 24 hours of data in RINEX format with 1, 15, and 30 s sample rate.

The Use of SWEPOS

A major task for SWEPOS is of course to provide a geodetic reference frame in Sweden. The data are sampled and transmitted over Internet to the NLS headquarter in Gävle. Real-time differential corrections are broadcast over the FM-RDS channel to be used for navigational applications. Real time carrier phase data from SWEPOS for relative cm-level positioning may be received in certain areas of Sweden via cellular phone modems or FM-DARC. It is also possible to obtain the data at a later time in order to use these sites as references in geodetic surveying.

The research group active in the area of space geodesy at Chalmers and the Onsala Space Observatory process all the data from SWEPOS, typically with a time delay of several months. This analysis results in time series of positions of the sites which are used in geodynamical studies of crustal motions. These include phenomena such as postglacial rebound and oceanic and atmospheric loading.

Water vapour data from GPS for forecasting

A collaboration between NLS, Chalmers, and SMHI was established with the goals to densify the existing GPS network making use of the existing observational infrastructure at SMHI data acquisition sites and to carry out a close to real time GPS data analysis followed by the inclusion of these results in an operational NWP model at SMHI.

The work to implement the system started in January 2002. For EU-COST purposes the processing running and the product are official since May 2002. Several improvements have been made since then. The latest being a modification to the orbit improvement analysis, which was implemented in February 2004. A priori satellite orbit and clock information is obtained from the IGS (Ultra Rapid Orbits). Thereafter, 20 IGS stations are used to improve the satellite orbits and clocks. These results are then used to process about 110 stations, including SWEPOS stations as well as other permanent sites in Northern Europe, in near-real time.

On the average the bulk of the data are delivered around the stipulated maximum delay of 1 hour and 45 minutes.

In addition to the near-real time data processing software was developed for a true-real time application where ZTD estimates are available within a few seconds of the data acquisition (Stoew et al., 2001; Stoew, 2001; Jarlemark et al., 2002)

The plans for GPS meteorology in Sweden

Today, observing data from the SWEPOS stations are transferred to NLS by TCP/IP. The GPS data (or rather GNSS data in order to include GPS, GLONASS, as well as any future Global Navigation Satellite System) from SWEPOS and data from about 40 additional sites in other European countries (special focus on the northern Europe) are analysed in near real-time using a PC-Linux operating system.

For redundancy, a second PC-Linux computer is placed at NLS (May 2002) for parallel processing trying to avoid missing data caused by computer break downs. SMHI, with support from Chalmers and NLS, operates the NRT processing. SMHI receives preprocessed, NRT data (e.g. estimates of the total zenith delay) from the computer at NLS. At SMHI these data will be included in weather forecasting models. Meteorological modelling data from SMHI will be sent to NLS and Chalmers to be used in research projects in order to improve the performance of positioning processing et cetera.

Today the delivered estimates only include the ZTDs for each station every 15 minutes. However, the intention is to include also the gradient estimation and possibly residuals. The ultimate goal could be to implement the Chalmers real time GNSS data analysis packages as a module in the NWP software at SMHI. In such a case, all the GNSS data have to be transferred to the computer facility of the SMHI.

Concerning the application of climate monitoring studies have started to assess the size of station dependent biases in the post-processed ZTD estimates. Several methods for station calibration of the Swedish GPS sites are used and evaluated. These studies are likely to continue for several years.

7.2.3 Norway

Hans-Peter Plag and Oddgeir Kristiansen

The national permanent network

The Geodetic Institute (GI) of the Norwegian Mapping Authority (NMA) runs on a continuous basis a smoothly growing network of CGPS sites which numbered early in 2004 about 35 stations at about 30 geographical locations distributed on the Norwegian mainland and Svalbard (see Figure 7.2). Twenty-one of these stations make up the Norwegian SATREF network. Most of the older SATREF stations were located mainly along the coast, and three new stations were recently established further in-land in order to improve the geographical distribution.

For the purpose of real-time positioning with cm accuracy, dense networks are established in the more populated areas. Such local networks are established in the Oslo area, on the south-west coast of Norway, and several parts of the west coast. As an example, in the Oslo area, eight stations are established with a spacing of 75 to 100 km.

From two locations with a total of five operational receivers, data is delivered to IGS and four additional sites provide data to EUREF. One site (Andøya) is established for co-location with a nearby tide gauge, and there, a second GPS receiver is established very close to the tide gauge. In Tregde, a GPS receiver is operated directly above and physically connected to the tide gauge. These two sites deliver data to the European Sea Level Service (ESEAS) and through this to GLOSS.

SATREF is a geodetic reference and DGPS system, which is currently made up of a network of twentyone reference stations and a control centre. The sites record data and provide corrections at 1 s sampling intervals. Observations and corrections are transmitted to the control centre in real-time. After a quality control of the corrections, these are distributed by different means for navigation and positioning. The observations are archived at the control centre. The SATREF network was initially set-up as early as 1991 and the sites have undergone considerable technological changes introducing inhomogeneities in the data. However, since June 1998, the sites can be considered stable.

The two IGS sites record GPS data at 30 s sampling interval into hourly and daily files. Routinely, daily files are up-loaded to the respective IGS regional data centre (BKG, Germany), while direct access to the sites may be granted for down-loading of hourly files.

The ESEAS sites as well as ancillary sites on oil platforms also record data at 30 s sampling interval. Down-load of hourly files is in principle possible for all these sites.

In Ny-Ålesund, a VLBI antenna is operated by the GI in addition to several GPS receivers and other permanent infrastructure. At that location, meteorological observations are available since 1994 including daily balloon soundings and observations of a Water Vapour Radiometer (WVR).

Analyses related to GPS meteorology

For all research applications, GIPSY is used at the GI. In particular, tropospheric effects are studied solely with the help of this program.

NMA contributed to the Demonstration project in the frame of WG 2 (see Chapter 4 for more details). Moreover, NMA is contributing ZTD estimates to the TOUGH project. This contribution is provided in cooperation with the Onsala Space Observatory, Chalmers University, Gothenburg, Sweden. For a

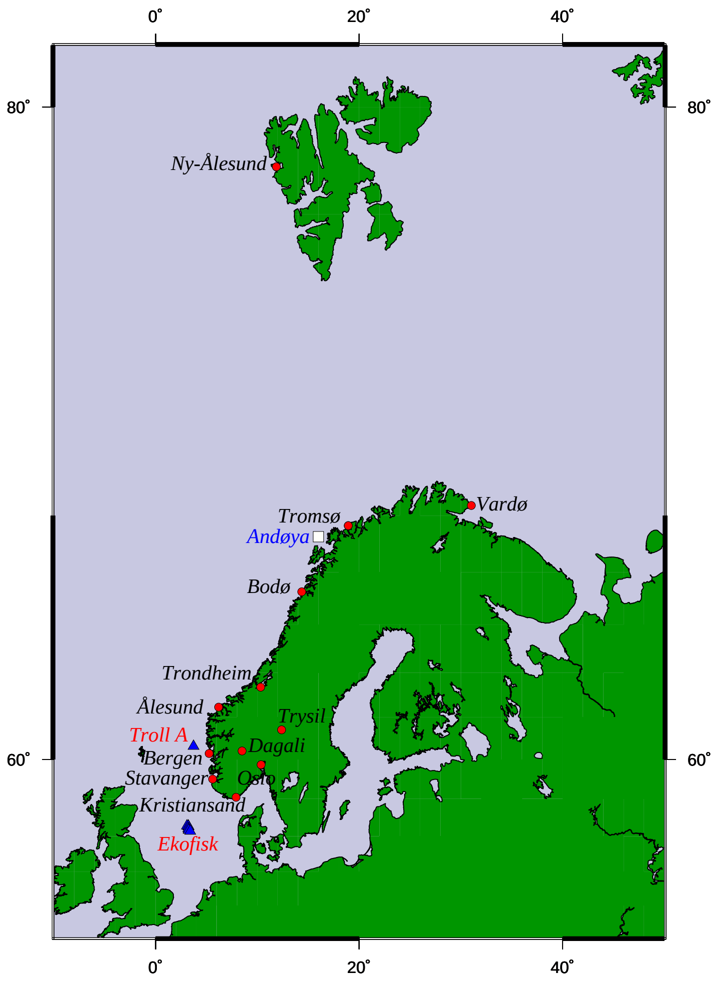


Figure 7.2: CGPS sites of the Norwegian Mapping Authority. Circles are STAREF sites, squares ESEAS sites, triangles CGPS receivers on oil platforms. Note that Tromsø and Ny-Ålesund are also IGS sites. The ESEAS site at Tregde in southern Norway close to Kristiansand is not shown.

large network of sites in Norway, Sweden and adjacent countries, total path delay (ZTD) estimates are provided in near real time (NRT) to a server used by meteorological institute to access the ZTD values for use in NWP. For the determination of the ZTD, the precise point positioning technique (PPP, see Zumberge et al., 1997) is used.

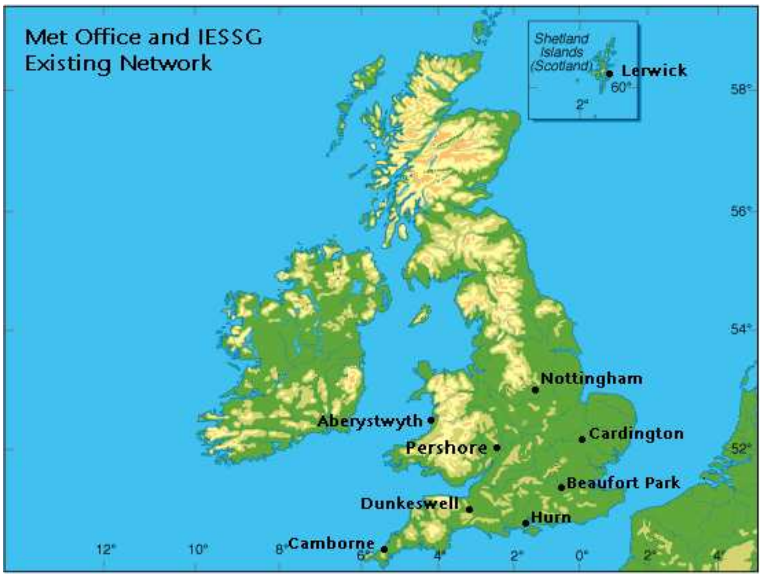


Figure 7.3: Near-real-time CGPS network in the U.K. in 2002.

7.2.4 U.K.

Existing real time network

The UK real time ground-based GPS water vapour network in 2002 consisted of eight Met Office sites operating remotely with automated contribution of hourly data to the national archive at Nottingham University and to the COST-716 near real time demonstration, together with the data from Herstmonceux and Morpeth (Newcastle) (operated as part of the IGS EUREF network) and also the data from the IESSG receiver in Nottingham (operated by IESSG, Nottingham University). All sites apart from Beaufort Park were installed to a standard suitable for reference geodetic work as well as for meteorology. A map of these sites is shown in Figure 7.3. At the Met Office sites, the GPS receivers were purchased by the Met Office and installed to geodetic standards in collaboration with IESSG, Nottingham. The sensors were installed to gain insight into the performance of GPS water vapour measurements in the U.K.

Data were communicated in the RINEX (Receiver independent exchange) format and were collected and archived by IESSG (Institute of Engineering Surveying and Space Geodesy) in Nottingham at approximately 15 minutes past the hour or HH+1:15 after the first data point. The data were then collected by GOPE (the Geodetic Observatory, Pecny) in the Czech Republic at HH+1:30, processed to obtain Integrated Water Vapour (IWV) measurements using the Bernese software, and displayed on the COST-716 website at HH+1:45. The time delay was a result of the time taken to calculate the IWV for the 46 sites processed by GOPE, and as such could be reduced if the processing were site specific to the UK region.

Since March 2001 the UK sites have had a Raw Data capture of 94.1% and a NRT data capture of 88.9%. Communication and PC problems have limited the capture rates. The main areas for improvement were in the transfer of data either from the GPS site to IESSG in Nottingham (usually a telephone / dial-up problem) and the interface between the computer at IESSG and GOPE in the Czech Republic (computer problems preventing access to data from IESSG's FTP site).

The sites providing data to the real time demonstration network in 2002 were a small fraction of the

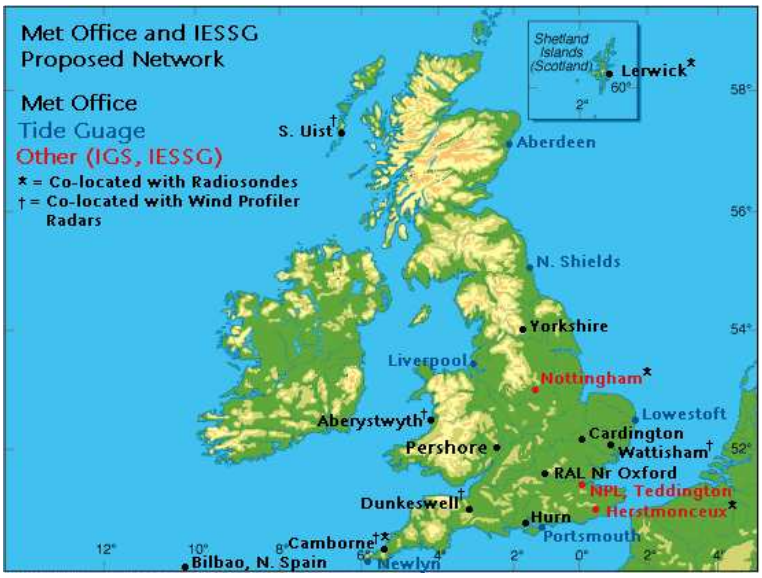


Figure 7.4: NRT IWV network for the U.K. in 2003.

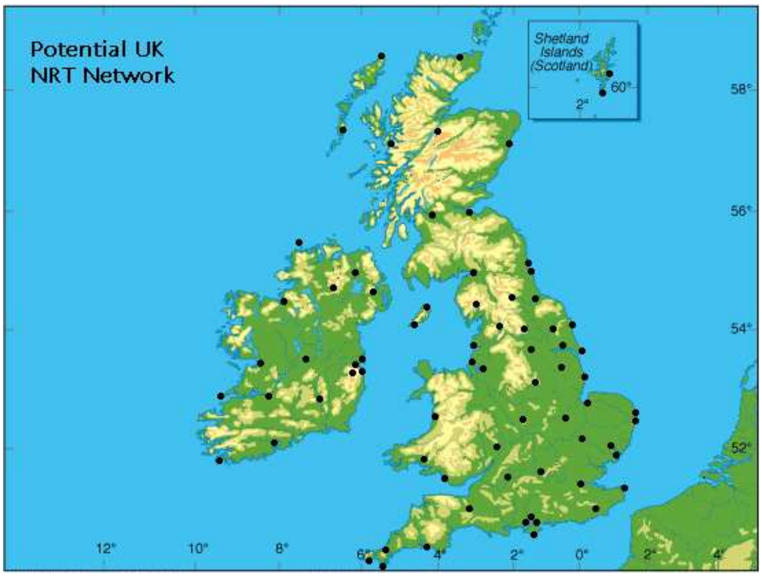


Figure 7.5: Potential NRT CGPS Network in the U.K.

total number of sites in the UK where suitable GPS receivers were deployed. For instance, the Ordnance Survey (UK national mapping agency) had a network of about 30 sites, data from which were freely available to the public, but not available through a link suitable for real time networking. Ordenance Survey data were made available after the event. Originally, the mapping agency was going to charge users for the observations from this network and the Met Office was not able to pay the amounts asked. In late November 2002, the Met Office placed a contract with Nottingham University to interrogate hourly data from six tide gauge CGPS sites. This gave the network shown in Figure 7.4. Note that care has been taken to co-locate GPS sensors with other upper air observing systems such as radiosondes and wind profilers.

Future directions

1) Network development Within the UK, the Met office is attempting to achieve as high as possible GPS network resolution through data sharing and partnerships with a variety of government agencies and universities.

In late 2003, the Ordnance Survey (UK) and Met Office agreed to collaborate in the area of GPS observatory. OS GPS sensors will be installed on a significant number of Met Office automatic weather station sites (see Figure 7.5), and in return the Met office will have access to the output from the real time kinematic sensors to generate GPS water vapour measurements. This should provide data from at least 100 sites across the UK in 2005.

2) Establishment of a real time GPS processing centres for the British Isles The Met Office plans to establish a national real time processing centre at the Met Office to process RINEX data instead of relying on an outside contractor to obtain ZTD and IWV data. This should start preliminary operations in June 2004.

3) Improvement of NRT data frequency In order to increase the data quantity, the communication links between the GPS sites and the data/processing centre may require improvement. In the long term, cost effective communications with the GPS sites will be sought, and as far as possible Met Office sites will attempt to share communications with collocated automatic weather stations. It is clear that the network density achievable will be limited by the payments requested for sharing operational networks with other national agencies.

7.2.5 Germany

Günter Rampe

The German Weather Service (DWD) cooperates with the GeoForschungsZentrum Potsdam (GFZ) which is an institute of the Helmholtz Association of German Research Centres (HGF) and is responsible for an operational determination of water vapour within a dense network in Germany (see Section 4.3.7).

The German GPS network

In Germany a network of permanent differential GPS reference stations called SAPOS has been established by the Land Surveying Agencies of the 16 states (see Figure 7.6). The final network will have a spacing of about 50 km all over Germany. At present more than 250 sites are already in place. This large network allows for further significant densification if the ongoing studies will propose it. The network is supplemented by 20 GPS receivers from GFZ installed at synoptic sites of the German Weather Service, giving optimal possibilities for validation of the GPS results.

For the NRT applications the data are transferred in hourly batches to GFZ and checked for quality. The data retrieval has been stabilized during the COST project by introducing Internet connection to the sites, presently 85% of the data are available within 5 minutes.

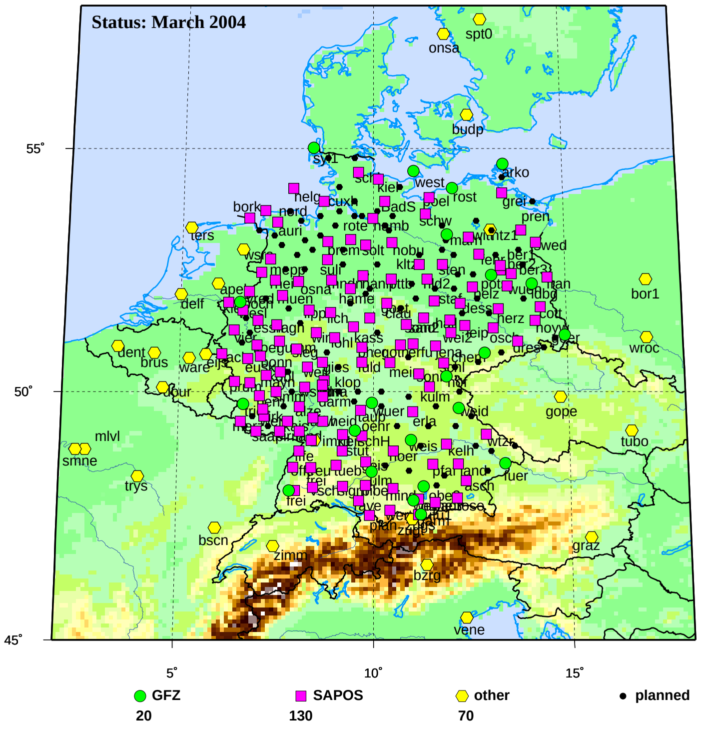


Figure 7.6: The GPS stations processed by GFZ and monitored at DWD (status as March 2004).

Product generation

Near-real time data analysis: The NRT data analysis is based on hourly retrieved data. The processing of the data has to be very robust, because such hourly repeated tasks have to be completely free from human interaction. The whole analysis should be finished within 10 to 15 minutes, demanding effective algorithms and technologies to be developed and implemented. A number of substantial components are already available and have demonstrated their performance during the COST project and in the framework of the IGS Analysis Centre at GFZ. The central software used is the EPOS.P.V2 package developed at GFZ. A technique of parallel processing of a large number of stations in clusters, where each cluster may be processed on a separate computer, is implemented, which keeps the computation time within 15 minutes for more than 200 stations even with an increasing number of parameters. The data are analyzed in sliding 12 hour windows shifted each hour where the result from the latest hour forms the ZTD products.

Estimation of the tropospheric results is based on high quality GPS orbits and clocks. To achieve sufficient quality in the GPS orbits, about 20 well-distributed global IGS sites in a 12 hour data window are used to stabilize the orbit parameters improvement. For a good clock coverage over Germany five additional German stations are included. The station coordinates are held fixed after they have been determined with millimetre accuracy.

Post-processing analysis: Whereas for the weather forecast the only product which can be used is the NRT one, all non real-time applications, such as atmospheric studies and climate investigations, will focus on post-processed results. These products have a better quality than NRT: they rely on stations globally distributed and on the very precise GPS orbits, available 1–2 weeks later with an accuracy of about 3–6 cm. Moreover, the post-processing can run with the same software for a long time, providing homogenous and stable time series of GPS data. In Germany the post-processed results have been used by GKSS (German HGF Centre) in projects like BALTEX and BRIDGE. For the near future, climate research activities are planned, for example one idea of GFZ is to reprocess the past 10 years of GPS data over Germany in a homogeneous way as necessary for climate monitoring.

GPS data validation

DWD has monitored and validated the NRT GPS data processed by GFZ from May 2000. The monitoring consisted of routine comparison of the hourly GPS data against radiosondes and against the forecast model. Especially important was the identification of biases and its temporal variations. The monitoring focused on the Integrated Water Vapour, (IWV), since this is the quantity to be exploited in the assimilation. IWV is derived from the Zenith Total Delay (ZTD) using pressure and temperature measured at the GPS station when available, or pressure and temperature values derived from the model output for stations not provided with meteorological sensors. IWV data from eight GPS sites were compared with IWV derived from nearby radiosondes (RS), IWV data from all stations were compared to IWV derived from the hourly analysis fields of the limited-area model “Lokal Modell” (LM) of the DWD. The examination of the monitoring results led to identify some problems of the GPS data which were afterwards solved. For example, it was found out that erroneously higher IWV values from some GPS stations were due to an incorrect antenna phase centre model.

The results from the comparison GPS versus RS IWV are summarized below:

- the systematic difference GPS minus RS (bias) is site and time dependent, but in general GPS data have a wet bias, in the order of 1 kg/m^2; the bias is particularly high around noon in summer periods;
- GPS and RS describe a quite different daily cycle of IWV in summer: the former observes an increase of humidity from night to day, in the order of 1 kg/m^2, the latter a decrease;
- an upper limit estimate of the RMS error of GPS IWV is 2 kg/m^2
- the relative error (stdv/mean) is higher in winter (approx. 9%) than in summer (approx. 5%)
- there is slight decrease of the standard deviation error from 2000 to 2002, likely due to the improvements introduced during the GASP period in the GFZ processing software.

The results from the comparison GPS versus LM IWV are similar to that from the comparison versus RS. This is not surprising since the LM analysis fields are obtained using radiosonde data. But since with LM is possible to monitor all GPS sites, some additional results were found:

- the RMS difference GPS versus LM IWV varies from 1 to 3 kg/m^2;
- there is no relevant difference in the results for the sites provided with meteorological sensors (GFZ/DWD) and those without sensors (SAPOS) sites;
- the RMS GPS - LM is slightly smaller for sites below 200 m than for those above;

- the IWV daily cycle of GPS tends to agree better with that of LM at coastal sites than at sites located near the Alps; this might be related to difficulties of LM with orography.

In summary, the validation activity at DWD has demonstrated a general good quality of GPS data processed at GFZ, with an estimated IWV RMS error in the order of 1–2 kg/m^2, which is satisfactory for assimilation purposes. An interesting finding of the more than three year monitoring is that the sequences of hourly GPS data reveal a diurnal cycle of humidity not correctly captured by the model and the radiosonde observations.

Data assimilation

Once the quality of the GPS data has been assessed, the experiences and capacities of DWD were used to estimate the impact those data would have on the numerical weather prediction of regional atmospheric models.

The experimental assimilation of the integrated water vapour (IWV) data into the limited-area model “Lokal Modell” (LM) of the DWD has been investigated and several numerical experiments have been performed to test and tune the use of IWV for the LM (see Section 6.2.2.). The experiment verification has shown that the impact of GPS IWV data is mostly concentrated in the very short range of the forecast (up to 24 hours). This is not surprising since the IWV nudging changes the humidity of the model and only indirectly temperature and wind, i.e. the model dynamic. It has been observed that in case of not so accurate forecast of rain patterns, the nudging of GPS data contributes to give a better picture of the event. However, if the model has completely missed an event, the IWV data alone are not sufficient to correct this. The positive impact on the precipitation found during the August 2002 experiment is very promising. The improved performance of the IWV nudging in respect to an experiment of one year before could be related to the different meteorological situations but also to improvements in the quality of the GPS data processed at GFZ, on the enhanced network of more than 100 stations, and on the reduced radius of significant influence assigned to IWV ($\approx$50 km instead $\approx$60 km in August 2001). The daytime-dependent bias correction was found to produce little differences but in the good direction. In order to see if with the latest GPS data the negative impact in the case of a low level inversion is reduced, it would be interesting to run a new experiment in winter.

It can be concluded that the evaluation and assimilation of GPS IWV data have been completed successfully. However, the impact of GPS data, especially in winter, has to be improved before starting to use them operationally. The crucial question is how to solve the problem of the vertical distribution of the integrated value of humidity. Ongoing work at DWD is aimed to investigate the usage of three-dimensional cloud cover analysis derived from satellites. The assimilation experiments give some hints for a future operational distribution of the GPS-stations. A distance of 50 km is sufficient for LM, given the current resolution of 7 km. However for assimilation purposes a homogeneuos distribution of GPS stations is more important than a regionally dense distribution.

7.2.6 France

Philippe Hereil

The GPS permanent network

France has 61 GPS stations distributed in 2 overlapping permanent networks:

- the RGP network (see Figure 7.7), operated by IGN (National Geography Institute), is established to build a national reference frame for topography and general geodetic purposes (see `http://lareg.ensg.ign.fr/RGP/index.html`). It consists of 46 stations, reasonably well spread over the country. Of these stations 16 belong to IGN while other stations belong to various institutes and universities. In total 10 sites contribute to the EUREF (European Reference Frame) permanent network while 2 of these are also part of IGS.
- The French part of the REGAL network (see Figure 7.8), mostly operated by research laboratories, including 31 stations (in 2004) concentrated in the southeastern part of France (see `http://kreiz.unice.fr/regal`), designed for direct measurement of the active deformation of the Alps (16 of these stations are included in the RGP).

Furthermore, 10 of the 61 sites, concentrated in the southeastern part of France, have contributed to the MAGIC European project, designed to improve weather predictions and climate models in the Western Mediterranean area by deriving measurement of atmospheric humidity from GPS data (see `http://www.acri.fr/magic`).

Network products

- **RGP**
  In total 34 stations deliver observations with a sampling rate of 1 s, archived in files including 1 hour periods of acquired data. Standard data files contain 1 hour or 24 hour of data in RINEX format with 1 s or 30 s sampling rate (see Figure 7.7). Observations of the other stations are done with a 30 s sampling rate with 24 hour collection periods. Data from 46 stations are acquired via dedicated lines to the IGN centre and processed with the Bernese (4.2) package on a weekly basis (use of IGS accurate orbits) to produce SINEX solutions. Two solutions are provided: one for the entire RGP network, another for the EUREF network for which IGN is a processing centre. This product and the GPS observations are available free of charge on the IGN web site (`http://lareg.ensg.ign.fr/RGP/index.html`).

  Facing the increasing interest of customers for near real time products, IGN processes the 1-hour time step stations, using preliminary IGS ultra-rapid orbits in the Bernese software. Given the interest of the meteorological community for ZTD, this parameter is also calculated and made available to the COST-716 community in near real time conditions.

  ACRI-ST also participates in the near real time ZTD production of the French RGP stations running on an hourly basis. Data are processed with the GAMIT software, using IGS ultra-rapid orbits and a 9-hour moving window with a one-hour forward step. ZTD is taken from the last hour of the window. This allows the comparison with the ZTD processed at common stations by IGN with the Bernese package.

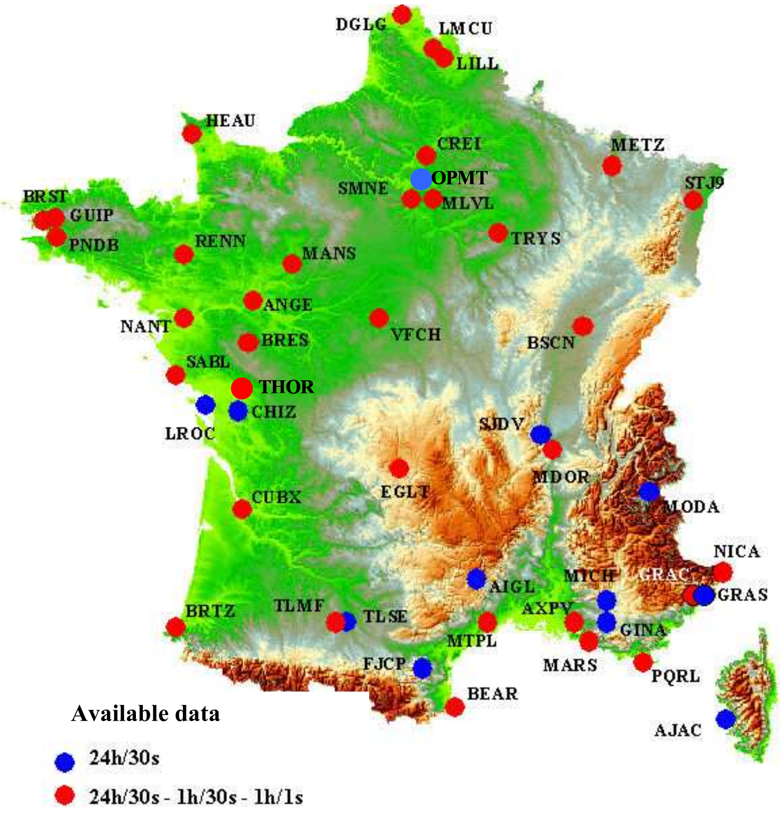


Figure 7.7: RGP network and available data in Mars 2004 (courtesy of IGN).

- **REGAL**
  Observations are delivered to the closest GPS centre via a modem transmission. Data is then transmitted to the storage centre via Internet, converted to the RINEX format and submitted to a quality control. Standard files contain 24 h of data with a 30-s sampling rate and are accessible to registered users. IGS accurate orbits are used to process weekly estimates and time series of the stations positions (use of GAMIT and Bernese softwares).

- **MAGIC**
  Three European centres process observations. ZTD is calculated with a 15-min time step, and two ZTD products are currently accessible to authorized users:
  - with use of IGS accurate orbits, post-processed ZTD is available after 2 weeks for all the REGAL stations;
  - with use of IGS ultra rapid orbits, near real time ZTD is available within 2 hours after the last observation for a few MAGIC stations located out of France.

Meteorological applications

- Mesoscale forecasting
  Mesoscale modelling is an intense domain of research at Météo-France. A project (AROME) is

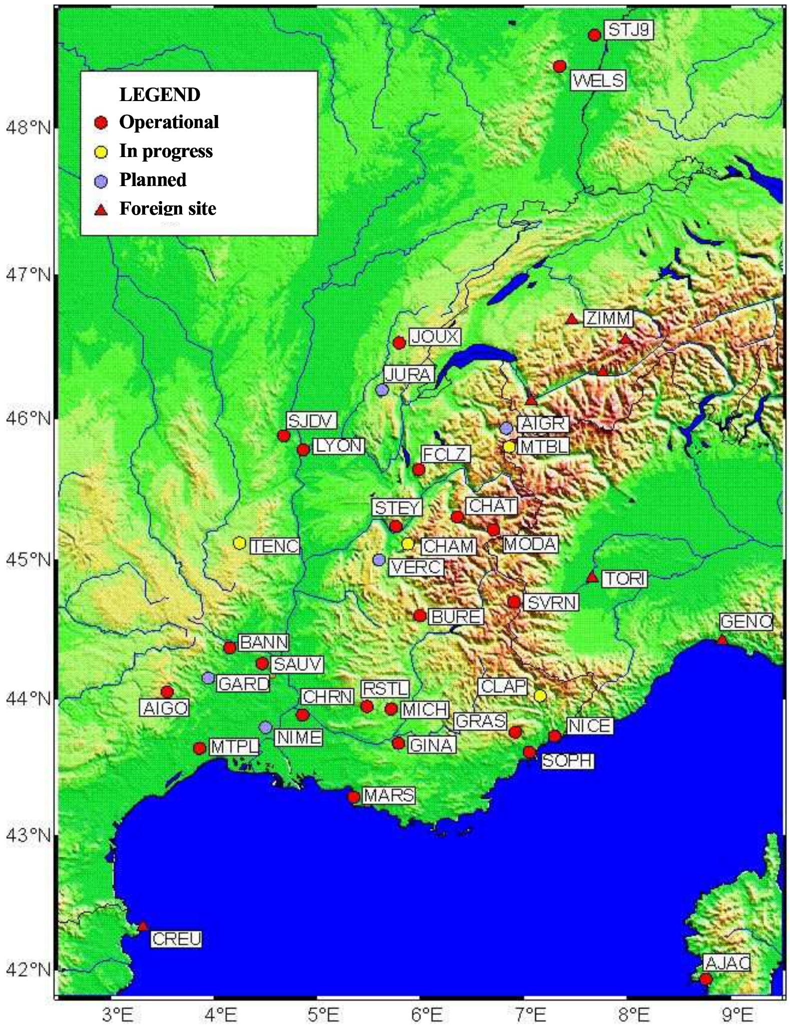


Figure 7.8: REGAL network in Mars 2004 (from A. Walpersdorf).

under study at Centre National de Recherches Météorologiques (CNRM) to develop in the decade an operational system of assimilation and forecasting at the meso-γ scale (typically 2–3 km resolution), covering a large part of France. Conclusions of preliminary sensitivity studies carried out at CNRM have reinforced the need of accurate descriptions of humidity field and boundary layer for realistic analysis and forecast of convective situations. In the forthcoming years, CNRM plans to investigate how new observation sources, including GPS, could contribute to a better description of humidity fields at the meso-γ scale.

In 2003, CNRM started on this last aspect through participation to the OHMCV (Observatoire Hydrométéorologique Méditerranéen Cévennes Vivarais) project implicating the meteorological and hydrological communities. The aim of this project is to study the meteorological and hydrological processes associated with episodes of intense precipitation and flash floods in the Mediterranean area. The strategy consists of:

- collecting a large amount of hydrometeorological data for a period running at least until 2010 in a limited area submitted to intense precipitation episodes in the southeast of France.

  - developing and improving both meteorological and hydrological models. The ability of the atmospheric model to assimilate new observation sources will be thoroughly investigated.

  Concerning the last item and its relationship to GPS data, CNRM plans to start on first tests in 2004 with the 3D-Var Aladin analysis and the Meso-NH non-hydrostatic mesoscale model, with two main goals:

  - to assess the ability of the system to assimilate GPS data ;
  - to evaluate the impact of GPS data, in conjunction with other observations such as radar data, on the initial conditions and forecast of the model for typical episodes of intense precipitation. In particular, an improvement is expected of the upstream humidity flow with the GPS data.

- Climatology:
  Météo-France climatological centre is interested in the integrated water vapour data calculated from GPS measurements. In complement to other measurements, these data, presenting a good temporal continuity, may be useful to study eventual modifications of the general circulation related to the climate change, and in particular concerning the trajectories of large cyclonic systems.

Plans for possible collaborations

To expand the RGP, IGN is looking for durable sites with power supply and Internet access to install new GPS stations with 1 hr / 1 s collection / processing of data. Most of Météo-France stations with staff offer an interesting environment for installing such receivers. Inversely, ZTD data, with their high temporal resolution, have a potential interest for Météo-France applications (see above). Collaboration has been engaged in 2003 between the two organisms. Two GPS receivers were installed in 2002 on the Météo-France sites Toulouse and Brest. The installation of another receiver in Strasbourg is currently studied by IGN.

Following the agreement terms, Météo-France offers power supply, eventual Internet access and hosting of receivers. IGN freely provides to Météo-France hourly ZTD in the RINEX format, processed in near real time (within 2-hour time lag) for most of the sites of the RGP network. ZTD data processed by IGN are now available for the COST-716 participants.

7.2.7 Czech Republic

Jan Douša

The GPS permanent array

Status until 2004 (the COST-716 period): Concerning the operational permanent GPS sites, the situation in Czech Republic was rather specific among the COST-716 participating countries and it quite well represents the other Eastern European countries. The characteristic is a very sparse permanent GPS network as concerns the commercial or non-commercial sectors. The reasons and the outlook could be characterized as follows.

- The still relatively high costs of the GPS instrumentation and stable on-line access. Some other practical limitations consist of the lack of secure locations for the permanent sites.

- The missing wide user community capable/willing to pay for any GPS real-time service in most of the country. The reason is also in the conservativeness of the user community. It significantly slows down any investments in the establishment and maintenance of the dense permanent GPS array (still expensive service with a long-time recoverability).
- Missing a powerful private surveying sector able to provide the investments into the permanent GPS array, or supporting the example for motivation in wide spectrum of potential users.
- The delay in setting up a permanent GPS array still gives a good chance to establish a multipurpose GPS network from its beginning in a very efficient way, possibly as a joint venture of several subjects. However, the problems can be expected due to a different readiness of the potential partners and their ability to share the finances, maintenance, responsibility, know-how, etc.

Only two on-line permanent GPS stations are actually operated by non-commercial institutes in Czech Republic. Both sites (GOPE, TUBO) were set up as EUREF stations, thus according to the EUREF/IGS standards for precise applications. Daily and hourly data are freely distributed through the EUREF/IGS services. At both sites the meteorological data are collected and distributed in meteo RINEX format, also on an hourly basis.

Two other permanent GPS stations were installed in September 2001 by the Institute of Rock Structure and Mechanics of Academy of Science of the Czech Republic in the Sudeten mountains for the primary aim of the geodynamical research. Unfortunately, the stations are still without internet access, which will be solved via a GPRS service in the future. The installation was supported by the CEDR project (Centre of Earth Dynamics Research - LN00700A, funded by the Ministry of Education, Youth and Sports of the Czech Republic) as a joint venture of five research and academic institutions coordinated by the Research Institute of Geodesy, Topography and Cartography (RIGTC).

Only four permanent GPS stations, located in the region of Central Bohemia have been run by the consortium of private companies “byS@t” since the autumn of 2001 and the data are charged to the users. The intention of the consortium is to make a stepwise country-wide extension of the permanent network but due to a lack of capital the realization schedule is unclear.

Status change in 2004: Although the above statements have not changed much, the overall situation has dramatically changed in 2004, thanks to the Czech Offices for Surveying, Mapping and Cadastre (COSMC). Besides the existing two operational GPS sites, it presents a plan of setting up 22 other permanent stations consistently distributed in the country. The project called “CZEPOS” was adopted and launched for the realization within the upcoming 3 years (2004–2006). The project is funded from the national government and primarily aimed for the surveying purposes (including an RTK system) and for the reference frame maintenance in future. Most aspects of the multi-purpose service should be enabled, though the current design is based on the COSMC infrastructure.

Fortunately, during the same period, additional 6–8 sites should be established within various special co-operated projects at universities, meteorological synoptic points, geodynamic points and others. The collaboration between the COSMC, academic institutes, research institutes and the Czech Hydro-Meteorological Institute is thus expected and tentatively negotiated.

The RIGTC/GOP is actually participating in the station and data flow design (especially for non-COSMC stations) and negotiating the collaborations for these sites, taking potentially responsibility of the data distribution through the GOP data centre, preparing the analyses, etc.

Before the end of 2006, the GPS active network should consist of about 30 stations in the Czech Republic with mean distance of approximately 80 km. Most of the data should be available for the GPS meteorology too at least during development and scientific exploitation.

Analysis and data distribution capability

The Geodetic Observatory Pecny analysis centre (GOP AC) operating in the collaboration between RIGTC and the Dept. of Advanced Geodesy of the Czech Technical University in Prague has already a long-term experience with the processing GPS data on a routine basis.

Primarily, the GOP AC was established as the local analysis centre of the EUREF Permanent GPS network and since 1997 it has been processing the European subnetwork of GPS sites for precise geodetic reference frame realization and densification. After the EUREF special project “Troposphere Parameter Estimation” was initiated in 2001, the precise estimation of troposphere has been included in the GOP EUREF post-processing scheme.

Since 1999, a near real-time analysis system has been developed in the GOP AC for the precise troposphere monitoring and for precise ultra-rapid orbit determination. From 2001, the tropospheric results have been provided within the COST-716 NRT demonstration campaign and they have already met the meteorological application requirements. Besides the two operating national sites, GOP has processed the EUREF sites from other Eastern European countries, and additionally, the GPS data from the Met Office (UK) and from the Netherlands within the campaign. GOP is also one of the partners in the TOUGH project, where it is primarily responsible for the GPS analyses of the sites from the central and Eastern Europe.

Finally, GOP operates as the data centre focused on the near real-time hourly GPS data flow. The centre contains not only freely available data from EUREF/IGS sites, but also, in its hidden non-anonymous subsystem, the non-free data from UK and the Netherlands networks. Besides, the GOP data centre collects and updates many other products and information generally useful for the NRT analyses, such as the precise orbits, ERPs, coordinates, site information, actual status of GPS system, etc.

Meteorological applications

The Czech Hydrometeorological Institute (CHMI) is responsible for the numerical weather modelling in Czech Republic. It applies to the densification of the global ALADIN model originated from the Meteo France. Nevertheless, due to the finance and man-power limits, there is not any project to study GPS data exploitation for the meteorological or climatological purposes as of 2004.

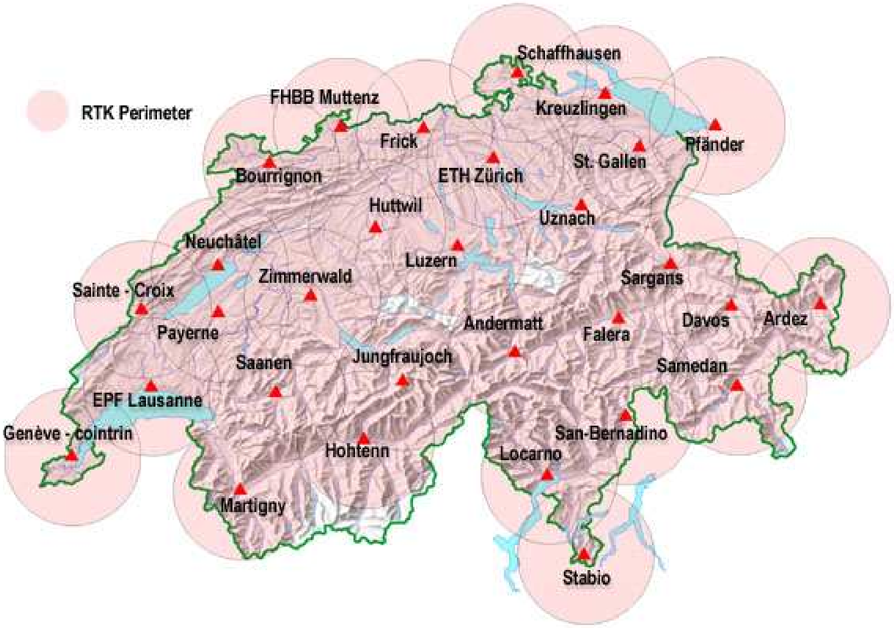


Figure 7.9: The Swisstopo AGNES (Automatic GPS Network Switzerland) network.

7.2.8 Switzerland

Dominique Ruffieux

The Swiss GPS network

The Federal Office of Topography (Swisstopo), in Bern, is responsible for GPS data processing and extraction of ZTD from AGNES, the Swiss GPS network (Figure 7.9).

This network of 30 stations is currently operational. Data are processed by Swisstopo and ZTD are extracted and transmitted to the users (for meteorological applications, currently the Institute of Applied Physics at the University of Bern (IAP) and the COST-716 community via its database). The ZTD values are used by the IAP in order to estimate IWV hourly values. These values are then transferred to MeteoSwiss to make various analyses in relation with the Swiss NWP Alpine Local Model (aLMo). Note that communication to all AGNES sites is performed using a dedicated federal communication network which is under the responsibility of the Federal Office of Telecommunication. Figure 7.10 illustrates the data flow as designed for the project phase.

The first main user of such GPS data is the IAP, involved in measurements of IWV with water vapour radiometers and sun photometers. This institute is very interested of using GPS information for comparison and validation purpose, as well as a complementary measurement technique. MeteoSwiss is also interested of using the GPS information, mainly for two types of purposes: comparison with the operational radiosounding performed at the aerological station of Payerne (see Figure 7.11), and comparison/validation/assimilation of ZTD and IWV data into the Swiss NWP model aLMo. A PHD thesis is currently performed at the IAP on this topic.

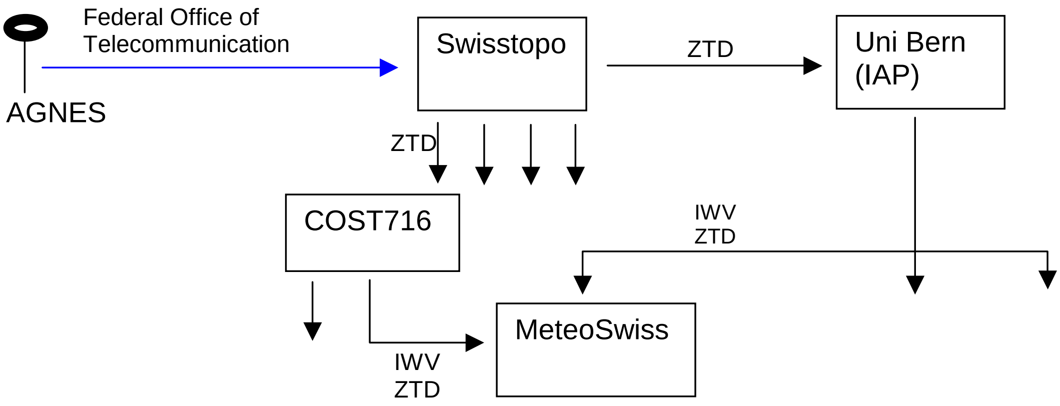
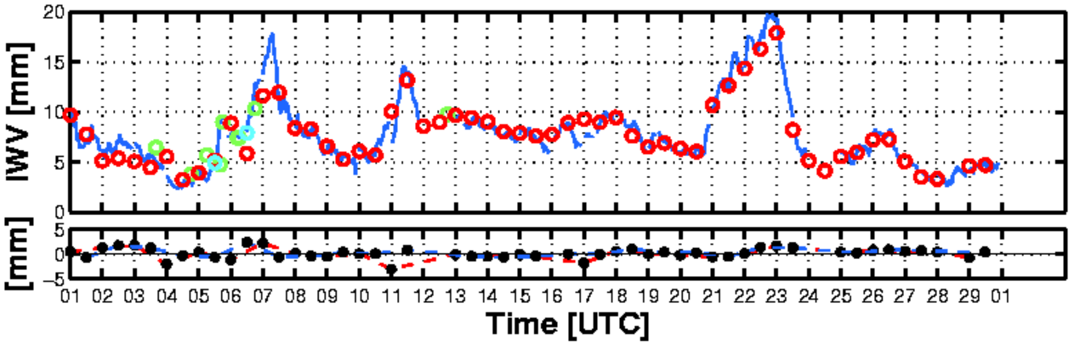
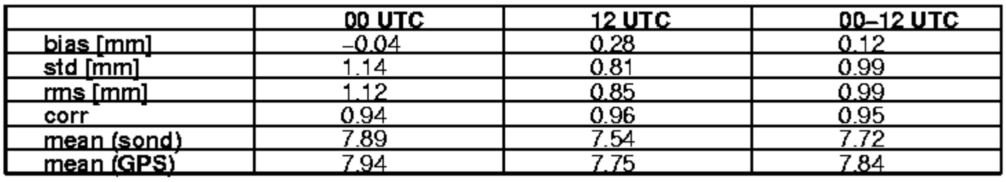


Figure 7.10: GPS data flow in Switzerland, project phase (within COST 716 time frame).





	00 UTC	12 UTC	00–12 UTC
bias [mm]	−0.04	0.28	0.12
std [mm]	1.14	0.81	0.99
rms [mm]	1.12	0.85	0.99
corr	0.94	0.96	0.95
mean (sond)	7.89	7.54	7.72
mean (GPS)	7.94	7.75	7.84

Figure 7.11: Operational comparison of IWV from GPS and radiosoundings, example with monthly statistics. Upper graph, the blue curve represents the GPS data, the red dots, the values estimated from the sounding at 00 and 12 UTC, the green dots, the values estimated from the other soundings and the cyan dots, the values estimated from the SnowWhite high quality humidity sensor. Lower graph, the difference between the sounding and the GPS data recorded at 00 UTC (blue line) and 12 UTC (red line). The table shows an overview of statistics based on 26 days of Feb. 2004 for the 00 and 12 UTC.

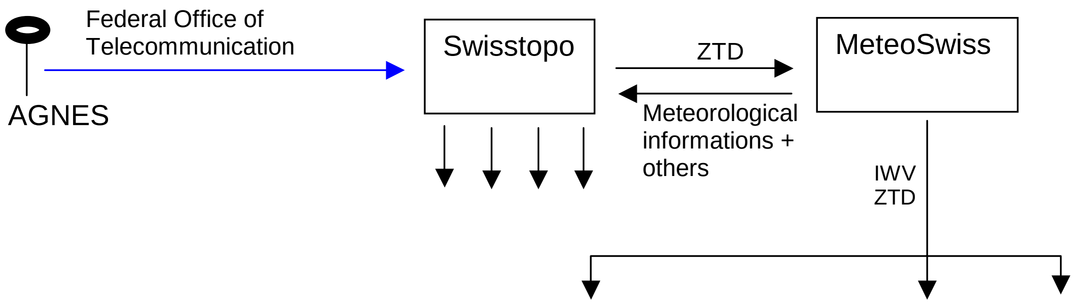


Figure 7.12: Proposal for the GPS data flow in Switzerland (meteorological and climatological applications), operational phase.

Table 7.1: Draft proposal for a data exchange between Swisstopo and MeteoSwiss.

Mode	Swisstopo	MeteoSwiss
Quasi-realtime	Hourly ZTD from AGNES	
Quasi-realtime		Hourly temperature
Quasi-realtime		Hourly humidity
Quasi-realtime		Hourly pressure
		Hourly aLMo ZTD
Continuous		Access to stations
According to Meteo-Swiss rules		First maintenance

Future organization for data exchange in Switzerland

The project period, which is running in parallel with the COST-716 activities, is preparing the operational phase (2004–). This operational phase will be formally conducted, based on an agreement between the two offices. Swisstopo will remain owner of AGNES and will provide customers with GPS informations like ZTD in quasi-real time. MeteoSwiss is currently working on a contract with Swisstopo based on an equilibrium in costs for both partners. Swisstopo is interested to get meteorological informations from the MeteoSwiss network as well as free access to MeteoSwiss sites for the setup of GPS stations (10 GPS stations are on or near a MeteoSwiss site at the present time). Some aspects of the maintenance of these stations may also be under the responsibility of MeteoSwiss; another product may be part of the contract with Swisstopo: the calculated ZTD from the aLMo outputs. Table 7.1 resumes the type of agreement planned between Swisstopo and MeteoSwiss.

This view is a preliminary draft on how things may appear in the near future between the geodetic community (Swisstopo) and the meteorological and climatological community (MeteoSwiss). Further discussions still need to be performed in order to formalise this agreement. Figure 7.12 illustrates what could be the operational organization within Switzerland.

7.2.9 Finland

A. Lange, M. Poutanen

The permanent network (FinnRef) of dual-frequency GPS receivers is operated by the Finnish Geodetic Institute (FGI). It consists of 13 stations that are situated in remote rural areas and the data transfer is quite expensive due to the modem lines used. The Bernese GPS Software is primarily used for geodetic processing but the integrated water vapour (IWV) values are computed from the Zenith Total Delays (ZTD) processed by Chalmers in Onsala, Sweden. A SuomiNet station of geodetic standards is hosted by the Helsinki University and the Helsinki University of Technology and the raw GPS data is available in real-time through the LDM service of UCAR, Boulder, Colorado. Small-scale GPS-networks are being established for virtual Real-Time Kinematic (RTK) land surveying by enterprises and local authorities.

The Finnish Meteorological Institute (FMI) works on the forward modelling of GPS slant-paths in connection with a TOUGH work package of FP5 (see also Lange, 2001). For the GPS processing, the GAMIT software of the Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, is considered to be used in combination with the HIRLAM data-assimilation.

7.2.10 Italy

Francesco Vespe

The Italian GPS network

Permanent networks of GPS receivers are presently established in many countries. They are primarily devoted to measure the motion of the Earths tectonic plate, to study deformations associated with earthquakes and volcanoes, to monitor the post-glacial rebound and the global sea-level changes. Beside these applications they can provide, if properly equipped with surface meteorological sensors, continuous and well distributed measurements of Integrated Precipitable Water Vapour (IPWV) which are of great interest for numerical weather prediction and climate research. The Italian Space Agency (ASI) manages a GPS network of 28 stations and further densification is in progress. The equipment generally consists of a Trimble 4000SSI or a Trimble 4700 receiver with a choke ring antenna. The growing of GPS real-time and near-real-time applications requires that the tracking network be switched from a daily to an hourly or sub-hourly data retrieval. Presently 20 Italian stations provide hourly data with a nominal latency ranging from 3 to of 10 minutes, the GPS receiver located in Matera provides high rate data as well. GPS raw data collected at the remote stations are sent to Matera/Centro di Geodesia Spaziale (CGS) through INTERNET or ISDN line, are converted into RINEX format and are transferred to ASI web and FTP site GeoDAF (`http://geodaf.mt.asi.it`). As far as the GPS atmospheric application is concerned, GPS zenith total delay (ZTD) are routinely produced in post-processing mode and monitored for a network of 51 stations covering the Central Mediterranean area Pacione et al. (2001). Over Italy the network has an higher denser resolution since all the available Italian GPS permanent stations are included in the routine processing. This activity started in January 1999 in the framework of the MAGIC project. The validation of the GPS post-processed ZTD has been performed. Throughout the whole year 1999, a high correlation is found when comparing GPS and Very Long Baseline Interferometry zenith tropospheric delay estimates relevant to the three Italian collocated stations Matera, Medicina, and Noto Pacione et al. (2002). Furthermore, the validation of the GPS-derived zenith total delay has been performed according to independent techniques such as ground-based microwave radiometer (WVR) and RAdiosonde OBservation (RAOB). The epoch campaign carried out during the whole 1999 at Cagliari Astronomical Station (Sardinia Island) allows us to compare GPS, ground-based microwave radiometer and radiosonde Integrated Precipitable Water Vapour relying on monthly, seasonal and annual bases, providing hints on of the GPS long-term stability. On an annual basis the comparison analysis on IPWV estimate between WVR and GPS has shown a standard deviation equal to 0.136 cm with a bias of -0.049 cm, while RAOB and GPS IPWV have a 0.193 cm standard deviation and a bias of -0.022 cm. More details on this campaign as well as on achieved outcomes can be found in Pacione et al. (2002). An assimilation test, as well as sensitivity experiments to verify the impact of GPS Precipitable Water on the precipitation forecast over the Mediterranean area have been performed considering the IOP7 (Oct 17–19, 1999) as a case-study. During the last stage of this event, a line of thunderstorms occurred over the North Tyrrhenian Sea and across the Italian regions, producing precipitation over the Central and Southern Italy. The resulting model using upper-air, surface and GPS Precipitable Water observations shows an improvement of the high resolution precipitation forecast over the area where the GPS receivers are located. In the middle of 2001 a near-real-time data stream, relying on IGS Ultra Rapid products, has been set-up and it is running operatively providing GPS ZTD estimates for meteorological applications. It has been developed within the European program COST Action 716 (`http://www.oso.chalmers.se/geo/cost716.html`) dedicated to the “Exploitation of Ground-based GPS for Climate and Numerical Weather Prediction Applications” (Elgered, 2001).

The GPS processing for the delivering of ZTD from a network of 41 stations, with a nominal latency of 1 hour and 45 minutes, is performed using a 24 hours sliding window and a standard network approach. The IGU orbits, retrieved twice a day 03:00 and 15:00 UTC, are kept fixed but checked and possibly satellites excluded based on the analysis of the post fit phase observation residuals. The stations coordinates are kept fixed to values provided by combining 1 month of the post-processed solutions, whose repeatability is at the centimetre level or even better. They are updated regularly (e.g. monthly) in order to take into account the tectonic movements of the area. The ZTD estimates of the last hour are derived from the 24 hours batch; they are averaged to 15 minutes sampling rate, put into COST format and sent to the U.K. Met. Office. A dynamic web page (`http://geodaf.mt.asi.it/GPSAtmo/ground.html`) is updated with the latest results. For more information of the processing strategy see Pacione & Vespe (2003).

In order to be useful for assimilation into the Numerical Weather Prediction Model the requirements of timeliness and accuracy must be reached, that is 75% of observations must arrive within 1h45’ to the met agencies and predicted GPS orbits must be used with minimum degradation of the ZTD products with respect to the post-processed ones. The performances of the system for the period June 2001–May 2003 is checked. We experience that 85% of the predicted solutions have been delivered; the statistic of the GPS hourly data availability per stations shows that 20% of them are available to the users too late to be processed in NRT mode or are lost. We notice that missing data and gaps cause problems in the analysis and instability in the ZTD estimates. To asses the accuracy of the NRT ZTD we compare post-processed versus NRT estimates for the period June 2001–May 2003. The monthly station bias ranges from -6 mm to 10 mm and the related standard deviation from 20 mm to 5 mm, this last decreasing in time due to processing tuning. Starting from February 2003 ASI is involved in the TOUGH project as a regional analysis centre for near-real time ZTD production and validation and to investigate the coordinate system bias induced into the GPS-derived ZTD.

GPS PW Assimilation Activities

The MM5 model by PSU/NCAR is run by the University of LAquila which is working in close cooperation with the Italian Space Agency in such matter. The MM5 adopt a nonhydrostatic model. In the first part of the activities it was run applying the nudging technique. Two way nested domains were applied whose dimensions are: 59x61 for the coarse domain and 67x100 for the nested one with the distance between two grid points, respectively, 27 km and 9 km. In the first experiments performed all over Middle-South Italy the GPS PW was successfully assimilated. The contribution of the IPWV estimated by GPS anyway was only slightly positive on meteorological analysis. Such not fully satisfactory evidences was in part due to Nudging technique adopted which implies a strong manipulation of IPWV by GPS to reduce them to the mixing ratio; in part to the not good distribution of the few GPS stations used for the experiments. So the Italian Space Agency funded a national follow-on project just to perform the experiment on a restricted area, where it was established a dense network of GPS stations centred at Matera station. In the meanwhile the University of LAquila moved from the Nudging technique to the 3D-Var approach just to assimilate IPWV and ZTD. The preliminary results obtained working on such regional network are very promising and will be made available very soon.

7.2.11 Spain

Antonio Rius

Spain has different networks of permanent GPS stations for different applications. For the purpose of demonstrating a prototype of NRT network for meteorological applications, a subset of stations was selected (See the maps of the Iberian Peninsula and the Canary Islands, Figure 7.13 and 7.14, respectively.). The stations are maintained and operated by the Instituto Geográfico Nacional (IGN), the Real Observatorio de la Armada (ROA), and the Institut Cartogràfic de Catalunya (ICC). ROA as well as the ICC have been the Spanish members of the MAGIC consortium responsible for the data gathering of the Iberian Peninsula. In addition the Observatorio Astrofysico de Canarias (Canary Islands) is maintaining a permanent GPS station to support their efforts in the monitoring of the atmospheric water vapour content. In addition ESA and NASA maintain receivers as part of their Space Tracking networks in Madrid, Villafranca del Catillo and Maspalomas (Figure 7.15).

Hourly data from a subnetwork of these stations is processed in NRT mode to retrieve Total Zenith Delays. These products are forwarded to other COST users in the agreed format. In addition, they are compared with the corresponding HIRLAM predictions computed by the Instituto Nacional de Meteorologia. Details of the used strategy could be found in Flores et al. (2000).

7.2.12 Netherlands

Hans van der Marel

Permanent GPS observations started in The Netherlands in 1992 with a station operated by the Delft University of Technology (TUD) at Kootwijk, which in 1994 became one of the first IGS stations. In 1997 a second IGS station was installed at Westerbork. In 1998 the TUD also started with GPS+GLONASS observations in Delft.

In 1995 the Survey Department of Rijkswaterstaat, the Cadastre and TUD, with assistance from the Netherlands Geodetic Commission, built a network of five permanently operating GPS receivers in the Netherlands (AGRS.NL). The AGRS.NL network has been operational since 1997 and is used for (height) monitoring, surveying, remote sensing, atmospheric water vapour retrieval and geodetic research. The data of the AGRS.NL is collected and processed on an hourly basis. Three of the stations are part of the EUREF permanent GPS network. In the spring of 2000 new receivers were installed at the sites of the AGRS.NL network. The AGRS.NL network was extended by TUD with two extra stations, bringing the total of sites with freely available data for science to eight. One of the receivers is located at

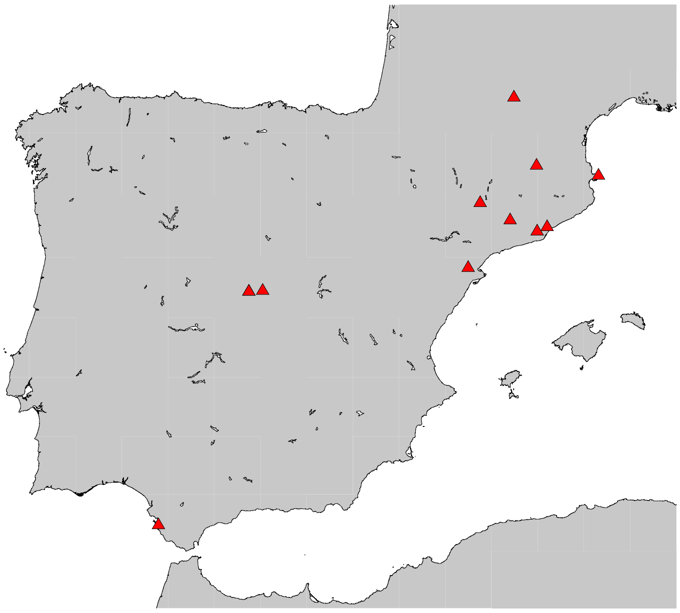


Figure 7.13: CGPS network for meteorological applications in Spain.

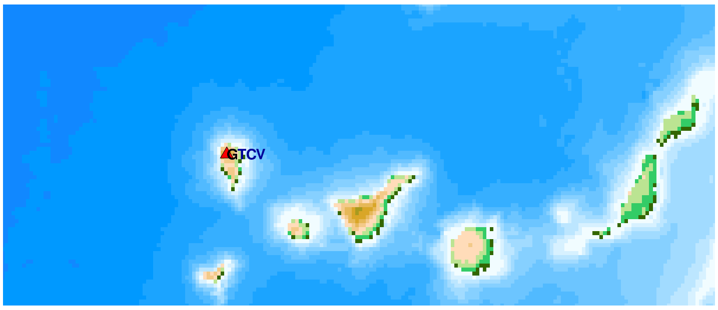


Figure 7.14: CGPS network for meteorological applications on Canary Islands.

the Cabauw Experimental Site for Atmospheric Remote Sensing (CESAR), where it is co-located with a number of other techniques to measure water vapour and related parameters. At some of the sites more than one receiver is installed.

In addition to the AGRS.NL sites several local GPS-RTK providers are active in the Netherlands. As of December 1, 2000, well over 30 permanent GPS-RTK stations are active, transmitting corrections either by radio or GSM. Of these GPS-RTK stations, fewer than 20 can make data available for post-processing today. In January 2003 also a network of 14 continuously operating reference stations was installed by a commercial provider for Virtual GPS Reference station data (06-GPS). The RINEX files of these stations are collected at a central site in real–time by the operator of the network. It should be possible to use (some of) these stations for meteorological applications, but today no formal arrangements have been made to use this data for meteorological applications.

In 1996 the TUD, the Royal Netherlands Meteorological Institute (KNMI) and the Survey Department started a project on GPS Water Vapour Meteorology in the framework of a national project. The objectives of this project were to set up an infrastructure for the acquisition, storage and processing IWV data in the Netherlands, using the AGRS.NL and some surrounding IGS stations to make an assessment

Figure 7.15: Location of the ESA and NASA GPS sites in Spain.

of the accuracy of GPS-IWV data; to investigate the usefulness of GPS-IWV data for weather forecast models and climate research; to study the feasibility of real-time processing of GPS-IWV data. The GPS data has been used during the CLARA project (Clouds and Radiation), which involved the co-location of various different techniques, including flight data, and was also used during later BBC campaigns and in the context of CESAR (Cabauw Experimental Site for Atmospheric Remote Sensing). Recently, several studies were started on the use of slant delays for meteorology. During the time period 2001–2003 KNMI and TUD worked on 3D-Var assimilation of GPS slant delays in the framework of a national project (SRON-GO2). Also, KNMI, working together with TUD, FMI and DMI, is responsible for the slant delay work package in the TOUGH project.

7.2.13 Belgium

Eric Pottiaux and René Warnant

The GPS networks

The Royal Observatory of Belgium (ROB) started to set up its ground-based GPS network in 1991. The number of stations in the network has grown year after year and has reached the number of 7 permanent sites in 1996. Four of them participate to the international GPS networks (IGS and EUREF). All GPS stations have been equipped with geodetic quality receivers and a particular attention has been paid to the quality of the sites (lowest possible horizon mask, long term stability of the site for geophysics and deformation studies). Throughout the years, the stations have undergone several technological changes leading to heterogeneity in the data that have to be taken into account when processing the observations and even more when interpreting the results. This is particularly important to take into account when targeting the necessary accuracy/stability for climate applications. All sites are now equipped with

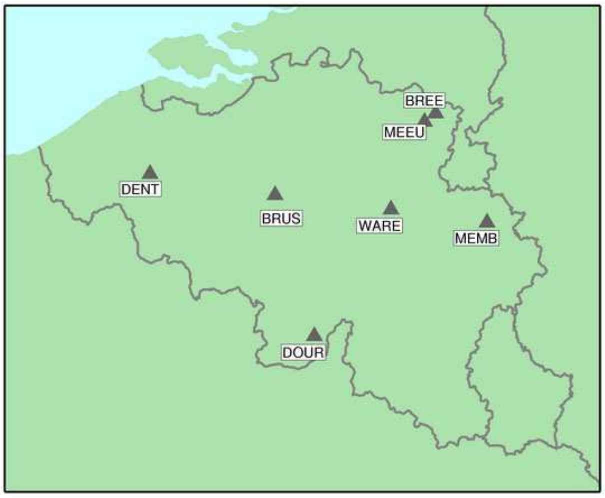


Figure 7.16: The GPS Network of the Royal Observatory of Belgium.

ASHTECH geodetic receiver/antenna, computer, Uninterruptible Power Supply (UPS), remote power control, and TCP-IP connections. The raw observations (with a sampling rate of 1 second) are sent every hour to a central data centre at the ROB through the internet where the RINEX files are created and made available (as it is requested in the IGS guidelines). In addition to the official EUREF/IGS receiver, 4 other receivers are collocated in Brussels for dedicated needs (redundancy of the official receiver, time transfer, Real time DGPS corrections to EUREF-IP, ionospheric studies). The Figure 7.16 shows the configuration of the ROB network.

In addition to the observations of the ROB network we collect data from 6 international data centres (BKGE, BKGI, IGNE, IGNI, GOP, CDDIS). Fetching the data across several data centres when necessary ensures the redundancy in case of a communication failure with one of the data centre. Together with the previous sites this forms a network of about 60 sites over Western Europe (Figure 7.17).

Finally, during the year 2003, Belgium has finalized the installation of a reference network of 60 permanent GPS stations. This network is under the responsibility of the National Geographic Institute, the Flemish and the Walloon Government. These stations play the role of reference for real-time GPS applications in Belgium (land survey, cadastre, topographic observation, navigation). The typical distance between two sites is about 25 km. The high spatial density of the network will strongly improve our capability to observe the atmospheric water vapour over Belgium (small-scale water vapour structures, slant delays, gradients, tomography) and will provide valuable information for many types of meteorological studies (nowcasting, Numerical Weather Prediction models). We are already able to process the data from this network in post-processing but we still experience some problems to access the data in near real time. The Figure 7.18 shows the configuration of this dense network.

Collocation with other instruments

The collocation of Radiosonde balloons (RAOB) and Water Vapour Radiometers (WVR) with the GPS sites is important in order to monitor the accuracy and the stability of the GPS ZTD estimates. The Royal Meteorological Institute (RMI) owns a long database of RAOB at the site of Brussels and the GPS ZTD estimates can be compared to the delay computed from the soundings (from 1991 until 2003).

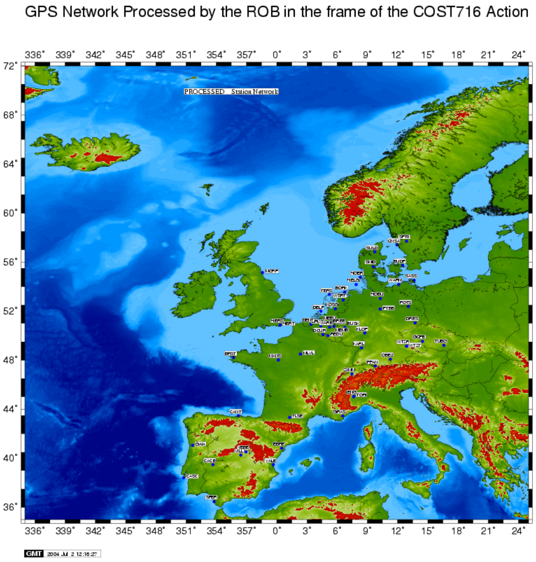


Figure 7.17: Network of GPS stations processed by the ROB in the frame of the COST716 Action.

Figure 7.18: The local network developed in Belgium for real-time positioning.

In addition, the ROB purchased a WVR and quasi continuous WVR observations are also available at Brussels since 2001. The collocation of these 3 techniques at Brussels represents a good validation tool for our ZTD solutions. Moreover, our WVR observations can now be processed and then compared to our GPS ZTD estimates in near real time.

WVRs are instruments that need to be operated carefully and that need an appropriate calibration. Therefore some of the WVR operators in Europe decided to carry out together a calibration of their instruments during the summer 2002 in Wettzell, Germany. During more than 60 days, 5 WVRs (of two different manufacturers), several GPS receivers and a VLBI antenna have been collocated. Radiosonde observations were also available at a site not far from Wettzell. The main goal of this campaign was to calibrate

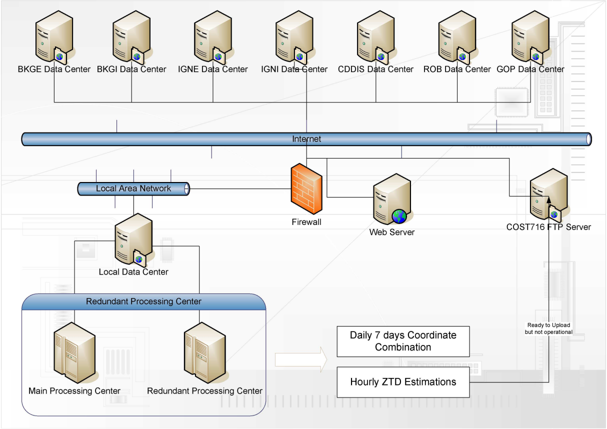


Figure 7.19: Diagram of the data and product flow at the ROB.

the WVR instruments and to investigate the results of cross-comparison between the geodetic ZTD estimates and the in-situ observation of the WVRs and RAOBs. The analysis of the data is still ongoing but preliminary results have already been presented at the EGS2003 and the conclusions will be published.

The use of the GPS network

At the present time the observations from the ROB stations and from about 50 other GPS sites collected through 7 international data centres are transferred by FTP to a local data server at ROB and used for tropospheric and ionospheric research. A redundant infrastructure of 2 Linux servers running the Bernese version 4.2 software are used in order to compute ZTD estimations avoiding this way missing data due to computer break down. The redundancy in terms of observations is ensured by cross-fetching the data from 6 international data centres in case of communication problem. The Figure 7.19 shows the data and product flow.

Our processing strategy makes use the IGS ultra rapid orbits (updated every 6 hours) and 30 s RINEX observation files. We compute a running “7-day coordinate combination” on a daily basis. These coordinates are then kept fixed in order to estimate ZTDs (every 15 minutes) for each station. Our strategy operates steadily since September 2003 but tuning of the processing system and implementation of new sites is still ongoing. The upload of the COST 716-formatted ZTD estimations on the COST 716 FTP server is ready to start since September 2003 but nevertheless it has not been implemented on an operational basis yet.

A web-based user interface has also been developed in order to monitor the entire infrastructure and in order to give a quality evaluation of our ZTD solutions. Among its capabilities it allows the user to monitor the observation and product database but above all it permits to have access to graphs and statistics of real-time comparisons between our ZTD estimates and those from all the other COST 716 Analysis Centres (AC) for each station included in our processing.

7.3 Product requirements

John Nash

7.3.1 Implication for future operational networks in Europe

The elements of the meteorological user requirements described in Chapter 3 that will influence future network design and operational procedures to the greatest extent are:

- **Horizontal spacing in network:** 10 to 100 km for nowcasting and 10 to 250 km for numerical weather prediction and climate applications.

  In meteorological networks, a spacing of 250 km is close to the current spacing between radiosonde launch sites, but the closer spacing required for nowcasting are more similar to the spacing between stations in meteorological surface observing networks. In geodesy, EUREF operations currently have spacing around 300 km, whilst national real time surveying networks tend to have spacing of around 70 km.

- **Timeliness of delivery:** 5 to 30 minutes for nowcasting, 0.5 to 2 hours for numerical weather prediction, and much longer for climate applications.

- **Accuracy/ Stability:** These requirements are interpreted as IWV targets of 0.5 kg/m^2 or better stability for climate measurements, accuracy 0.5 to 2 kg/m^2 for numerical weather prediction and accuracy around 2 kgm^{-2} for best use in nowcasting.

Thus, the shorter time of delivery for nowcasting can be traded against some decrease in the accuracy of the acceptable GPS water vapour solutions. Climate work has a target for stability which corresponds to a stability of the geodetic reference frame of the order of $1.0 \cdot 10^{-2}$ mm/yr or better. Currently, the global geodetic reference frame is far from meeting this demand. Thus, it is important to archive sufficient raw data and associated meteorological parameters to allow reprocessing in future if GPS solutions improve. In addition, sufficient GPS sensor sites should be collocated with radiosonde or microwave radiometer measurements so drifts in the GPS solutions can be identified by comparison with the measurements from these other systems.

In planning for a future operational network, the spacing of the network considered will probably influence the structure of the organization. The network density where raw GPS data are currently freely available and circulated internationally is relatively small. Raw GPS data with relatively high network spacing are normally processed nationally and are not made available freely in real time.

Experience during 2003 has shown that national meteorological services find it difficult to justify the expenditure required for a dedicated national GPS water vapour network for meteorology alone. Thus, it is essential that the future plans for GPS water vapour networks are based mainly on the use of multipurpose sensing sites and communications, with suitable collaboration between geodesy and meteorology.

7.3.2 Quality evaluation

It is suggested that quality control and evaluation should be performed in at least three steps. Responsibility for sustaining meteorological monitoring would rest with the management of future European collaborative efforts.

- Quality control of reception of GPS signals. Sites where GPS reception is very noisy or unstable should be identified by the processing centres, and the information should be fed back to the site operator. Data from these sites should have adequate quality labels warning users of the poor quality. Persistent poor quality should be listed and forwarded to the network quality centre for further action.
- Daily evaluation of availability of data and timeliness of delivery should be monitored by the network quality centre. Responsible site operators should be notified of persistent communication failures. Processing centres should be consulted if timeliness of delivery becomes poor. If a site shows large bias or random errors compared to NWP first guess forecast fields the site operator should be notified as soon as possible.
- Quarterly evaluation summaries. Trends in network performance should be summarized on a quarterly basis. First guess forecast fields of IWV over Europe have errors of between 2 and 3 kg/m^2. Thus, it is recommended that stability of network products is also checked on a quarterly basis by comparison against good quality radiosondes at a suitable number of locations across Europe.

The effort required maintaining the quality evaluation centre is likely to be between 1 and 2 staff weeks per month, depending on the scope of activities required by a future operational project.

7.4 Current state of the art and limitations

7.4.1 GPS data and error analysis

Jan Johansson

General aspects of GPS data analysis

In present-day GPS, each satellite is transmitting two pseudo-random noise codes. One code is for civilian use, and the other is normally a military code with higher chip rate allowing for a more accurate positioning. The receiver generates a copy of the code, and continuously correlates it with the code received from the satellite. The time shift of the internal code is a measure of the signal travel time from the satellite. Hence, by multiplying the speed of light with the measured time a distance to the satellite is obtained. Measuring the ranges to three satellites yields a 3D position. However, we also have to solve for a clock offset in order to match the receiver's internal clock with the satellite system time. Ranging towards four different satellites simultaneously gives an unambiguous solution.

For yet higher accuracy, the code measurement is discarded and instead the phase of the underlying carrier, with its higher frequency (compared to the previously mentioned code rates), is used. Because the wavelength of the carrier is much shorter than the wavelength (bit length) of the codes, the precision of the carrier phase measurements is much higher than the precision of the code measurements. For the satellite-based navigation systems currently available, the wavelength of the carrier is about 20 cm. As a rule of thumb, phase measurements can be made to about 1% of the wavelength. This implies a precision of 2 mm in range measurements, or time synchronization at the pico-second level. Despite this apparent superiority, real-time systems are only beginning to use carrier-phase navigation because of the well-known problem of integer-cycle ambiguity resolution. All phase ambiguity parameters need to be resolved in order to estimate, e.g., receiver coordinates and clocks.

Error sources in GPS data analysis

The accuracy of GPS (or GNSS) positioning is limited by two factors, namely the range measurement errors, and the satellite-to-user geometry. Here we give a brief overview of the main GPS error sources. Range errors arise from a combination of:

- Uncertainties in the satellite clock bias broadcast from the satellite.
- Uncertainties in the satellite ephemeris.
- For GPS the intentional degradation (dithering) enforced by the U.S. Department of Defense, called Selective Availability (SA), and is the most significant error source in many real-time applications of GPS. It is associated with the satellite ephemeris and clock. Since 2 May 2000, SA has been discontinued by the U.S. authorities. However, the possibility to again degrade the accuracy remains.
- Phase errors introduced in the receiver tracking, depending on noise on the received signal and the type of correlation hardware and software.
- Errors in the model used to correct for ionospheric propagation delay.

- Errors in the model used to correct for propagation delay caused by the neutral atmosphere.
- For time and frequency applications, errors in location, antenna delay, and antenna-cable delay have to be considered. Signal delay variations in the receiver hardware are associated with temperature variation near the equipment.
- Multipath effects due to the antenna environment.
- Undesired signal interference.
- Receiver user friendliness and human blunders. In many applications, the installation of the GPS receiver and antenna plays an important role. A bad choice of location for the GPS antenna may result in serious multipath problems and difficulties to resolve the phase ambiguity parameters as mentioned above.

Basic definition of the terms

We may divide the GPS carrier phase data analysis into three different categories, depending on the duration between the time of data collection and actual time of data processing.

Real Time (RT) processing results are available within one second or less. The main RT applications of GPS are the navigation and process control, where positions may change rapidly. RT applications will be based on very accurate predicted orbits, normally provided via the GPS satellites themselves. Any improvements to the system's accuracy must also be available in RT, e.g. differential corrections.

Near Real Time (NRT) processing results are available within a few hours. The main characteristics of NRT applications are that positions are computed sequentially and in an operational mode. If there are problems, these cannot be solved through delayed processing. Examples are the use of GPS for meteorological applications, where the final products must be available within a given delay of, e.g., 1 hour. The main difference between RT and NRT is in the used orbit parameters, which for NRT solely rely on processed data and not on predictions. For example, NRT ultra rapid orbits can computed on the basis of the IGS network in order to replace the broadcast ephemerides available in RT.

Postprocessing is defined as any processing that is not operational and allows advanced processing methods including problem detection and subsequent correction. There is no upper time boundary for postprocessing.

GPS analysis strategies

Jan Johansson, Jan Douša, Oddgeir Kristiansen

Currently, two basically different strategies are being used to estimate tropospheric parameters, namely:

(1) Regional analysis: in this analysis, all GPS sites are incorporated at a time and all tropospheric parameters are solved for simultaneously. The station coordinates are kept fixed. The standard IGS ultra-rapid orbit product can be used or satellite orbits can be relaxed in the network solution. Advantageously, the double difference solution is applied. In this analysis only a limited number of stations (of the order of 50) can be processed simultaneously. A larger volume of sites can be handled using a cluster processing, possibly combined into a unique solution on the normal equations level.

(2) Precise point positioning: for a single site, tropospheric parameters as well as station coordinates are estimated independently of other sites. In this approach the satellite orbits and clocks are determined separately as global parameters prior to the analysis of the single stations. The global parameter can be ultra rapid products available at IGS or NRT products determined specifically for the ppp analyses. The method can be used for an arbitrary number of single stations.

Available software tools for GPS data processing

Several GPS data analysis tools are available today. Many of the commercially available software packages are aimed at specific applications. However, there are also more general and non-commercial tools available. There are three main software packages used in high-precision application of GPS (GNSS), namely GIPSY/OASIS, GAMIT and the Bernese software. They are all developed at universities and research institutes. They share some common features:

- Processing of all observables recorded by the high-accuracy (carrier phase) GPS and GLONASS receivers
- Permanent network processing (hourly, daily, etc)
- Ambiguity resolution on short and long baselines
- Modelling of the propagation effects due to the ionosphere and the neutral atmosphere
- Modelling of forces associated with satellite orbit determination
- Orbit determination and earth rotation parameters
- Geophysical models for such effects as the earth tides, as well as the indirect influence of the ocean tides on the position of the receiver antenna

These three software packages are all providing both the executables and the source code to the users. Thus, the packages are basically developed, maintained and upgraded by all users giving feedback and suggestions of improvement including implementation of new models.

Even though these software packages share the same basic models, there some significant differences between them. These are related to how the observations are utilized. As mentioned above, a GPS data observation can be defined as the measurement of the distance between one satellite and one receiver, sometimes referred to as a “zero difference”. For high-precision applications, we need to remove or model as many of the error sources as possible in order to first solve phase ambiguity parameters and end up with high-accuracy estimates of e.g. station coordinates. Some software packages are based on the original code and phase observations complemented by some a priori model and assumptions. This is the basis for the GIPSY-OASIS software discussed below. Many of the most significant error sources, such as station and satellite clocks, may be eliminated (or greatly reduced) by forming differences between several satellite-to-station observations. Taking the difference between the observations from two stations to the same satellite normally is referred to as a single difference observable. If we in addition take the difference between two single differences we get a double difference where we have eliminated the station and satellite clock errors. In order to form these differences, an a priori use of the code observation is required for the initial determination of the receiver clocks. The code observations cannot be utilized further in the estimations process. Both the Bernese Software and the GAMIT (see below) are based on a double-difference approach.

Double-differences of GPS phase observations greatly reduce the effect of errors in satellite and receiver clocks and significantly reduce the atmospheric effect for short baselines where the GPS signals travel along nearly the same paths through the atmosphere. The positive correlation of the tropospheric effects is reduced if there are differences in station heights and larger station separations. We shall note the inherent geometrical weakness in the GPS baseline results which usually makes the determination of the vertical baseline component worse by a factor of 3 compared with the horizontal baseline component, if an elevation cut-off angle of 15 degrees is used. Additionally, another rule of thumb is that a residual atmospheric delay error of 1 cm causes a 3 cm error in the relative height difference between baseline stations.

Theoretically, the use of a lower cut-off angle could reduce this high correlation between atmospheric parameters and heights and thereby allow for more accurate determinations of the ZTD and the height coordinate. However, observations at elevation angles less than 15 degrees will also include problems such as less accurate mapping functions, influence of the higher order ionospheric terms, and also effects due to signal scattering and multipath related the GPS antenna and its environment.

GIPSY-OASIS

The GIPSY/OASIS software (Webb & Zumberge, 1993) was developed at the Jet Propulsion Laboratory (JPL) and the California Institute of Technology (CALTECH) in Pasadena. The software relies on the original code and phase observations (although the weighting of the phase data is more than 100 times larger). Thus the software is quite general and is also capable of processing data from other systems such as e.g. Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), and Doppler Ranging System (DORIS). The GIPSY software package deviates in some crucial aspects from most other available GPS processing packages:

- GIPSY is a “zero difference” software, not based on double differences (as long as one does not solve for integer ambiguities).
- GIPSY is based on filtering technique (Square Root Information Filter - SRIF) rather than traditional least square adjustment. The approach in GIPSY is to estimate all parameters, rather than eliminating them through differencing techniques. Normally the software is used in a network approach where observations from many stations are processed together. In such an approach it is possible to solve for parameters such as
  - Satellite orbital and clock parameters
  - Phase ambiguity parameters
  - Station coordinates and clocks
  - Station-dependent signal propagation path delay

Bernese Software

The Bernese Software is a very popular tool in processing of GNSS data for geodetic purposes. The software has been developed at the Astronomical Institute, University of Berne in Switzerland (Rothacher & Mervart, 1996). The software is capable to analyse all principal observables by high-accuracy geodetic GNSS receivers using a differenced or an undifferenced processing technique. All relevant parameters can be solved for simultaneously. The package also provides a sophisticated tool (ADDNEQ2) for efficient combination and manipulation of the analysis results on the normal equations level.

The software is available with both executable files and the source code for almost any computer platform. The software is not free of charge but the cost is generally very low for scientific use and use within an organization. It is more expensive if the software is to be used for commercial applications.

Software description GIPSY-OASIS

The modelling of the troposphere is based on a stochastic model which treats the unknown residual delay as a time-varying parameter, a random walk process. The zenith delay is modelled at every epoch as the sum of the previous zenith delay value plus the noise of purely random process called the process noise which constrains the delay changes. The mathematical adjustment is carried out using a Kalman filter (Brown & Hwang, 1992). Stochastic models are used under the assumption that the propagation path delay varies within a limited range over a short time interval. Hence the delay parameter can be estimated in a way similar to clock drift parameters.

After the computation we have precise orbit and clock information for every observation epoch. It is then possible to use this satellite orbit and clock information to compute the precise position of one individual station from phase observation data. This is the precise point position (PPP) strategy, often applied together with GIPSY. To facilitate quick and easy PPP processing for GIPSY users, daily precise satellite orbits, clock information, and earth orientation parameters are provided from JPL. Both fiducial and non-fiducial products are available. For the non-fiducial products, the transformation files to a terrestrial reference frame are also supplied. One important aspect of the PPP strategy is computation efficiency. While computation time will grow as the cube of number of stations when solving for the position of several stations simultaneously, the computation time will grow linearly with the number of stations when the PPP strategy is applied.

7.4.2 Stability of reference frame and station motion model

Hans-Peter Plag

The Earth's surface is perpetually deformed due to a variety of internal and external forces, acting on time scales from seconds to millions of years. In order to avoid contamination of the ZTDs or other tropospheric parameters by the station motion, the relevant part of the station motion needs to be accounted for both in the realization of the reference frame and the station motion model used in the analysis.

Earthquakes may lead to displacements of several meters of larger areas within a few seconds with the associated displacement field extending for several hundred kilometres. Seismic ways including free oscillations of the Earth have periods of up to 1 hour and far away from the seismic source, these waves can have amplitudes of a few cm. Earth tides lead to surface motions of up to 40 cm and somewhat smaller on semi-diurnal and diurnal time scales, respectively. Ocean tidal loading may contribute at the same periods as the Earth tides up to several centimeters in vertical displacement at coastal sites and several millimeter for the horizontal station components. Atmospheric and hydrological loading induces vertical displacements of more than 1 cm on up to seasonal time scales. Polar motion introduces motion of several millimeters at the annual and the Chandler period (the latter being approximately 14 months). Post-glacial rebound leads to secular vertical motion of up to 10 mm/yr and horizontal motion of several mm/yr. Plate tectonic motion contributes secular horizontal motion of up to 10 cm/yr while in some deformation zones at plate boundaries even larger velocities can occur.

A good means to understand the state-of-the-art in modelling station motion is the analysis of coordinate time series determined in geodetic analyses of long CGPS observations. In these time series, residual periodic signals are found to have amplitudes of up to 1–2 cm. For the seasonal period, a large part of the signal is assumed to originate from atmospheric and hydrological loading (see e.g. Blewitt & Lavallée, 2002) while the origin of several intraseasonal signals remains obscure. The seasonal signal is dominated by large spatial scales and models are emerging which will allow to remove the signal from the time series. On shorter time scales, incorrectly modelled station motion due to Earth tides, ocean tidal and other surface loading, and polar motion can contribute to periodic degradation of the site coordinates. However, presently available models for station motion are correct on the 1–2 cm level (see e.g. McCarthy, 1996).

Thus, the degradation of the accuracy of coordinates with time will primarily depend on the ability to predict the secular velocity of the point. Therefore, in this section we will not discuss these contributions and only concentrate on secular motion.

All points on the Earth's surface exhibit a secular velocity relative to the ITRF. In order to maintain the accuracy of coordinates for any given point over time without re-observations, models to predict the point motion with sufficient accuracy are necessary. Long time series of daily or weekly point coordinates derived from continuous GPS (CGPS) observations show that most sites in tectonically passive areas exhibit a linear velocity super-imposed by intraseasonal to seasonal nearly periodic signals. Here the station motion model used in the analyses has already taken into account most of the station motion due to Earth tides, polar motion and ocean tidal loading.

For most sites on Eurasia, the linear horizontal velocity is of the order of a few cm/yr while vertical velocities, particularly in the formerly glaciated regions, can be as large as 1 cm/yr. On other tectonic plates, secular horizontal velocities may reach magnitudes larger than 10 cm/yr. The presently most accurate global model of the horizontal velocities is the NUVEL-1a-NNR model (DeMets et al., 1994) which is primarily based on geomagnetic data. This model gives average estimates for horizontal velocities over the last 3 Ma. Models based on present-day geodetic observations have been presented for example by Drewes (1998) and Kreemer & Holt (2001). For some tectonic plates the present-day models show discrepancies of up to 40% with respect to the 3 Ma average velocities as represented by NUVEl-1a-NNR.

For the vertical velocities no global model taking into account most major processes exists. However, for postglacial rebound as one of the major causes in Northern Europe and Canada, geophysical models provide predictions with an accuracy on the 2–3 mm/yr level of accuracy (see e.g. Plag et al., 2002).

Since its formation, EUREF has made an attempt to realize a Eurasian Terrestrial Reference System (ETRS) which would result in minimum velocities for any point on the Eurasian plate with respect to the ETRS. The degree of success of EUREF in achieving this goal provides a good measure of how good coordinates can be maintained over time.

Originally, EUREF used the NUVEL-1A-NNR pole of rotation to describe the plate tectonic motion of the stable part of Eurasia. Altamimi & Boucher (2002) showed that in some parts of Europe the discrepancy between this model and observations was as large as 3 mm/yr resulting in an error of 3 cm per decade. Nocquet et al. (2001) studied the problem in defining a stable part of a tectonic plate on the basis of selected stations and showed that there is a significant dependency on the station selection. Based on a considerations by Plag et al. (2002) of the station motion model used in the GPS analysis, Kierulf et al. (2002) showed that using a combined model for rigid plate motions and intra-plate motion, the accuracy of the model horizontal velocity field can be close to 1 mm/yr for most of the Eurasian plate. Based on similar consideration, Nørbech & Plag (2003) were able to determine a transformation between the ITRF and different realizations of the ETRS on the same accuracy level.

Thus, it can be assumed that for the horizontal components, velocity models with an accuracy of 1–2 mm/yr seem to be achievable in many regions (particularly, the stable part of the plates). However, for presently available models and a time span of, e.g., 10 years, the model error can be as large as 3 cm and in tectonically active regions, errors larger than that appear to be likely.

For the vertical component, the situation is far more complicated. Except for the regional phenomenon of post-glacial rebound, the spatial scales in the vertical motion are much shorter than for the horizontal components (typically of the order of a few km) and large differences (several mm/yr) can be found over distances of a few tens of kilometres. In some locations, considerable non-linear vertical motion of up to several centimeters per year is caused by human activities such as ground-water and oil exploitation. Presently, no models exist to predict these motions.

The global reference frame ITRF currently is defined through a set of 3-D coordinates and secular velocities for approximately 200 sites distributed globally. Transition from one ITRF to the next not only changes the coordinates of the sites but also the velocities associated with them. Thus, the coordinates at current epoch used for a certain ITRF site change with transition from one ITRF to another. Consequently, such a change introduces a step in the ZTD time series of a given station.

7.4.3 Correlation of tropospheric parameters with other signals

In most of the NRT determination of ZTDs, the station coordinates are kept fixed at their ITRF value at the central epoch of the observation. However, keeping the station coordinates fixed at this value does not imply that the station does not move in the analysis. The station motion model normally includes Earth tides, polar motion and ocean tidal loading as known geophysical processes affecting the station coordinates. Another known cause is attributed to surface loading due to atmospheric and hydrological loading, which deforms the Earth surface and changes the station coordinates at a level of several centimetres.

Particularly the station motion due to atmospheric loading is prone to be correlated with the tropospheric delay. Therefore, not accounting properly for atmospheric loading will affect the ZTDs and other parameters estimated in the GPS analyses.

7.5 Options for an operational implementation of meteorological applications

7.5.1 Introduction

As discussed in Plag et al. (2000), any network delivering products to users can be discussed from three different points of view realizing different aspects of the network (Figure 7.20). In the next section, we discuss the different options for the physical network, which is the network of GPS sites as well as the data centres collecting the GPS observations in a specific format (most likely, the RINEX format). We then turn to the application network, which consists of the analysis centres computing tropospheric parameters and the distribution media making these products available to users from the meteorological organizations. Finally we discuss options for the institutional network with respect to ownership of the infrastructure, the application network and the products.

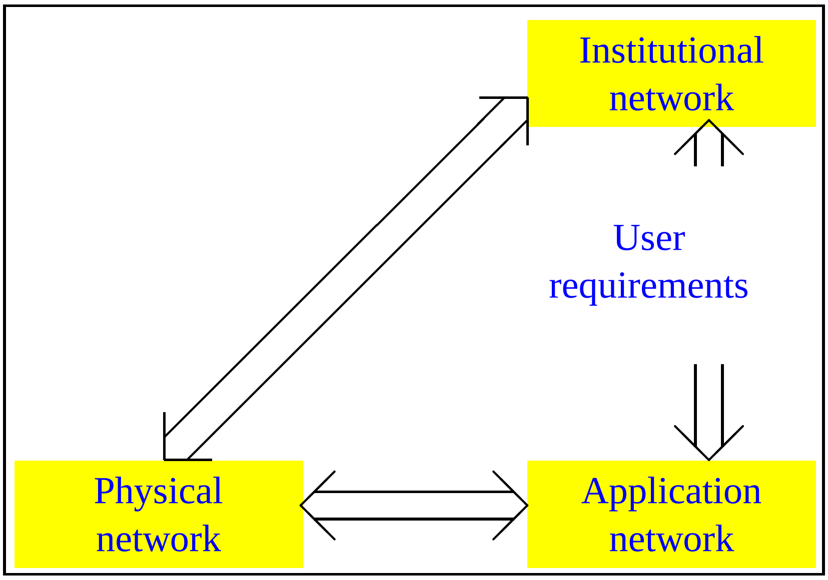


Figure 7.20: The Network Triangle. An operational monitoring network can be considered to consist of three networks covering the physical, logical and institutional aspects. Ideally, the application network meets well defined scientific and/or societal needs. The institutional network provides the necessary resources and the mandate for maintenance of the network. The physical network needs to comply with the specifications resulting from the application network (modified from Plag et al. (2000)).

7.5.2 Physical network

Jan Johansson

For the implementation of GPS networks fulfilling the requirements for use of GPS-derived troposphere parameters in operational meteorological applications (basically NWP) several general options exist.

1 **Dedicated networks:** New networks of dedicated GPS sites are established from scratch according to the specifications derived from the requirements of meteorological applications. Site specifications are set up and the spatial resolution is selected according to meteorological requirements and economical constraints. GPS data are available at the dedicated data centres according to the requirements, most likely hourly data made available in near-real time (i.e., within a few minutes).

2. **Least Cost networks:** National and regional GPS data centres of the national geodetic authorities acquire data from existing GPS networks run by these national authorities available according to the meteorological requirements.
3. **Augmented multi-purpose networks:** The existing national GPS networks are, where necessary and reasonable, augmented with new stations improving the spatial resolution for the meteorological applications. New sites are selected, where possible, to serve more than one purpose (e.g. meteorological application, reference frame issues, navigation, or real-time RTK services). The data of existing and new sites are made available through existing data centres according to the meteorological requirements or better.

7.5.3 Application network: analysis and distribution of products to meteorological users

Jan Johansson

Here it is assumed that for a considerable time to come, the products of interest for the meteorological applications will not be the raw GPS data but tropospheric parameters (i.e. ZTD or slant delays). It has to be pointed out that the analysis will require considerable skill. Currently, a few regional analysis centres in Europe are capable of providing the tropospheric estimates with sufficient accuracy and long-term stability. Taking this situation into account, we identify the following options:

- **EUREF:** Some of the EUREF analyses centres may be willing to take the task of computing tropospheric parameters from a large number of non-EUREF stations. The general EUREF scheme would ensure that the resulting products are in agreement with common standards. However, currently it is not likely that EUREF is willing to commit resource to this NRT application.
- **National Meteorological Services:** The European NMSs might decide to set up their own analyses centres using GPS observations either from the dedicated or the multipurpose network to determine the required tropospheric parameters. This would, however, require a duplication of the presently available knowledge in analyses.
- **National solutions:** In each country, specific solutions might be found either based on agreements between the geodetic authority running the GPS network and data centre and the meteorological office or just based on the meteorological office's own capability.
- **European service:** A special, dedicated service might be set up on European level comprising regional analyses centres as well as the distribution means for the resulting products. This solution would not only ensure that all relevant sites are analysed but also easily make sure that each NMS has access to all (and not only the national) products relevant for the specific NWP run by this service.

7.5.4 Ownership of infrastructure, data, and products

Current situation in the geodetic community

Hans-Peter Plag

In most of the European countries, the national geodetic organizations have established CGPS networks on various levels and for a range of different applications. These applications may include defining and maintaining the geodetic reference frame, differential GPS and RTK services, research networks providing observations of the Earth's surface kinematic, trial networks for meteorological applications, monitoring of infrastructure, co-location of tide gauges in order to determine absolute sea level changes. The latency of data depends on the different applications ranging from real time to latencies of several days while sampling intervals typically are 1 s for real time applications and 30 s for larger latencies.

The spatial resolution of the networks vary from network to network (see Section 7.2). Ownership may be residing with the national geodetic agency, research institutes, or national organizations involved in RTK, meteorology, hydrography. In some cases, the networks are owned by private enterprises.

The geodetic community has a long experience in international cooperation. Maintaining a global or regional reference frame based on space-geodetic techniques cannot be achieved on a national level. Therefore, the advent of these techniques stimulated a rapid growth in international cooperation. Most of this cooperation is based on so-called voluntary commitment. The IGS[1] is an example of a very successful service based on this principle.

Current situation in the meteorological community

John Nash

Within Europe few national meteorological services have installed GPS sensors for purely meteorological use, (see Section 7.2). Access to the water vapour data from the sites contributing to the COST 716 demonstration network is based on research agreements with the network operators in the geodetic community or memoranda of understanding with government agencies/ universities operating networks. Some of these agreements specifically exclude the use of the water vapour for meteorological operations, as opposed to research. The financial resources available for operational ground based meteorological observations are limited, so convincing evidence of the benefits of a new observing system is essential if available resources are to be diverted from other operational measurements, or new operational funding is to be made available. Insufficient evidence of the usefulness of water vapour observations has hindered the progress towards operational arrangements in several countries. For this reason it became clear that an immediate transition to operations following the completion of COST 716 was not practical.

Whilst satellite based meteorological observations have been organized on a European scale for some time, co-ordination of operational surface based observing systems on a European scale started more recently. Most of the projects involving for instance, weather radar (OPERA), wind profiler radar (WINPROF), and observations from commercial aircraft (E-AMDAR), have been organized by the EUMETNET organization. EUMETNET is a co-operation between 18 western European meteorological services. In the case of the wind profiler radars, data are supplied from a variety of organizations, including research facilities and airport operations, but no payment passes between the central organization and the participants. In some cases , national arrangements for financial support to research are made to maintain the continuity of operational data supply to the European data hub. In the case of the observations

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[1] See the web page at `http://www.jpl.nasa.gov/igs`.

from commercial aircraft, financial support is required to pay for the data transmission from the aircraft to the meteorological data network. Arrangements with the individual airlines are mostly based on national arrangements, but the European scale network manager and coordination committee also have a role. Financial resources on a European scale are distributed to support the requirements of the future European observing networks, as co-ordinated by the EUMETNET Composite Observing System Programme (EUCOS). The European co-ordination of the systems also seeks to maintain uniformity in the software used to derive the meteorological observations. Both EUMETNET wind profiler and Aircraft projects have established data monitoring hubs so that instrument experts can identify problems in the data received from the various organizations and feedback advice when remedial action to observing systems is required.

Circulation of observations between countries on a global scale is organized by WMO on the basis of co-operative agreements between member countries. Within Europe regional observing networks are specified as part of Region VI which covers a much larger area than the current EUMETNET cooperation. Countries are committed to circulate an agreed list of observations that have been freely available historically to all other members. Free circulation in real time is not necessarily the case for the output from new observing systems. For instance, some types of weather radar information are not circulated internationally, particularly if these are being provided under commercial contracts to national users. It is recommended that processed GPS water vapour measurements be treated by national meteorological services as the type of observation that is made freely available to all national and international users. It is probable that unprocessed real time GPS data will have significant commercial value in future. If this is the case, it may be unwise to expect all observations from national GPS network operators to be made freely available to a European processing centre. Thus, if GPS water vapour networks with high spatial resolution are required by meteorologists then it seems probable that national /regional processing for real time observations may be essential in addition to any centralized processing on a European scale.

The EUCOS programme identified certain observations as essential for the future observing networks in Europe necessary for regional forecasting. In the case of the current radiosonde network, the number of stations identified was about half the total currently making observations. In practice most of the remainder of the radiosonde sites continue to operate because they are required for national purposes and are nationally funded. This raises the issue as to whether the high spatial resolution water vapour network required for nowcasting and short term numerical weather prediction should be funded by national resources with a low spatial resolution network processed and supported on a European scale. This will be one of the issues to be addressed by meteorologists within the proposed EUMETNET GPS water vapour project, see Section 7.8.

Future models for ownership

The principal options for ownership or payment are

- Investment share/shared ownership
- Mutual data exchange
- Product- and/or access-based

7.6 Implementation options for climate applications

Hans-Peter Plag

The requirements for climate applications appear to be very demanding in terms of stability of the geodetic reference frame, which is implicit in the satellite orbits and clocks as well as, for some analysis strategies, and in the coordinates of key stations used to fix the reference frame. Present experience with the IGS products clearly demonstrates that the products generated with relatively low latency (up to several days for the precise orbits and clocks) do not exhibit a long-term stability in agreement with the requirements for climate applications.

However, the requirements given in Section 3.3 are not well consolidated. It appears that the climatologists somehow will make use of whatever they get, and therefore, archiving the data and hoping that future generations will be able to make use of the data seems to make sense if the costs are not high.

In applications having demanding requirements to the long-term stability (though still less than for climate applications), such as vertical land movements at tide gauges for detection of secular sea level changes, where the accuracy requirements are as low as 0.5 mm/yr, experience has shown that only a reanalysis of long data sets with a homogeneous, well-defined high-accuracy analysis startegy eventually may be capable to provide the required long-term stability.

For climate applications, this results in the requirement to build up GPS data archives that would allow reanalyses of databases covering 10 years or more. The meta information made available in addition to the GPS observations themselves needs to be comprehensive in the sense that the possible causes for inhomogeneities in the data are documented sufficiently.

National, regional and global GPS data archives are build up by a number of different organizations. On national level, in most European countries, the national mapping authorities are responsible for a national GPS network and they archive the GPS observations, though with different level of meta data. On regional level, EUREF is receiving data from a sparse set of committed stations operated normally by national authorities, and the data is archived in a publically accessible archive. Stations are committed on a voluntary basis, which introduces some temporal variation into the station distribution and also some variations in the quality of the meta information provided to the EUREF data centre. ESEAS is archiving data from GPS sites co-located with tide gauges, and it can be expected that these data will also be publically available. On global level, IGS is receiving and archiving observation from a network of currently about 300 stations. Similar to EUREF, station commitment to IGS is on a voluntary basis.

To ensure availability of GPS data for climate applications the climatological community should provide clear requirements to the geodetic community. With respect to applications requiring low spatial resolution (of the order of 500 km), the presently available infrastructure for data archiving on regional level (EUREF) appears to be promising and close to be sufficient. However, for a sufficient spatial resolution, sub-regional and national archives will have to be consulted. On national level, metadata may not be sufficient in all data archives, and efforts should be made to inform the operators of relevant networks on national level about the requirements.

7.7 Cost analysis for relevant implementation options

The costs shown in this section were based on information provided to the Working Group (WG 4) during the last year of the project. In certain areas there was general agreement about the costs involved whereas in others such as communications, there was a wide range of opinion about the magnitude of the costs involved.

The cost analysis was split as follows

- GPS site investment
- GPS site maintenance
- Communication
- Processing
- Validation and monitoring
- Archiving

7.7.1 Cost estimates

Tim Oakley, Jan Douša, Gerd Gendt, Daniel Ineichen, Elmar Brockmann, Oddgeir Kristiansen, Antonio Rius, and Jan Johansson

The tables below provide estimated costs for the purchase, installation and maintenance of a GPS site. Additional tables are provided on costs for communications and processing centres for the different member countries, as costs differ significantly nationally. The figures provided are current costs (year 2002) and are given in Euro.

GPS Site costs (per 1 site)

Equipment When installing a GPS site it is recommended that the equipment is co-located on an existing instrument site, with an enclosure/building. The figures in Table 7.2 are based on an installation on an existing site, with no special requirements for the antenna mounting and/or cable ducting/length.

Note 1 — It is recommended that GPS equipment is co-located with existing surface measurements and infra-structure. The quoted figure is to purchase the surface instruments but does not include installation, calibration and maintenance.

Maintenance The figures in Table 7.3 below are based on maintenance for a standard site, which also have a caretaker visiting the site at least once a week.

In Table 7.3, the spares estimate is based on 1 complete spare per 10 sites but this figure is dependent on network redundancy and the support agreement with the vendor.

Communication The figures given in Table 7.4 are based on the GPS system being the only user of the communication link. By co-located the equipment with other instruments requiring networking/data transfer the pro-rata costs per system can be substantial reduced.

Table 7.2: Cost estimates related to installation of GPS networks.

Equipment	Maximum Costs (EURO)
GPS (Antenna + Receiver)	20,000,–
Installation (work services)	5,000,–
PC + UPS	2,500,–
Comms. connection	500,–
(National lease line)	2000,–
Surface measurements and/or lightning protection (see note 1)	5,000,–

Table 7.3: Cost estimates related to maintenance of GPS networks.

Maintenance	Average Costs (EURO)
2 Site visits per year (1 maintenance & 1 emergency)	3,000,–
Spares (see note 2)	2,500,–
Rent costs	Variable
Local archiving (depends on requirement)	500,– to 2000,–

Processing centre costs (per 1 centre)

The costs associated with setting up and running a processing centre is very much dependent on the national costs both for manpower and equipment. Table 7.5 provides an estimate of the current equipment and staff costs for each of the main European processing centres. These figures should be used as a guideline for what it would cost to set-up and operate a processing site.

7.7.2 Comments on cost estimates

John Nash

A GPS water vapour network capable of resolving mesoscale structure in water vapour fields requires a spacing of about 50 km in the horizontal. The installation cost of such a network becomes a non-trivial investment for operational meteorology, see Table 7.2. This suggests that some form of shared investment between GPS network operators and national meteorological services may offer the most practical way of achieving the resolution required, given that further demonstrations of the usefulness of the GPS measurements offer convincing evidence of benefit to users. Maintenance, see Table 7.3, is also an area where national meteorological services may cooperate with the main national GPS network operators. It is possible that the infrastructure associated with the meteorological services surface observing networks can be used to minimize the installation costs of the GPS network operator.

Developments in communications infrastructure offer methods of reducing communication costs, but the methods used will need to be considered in more detail by follow-on projects.

Table 7.4: Cost estimates related to communication of GPS data.

Communication	Estimated Costs per year
Leased line	
UK London - Glasgow 650 km	15,000,–
Bern to Karlsruhe	20,000,-
ISDN line	
Germany	800,–
Czech Repub.	460,–
Italy	500,–
UK, hourly FTP - actuals	1,000,–
ASDL (Switzerland)	
256 kbit/s	400.–
512 kbit/s	650.–
2 Gbit/s	2’800.–
Telephone line	
Czech Repub.	410,–

Methods of minimizing the number of operational data processing centres will also need to be considered by follow on projects.

Table 7.5: Cost estimates related to geodetic data processing (in euro)

Processing Centre	GFZ (Germany)	GOPE (Czech Rep.)	IEEC (Spain)	ASI (Italy)	LPT (Switzerland)	NKG (Norway)	NKGS (Sweden)
Personnel costs (per year)	1.0 person (split btw 3 staff)	1.0 person (split btw 2–3 staff)	1.0 person	1.0 person	1.0 person (split bet. 3 staff)	0.3 person	0.5 person
Hardware (per 3–5 years)							
Processing	6000,-	4500,-	6000,-	6000,-	30000,- (2 Linux PC plus RAID)	2000,-	5000,-
Backup	6000,-	3000,-		3000,-			3000,-
Archive	30,000,- (RAID system)	estimate below (no central res.)		10,000,-			3000,-
Communications (per year)							
(1) Internal	0,- (central Internet)	0,- (academic)	0,-	0,- (ASI)	0,- (central facility)	0,-	0,-
(2) Primary		4800,- (leased line)		5000,- (fixed, no limit)	100 000,- (fixed line)		
Data archiving (per year)	n/a (central resource)	3500,- (estimate)	n/a	n/a (central resource)	n/a (central resource)	n/a (central resource)	3000,-

7.8 Recommendation for an implementation plan

After extensive discussions, particularly at the Final Workshop of COST 716, the following structure was recommended for an implementation plan. This plan would take the demonstration phase of the GPS water vapour network towards operations and would be based on a EUMETNET GPS Water Vapour Programme to represent meteorological interests collaborating with EUREF to provide the geodetic expertise. On the meteorological side one of the aims of the project would be to prepare an operational network that could be handed over to EUCOS as part of the composite observing system by about 2008.

A draft proposal for a future EUMETNET Project was prepared in February 2004 after consultations between the Chairman and Vice Chairman of COST 716 and the chairpersons of WG 2, 3 and 4. The main objectives suggested for this project were:

1. To continue the transition from research to operations of the production and exchange of total zenith delay and total water vapour from GPS networks in Europe.
2. To work with the geodetic community and the data processors in order to agree on and implement a data processing strategy for long term meteorological applications and climate research
3. To establish a hub for GPS water vapour measurements and quality monitoring facility suitable for future operations
4. To co-ordinate meteorological exploitation of national sources of GPS data by cost-effective agreements
5. To provide meteorological support for expansion of GPS observing networks
6. To identify the potential benefits of feedback of meteorological data to the GPS user community in order to improve the capability of real time surveying and precise positioning applications
7. To report on the progress of water vapour/total zenith delay data assimilation research
8. To promote the use of GPS water vapour measurements in operational meteorology by the provision of suitable teaching material and documentation

The suggested structures for such a project are found in more detail in extracts from the proposal to EUMETNET in Appendix C.

Chapter 8

Conclusions and Recommendations

8.1 Conclusions

The COST Action 716 has run for five and a half year, including a six month prolongation due to the transition of COST from the European Commission to the European Science Foundation (ESF). Fifteen countries have been active in the action and involved in one or several of the Working Groups (WGs):

1. State of the art and Project Requirement
2. Demonstration
3. Applications
4. Planning for the Operational Phase

The WGs has produced a number of accomplishments. All documents can be found on the web page of action.

- WG 1 delivered a state-of-the-art report in April 2001.
- The demonstration experiment of WG 2, in the MoU planned to be three months, developed into a three year long operational experiment. Although these data are of a varying quality there has been continuous improvements and they meet the operational requirements in terms of latency of delivered data and accuracy. It is also worth to mention that in the MoU there was an estimate of a ground-based GPS networks of some 85 sites, now, at the end of the action more than 400 sites are delivering data to the central hub at the UK Met Office.
- The action has developed a GPS data message type in the BUFR format which has been approved and agreed upon by the WMO.
- The application of nowcasting was added during the work of the action. In the MoU only NWP and climate were identified as possible applications. Nowcasting has been studied both in WG 3 and WG 4.
- Climate research has, due to the limited lengths of the available time series, focused on model validation.

- We have studied the user requirements in terms of long time stability for climate monitoring and found that there are large uncertainties in these specifications. WMO's requirements do not apply to all the different applications in the area. We recommend that these requirements are revisited and possibly modified/extended.

8.2 Recommendations

Based on the experiences obtained during COST Action 716, summarized in the conclusions above we recommend the following actions and activities for the future exploitation of ground-based GPS data in meteorology:

- A continued collaboration between geodetic and meteorological communities in order to make the best use out of already made investments in infra structure using tax payer support within the different countries.
- Along the same lines, the best return of investments in new GPS sites may be in countries where the network density is less than in neighboring countries.
- Stronger coordination of data analysis centres—the proposed EUMETNET project need support in order to make such requests. For an operational service to be able to provide a high quality and homogeneous data set there is a need for more top-down control and less "best effort" accomplishments.
- Careful archiving of RINEX data and site documentation
- Continued impact studies using the full European network in NWP
- Revisit the user requirements for climate monitoring.
- Assessment of the long term stability of GPS water vapour time series for climate monitoring

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Appendix A

List of Meetings and Workshops

A.1 List of meetings

A.2 List of workshops

Table A.1: List of meetings within COST Action 716

Date	Place	Management Committee	Working Group
1999 January 8	Brussels, Belgium	1st	–
1999 April 23	Delft, Netherlands	2nd	WG1
1999 September 28–29	Brussels, Belgium		WG1, WG2, WG3
1999 September 29		3rd	
2000 March 4	Matera, Italy		WG2
2000 July 10–12	Oslo, Norway		WG1, WG2, WG3
2000 July 13		4th	
2000 December 11–12	Sophia Antipolis, France		WG1, WG2, WG3
2000 December 12		5th	
2001 March 28	Nice, France		WG2
2001 June 25–26	Norrköping, Sweden		WG2, WG3
2001 June 26		6th	
2001 November 6	Bracknell, UK		WG3 Expert Meeting
2001 November 12–13	Bracknell, UK		WG4
2002 May 16	Offenbach, Germany		WG2, WG3, WG4
2002 May 17		7th	
2002 October 14	Bern, Switzerland		WG2, WG3, WG4
2002 October 15		8th	
2003 June 16	De Bilt, Netherlands	9th	WG3, WG4
2004 October 20–21	De Bilt, Netherlands		Expert Meeting[1]
2003 December 1–2	De Bilt, Netherlands		WG2, WG3, WG4
2003 December 3		10th	
2004 February 26–27	De Bilt, Netherlands		Expert Meeting[2]
2004 May 17–18	Delft, Netherlands		Expert Meeting[3]

[1] Planning for the Final Workshop
[2] Planning and writing the Final Report and the EUMETNET proposal
[3] Finalizing the structure of the Final Report

Table A.2: List of workshops within COST Action 716

Date	Place	Title	URL (http://)
2000 July 10–12	Oslo, Norway	The COST Open Workshop: Towards Operational GPS Meteorology	www.gdiv.statkart.no/cost716/
2002 Jan. 28–29	Potsdam, Germany	The Second Workshop of the COST Action 716: Exploitation of Ground-Based GPS for Meteorology	op.gfz-potsdam.de/D1/COST716/
2003 Dec. 1–3	De Bilt, Netherlands	The Final Workshop of COST Action 716	www.knmi.nl/samenw/cost716/final-workshop/

Appendix B

Members of Management Committee and Working Groups

B.1 Members of the Management Committee

B.2 Members of the Working Group 1

B.3 Members of the Working Group 2

B.4 Members of the Working Group 3

B.5 Members of the Working Group 4

B.6 Contributors to COST 716 sorted by affilation

Table B.1: Members of the Management Committee

Representing Country	Name	Affiliation[1]
Sweden	Mr. Gunnar ELGERED[2]	Chalmers Univ. of Technology
Norway	Mr. Hans-Peter PLAG[3]	Norwegian Mapping Authority
Austria	Mr. Peter PESEC Mr. Günter STANGL	Österreichische Akademie der Wissenschaften Österreichische Akademie der Wissenschaften
Belgium	Mr. Hamid NEBDI Mr. Ren WARNANT	Royal Meteorological Institute Royal Observatory of Belgium
Czech Republic	Mr. Jan DOUSA	Research Institute of Geodesy
Denmark	Mr. Kai BORRE Mr. Per HOEG	Dansk GPS Center, University of Aalborg Danish Meteorological Institute (DMI)
Finland	Mr. Martin VERMEER Mr. Antti A. LANGE	Helsinki University of Technology Finnish Meteorological Institute (FMI)
France	Mr. Marcel ZEPHORIS Mr. Gilles SOMMERIA Mr. Joel VAN BAELEN	Meteo-France METEO-FRANCE/CNRM 2 CNRS - CNRM/GAME
Germany	Mr. Wolfgang BENESCH Mr. Günter RAMPE Mr. Christoph REIGBER Mr. Gerd GENDT	Deutscher Wetterdienst (DWD) Deutscher Wetterdienst (DWD) GeoForschungsZentrum Potsdam (GFZ) GeoForschungsZentrum Potsdam (GFZ)
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Italy	Mr. Marco FERMI Mr. Francesco VESPE	Telespazio S.P.A. Agenzia Spaziale Italiana
Netherlands	Mr. Hans van der MAREL Ms. Sylvia J.M. BARLAG	Delft University of Technology KNMI Royal Meteorological Institute
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Sweden	Mr. Nils GUSTAFSSON	Swedish Meteorol. and Hydrological Inst.
Switzerland	Mr. Christian MÄTZLER Mr. Jean QUIBY	Universität Bern MeteoSwiss
U. K.	Mr. Alan DODSON Mr. John NASH	University of Nottingham The Met. Office
EC	Mr. Magne LYSTAD	Rapporteur TC, COST Meteorology
EC EC	Mr. Zoltan DUNKEL Mr. Pavol NEJEDLIK	Secretary, COST Meteorology (1999–2001) Secretary, COST Meteorology (2002–)

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[1] Additional coordinates are found at `http://www.oso.chalmers.se/geo/cost716.html`

[2] Chair

[3] Vice chair

Table B.2: Members of the Working Group 1: State of the Art and Product Requirement

Representing Country	Name	Affiliation
Austria	Mr. Peter PESEC[1,2]	Österreichische Akademie der Wissenschaften

[1] Chair

[2] No other official members were appointed. The national delegates in the Management Committee acted as corresponding members supplying information for the State of the Art Report from WG 1.

Table B.3: Members of the Working Group 2: Demonstration

Representing Country	Name	Affiliation
Netherlands	Mr. Hans van der MAREL[1]	Delft University of Technology
Austria	Mr. Peter PESEC	Österreichische Akademie der Wissenschaften
Belgium	Mr. Rene WARNANT	Royal Observatory of Belgium
Czech Republic	Mr. Jan DOUSA	Research Institute of Geodesy
France	Ms. Olivia LESNE	ACRI ST
France	Mr. Erik DOERFLINGER	CNRS LGTS/ISTEEM
Germany	Mr. Gerd GENDT	GeoForschungsZentrum Potsdam (GFZ)
Germany	Mr. Georg WEBER	Bundesamt für Kartographie und Geodäsie
Italy	Ms. Rosa PACIONE	Telespazio S.p.A.
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Sweden	Mr. Jan JOHANSSON	Chalmers University of Technology
Switzerland	Mr. Elmar BROCKMANN	Swiss Federal Office of Topography
UK	Mr. Jonathan JONES	The Met. Office

[1] Chair

Table B.4: Members of the Working Group 3: Applications

Representing Country	Name	Affiliation
Netherlands	Ms. Sylvia BARLAG[1]	KNMI Royal Meteorological Institute
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UK	Mr. Adrian JUPP	The Met. Office

[1] Chair
[2] Hosted by the Deutscher Wetterdienst (DWD) during the COST 716 time period

Table B.5: Members of the Working Group 4: Planning for the Operational Phase

Representing Country	Name	Affiliation
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Finland	Mr. Antti LANGE	Finnish Meteorological Institute
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Germany	Mr. Günter RAMPE	Deutscher Wetterdienst
Germany	Mr. Klaus-Jürgen SCHREIBER	Deutscher Wetterdienst
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UK	Mr. Tim OAKLEY	The Met. Office

[1] Chair
[2] Vice chair

Table B.6: Contributors to COST 716 sorted by affilation

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continued on the next page

Table B.6: Contributors to COST 716 sorted by affilation—continued

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continued on the next page

Table B.6: Contributors to COST 716 sorted by affilation—continued

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continued on the next page

Table B.6: Contributors to COST 716 sorted by affilation—continued

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Appendix C

The EUMETNET GPS Water Vapour Programme (E-GVAP)

Appendix C contains the main (selected) parts of the proposal submitted to EUMETNET by DMI, KNMI, and The Met Office (U.K.):

Version of 2004-08-16, DMI

Correction of duration inconsistencies 2004-09-07, DMI

(The layouts are different due to different typesetting softwares.)

Summary

Title of Programme	E-GVAP
Objective	Take actions to prepare the European GPS water vapour network to function operationally
Starting date	1 March 2005
Duration of programme	4 years
Cost over two years	516,000 Euros
Cost of first year	129,000 Euros
Date of proposal	July 2004

The programme will take actions to prepare and coordinate future operational processing of GPS water vapour on both European and national scales. It will facilitate the transfer of the COST 716 GPS water vapour network from research funding to operational service as far as possible in liaison with the geodetic community. Suitable standards for processing operational GPS water vapour measurements will be agreed with the geodetic GPS community.

Activities will be designed to improve meteorological collaboration with operators of national GPS sensor networks. This will include developing possibilities for reducing operational costs by sharing facilities with non-meteorological GPS applications and by providing feedback of meteorological data to improve the products of these other GPS applications.

It will also promote methods of introducing the use of GPS water vapour measurements to operational meteorologists.

The costs of the programme are expected to be 129,000 Euros per year over four years.

The support of the programme shall be investigated after the EUMETNET council has decided on it and written a resolution. Amendments to the proposal requested by the council can be taken care of through this and the call for a responsible member.

C.1 Background

C.1.1 Results of the EU COST Action 716

Total water vapour measurements

The COST Action 716 on Exploitation of Ground-Based GPS for Operational Numerical Weather Prediction and Climate Applications ran from 1998 to April 2004. As part of it a demonstration experiment on near real time (NRT) processing of total water vapour from a network of GPS receivers was set up in Western Europe. The experiment was performed as a cooperative effort between universities involved in the application of GPS sensing to either geophysics or meteorology, national/international geodetic institutions and mapping agencies, and national meteorological services within Europe. It clearly demonstrated the feasibility of delivering high quality processed GPS data for NWP in NRT.

The GPS receivers were mostly hosted at geodetic or survey sites within Europe, with a limited number collocated with meteorological observing sites. The observations were processed by up to 8 geodetic institutes interested in GPS research. Water vapour observations were forwarded to a central meteorological database with most processing centres achieving product delivery timeliness suitable for numerical weather prediction.

Over much of western Europe the GPS measurement technique has already provided continuous monitoring of total water at a spatial resolution in the horizontal better than the existing radiosonde network. The vapour pressure of water drops very rapidly with temperature, so most of the water vapour sensed is in the lower troposphere, i.e. at heights up to about 3 km in the winter and about 5 km in the summer. As the GPS technique primarily senses water vapour in the lower troposphere, the measurements can be expected to complement water vapour measurements from satellites. Satellite measurements (for example HIRS, AMSU(B), GPS radio occultations) are best able to provide the distribution in the horizontal of water vapour in the upper and middle troposphere and the GPS water network the structure in the lower troposphere.

The GPS water vapour measurements provide an independent water vapour data set that has already identified day-night variations in radiosonde humidity sensor performance. In future, operating the two systems together offers the advantage of monitoring the stability of radiosonde measurements. If a radiosonde measurement is in a relatively stable situation with little change of total water vapour with time it is likely to represent a fairly large area around the location in the lower troposphere. On the other hand if the total water vapour fields are changing rapidly with time, the radiosonde ascent can only be expected to represent a very limited area in the lower troposphere. Hence, the availability of total water vapour from GPS sensors should improve the quality and usefulness of water vapour measurements available to operational meteorologists. In some countries, interpolation of humidity fields between radiosonde sites in numerical models is based on an assumed empirical relationship between vertical structure, surface observations and surface cloud observations. GPS water vapour networks should allow these assumptions to be largely replaced with actual observations of water vapour.

At the end of COST 716 there were about 450 GPS sensing sites available for research. The distribution of available sites varied a great deal from country to country within Europe. Individual processing centres typically processed observations from 50 up to 200 sites, but none used the complete set of sites available. Total zenith delay (TZD) observations were sent from the processing centres to a central data bank maintained by the UK Met Office in NRT, with at target time chosen to suit regional NWP. The data were then validated and used for NWP impact experiments by other partners in COST 716 and by other research and development projects, such as the current European Framework 5 project TOUGH and the former EU project MAGIC. In addition KNMI provided a NRT service displaying on a web site the GPS integrated water vapour (IWV) against IWV from HIRLAM forecasts and neighbouring radiosonde measurements. A part of the COST 716 network is included in the TOUGH project, which finishes by January 2006, but important contributions are not, most noticeable the data from Germany, which amount to roughly half the total COST 716 stations.

Usefulness of observations

Accuracy assessment during COST 716 showed that most processing centres were capable of producing NRT observations of adequate quality to be useful. The higher accuracy required by climate use was a continuing challenge, but observations for this use are probably best processed with a greater time delay, avoiding errors inherent in using rapid calculations of the precise orbits of GPS satellites.

Recent observing system studies have shown that a network of water vapour measurements across Europe is likely to improve the forecasting of extreme rainfall events mostly from 6 to 24 hours ahead. Research into improving the assimilation and use of the GPS data is continuing and relies on the continued supply of GPS measurements from the European sites.

Total water vapour measurements from a dense network of surface sites (typical spacing 50 km) were shown to contain information useful for nowcasting summer convection.

In another application, the GPS water vapour measurements have been used to identify forecast errors in operational models and to verify the improvements in numerical forecasts available from the inclusion of new satellite water vapour measurements.

A BUFR format for GPS meteorological data has been made in the above pilot projects and approved by the WMO, enabling dissemination via the meteorological GTS/RMCDN network. GPS TZD data from a small subset of the COST 716 sites (where the formal agreements could be made) are being distributed on the GTS network.

Status of GPS water vapour networks

The availability of the water vapour measurements has grown much more rapidly than expected within the COST 716 demonstration. There are considerable differences in the status of the sensing systems within each country. In some case, the observations are only available for research under the current national arrangements. In other countries agreements are in place that allow the measurements to be used for meteorological operations. However, the number of countries/regional groups where a permanent arrangement for GPS water vapour observing has matured is low.

For GPS observations to be cost-effective for meteorologists, cooperative arrangements between the national meteorological services and institutions deploying the GPS surface sensors must be established.

This process started under COST 716, but it could not be completed in a satisfactory manner for most countries by the end of the action. Similarly, most of the GPS data processing centres were working using research funding and were not funded to form the backbone of a European processing system for an operational water vapour network operation.

Thus, this project is proposed to ensure that the availability of GPS water vapour measurements within Europe does not cease, but rather continues to develop following the successful start by COST 716. It will be essential to liaise with the geodetic data processing centres to establish a long term policy for processing operational GPS water vapour measurements, and to coordinate national/regional processing efforts to ensure availability of operational data from the whole of the European network.

The COST 716 action ended in April 2004 and the present proposal aims to continue and improve the networking activities started by COST 716 and to develop towards cost-effective network operations. COST 716 identified that the costs of a dedicated GPS water vapour network for meteorology at spacing in the horizontal of 100 km or better would usually be too expensive for national meteorological services. Thus, national agreements are required so that the costs of operating GPS sensing facilities (sensors + communications) can be shared between meteorology and agencies using GPS sensors for other applications. The aim is to reduce operational costs for both sets of GPS applications. The EUMETNET project must take actions to foster the necessary collaborative agreements. Both concerning a continuation of the current GPS data processing on operational terms, and to initiate/guide expansions in areas with currently poor coverage.

C.2 Programme

C.2.1 Objectives of the programme

COST 716 made substantial progress in developing a network of surface based GPS water vapour measurements suitable for operational meteorology. However, the current COST 716/TOUGH observing networks are mainly based on short-term arrangements funded to a large extent by European and national research activities and national survey institutes. In some countries, major problems have been experienced when attempts were made to plan the change from research to operational funding. The problems regard compensation both for use of GPS data not freely available for operational meteorological use as well as for the processing efforts undertaken by the geodetic community. COST 716 recommended that a follow on project to facilitate the move from research toward operational status was essential. Otherwise there is a strong risk that the network established would fall into disuse within a few years in many countries. The proposed EUMETNET project is the meteorological response to the recommendation from COST 16 with the key issue to make sure that data processing and exchange continues.

The main objectives of the programme are:

1. To continue the transition from research to operations of the production and exchange of total zenith delay and total water vapour from GPS networks in Europe.
2. To work with the geodetic community + data GPS processing centres to agree and implement a data processing strategy for long term meteorological applications and climate research.
3. To establish a data hub for GPS water vapour measurements and quality monitoring facility suitable for future operations.

4. To co-ordinate the meteorological exploitation of national sources of GPS data by cost-effective agreements.
5. To provide meteorological support for expansion of GPS observing networks.
6. To identify the potential benefits of feedback of meteorological data to the GPS user community in order to improve the capability of real time surveying and precise positioning applications.
7. To report on the progress of water vapour / total zenith delay data assimilation research.
8. To promote the use of GPS water vapour measurements in operational meteorology by the provision of suitable teaching material and documentation.

C.2.2 Programme details

It is proposed that three project teams will deal with the programme issues:

1. **Operational liaison group for GPS water vapour**
   [Managing the interaction between meteorologists and the wider GPS sensing community]
2. **Expert team on data processing and standards**
   [Dealing with quality issues associated with GPS data processing]
3. **Expert team on promoting use of the observations**
   [Including liaison with data assimilation and observing system experiments, and with other water vapour network users]

The programme management will set up the agreements with the NMS who will provide the support to enable the individual project teams to function. The programme management will provide the necessary project co-ordination and organize the half-yearly plenary meetings. The PM will work under the guidance of PB-OBS, providing progress reports on the defined work packages.

C.3 Organisation

C.3.1 Programme team

The Programme will be run by a responsible member providing a PM who will be responsible to deliver the necessary results. The overall management of the programme will be handled at meetings taking place every six months. Each NMS sends a representative to these meetings and sponsors its own delegate who is responsible for the national meteorological coordination with the operators of the national GPS sensor network.

C.3.2 Expert teams

Three expert teams who will be responsible for assigned tasks within the project will support the programme. The work of the three expert teams will be performed in parallel. Expert team meetings will be organized where deemed necessary by the programme management, given the available budget resources. It will be essential that all NMS be represented in the operational liaison group. The expert team meetings have to be financed by the programme as they will contain many members from the geodetic side, not funded for this type of work by other means.

C.3.3 Reporting

The PM will provide regular progress reports to PB-OBS, following the half yearly plenary meetings, and will include specific results from expert meetings. Data availability and quality will be summarized in quarterly reports, once the necessary monitoring mechanisms are established.

C.3.4 Risk assessment

The success of the programme will not purely depend on the resources made available by the NMS, but will be critically dependent on whether successful operational liaison can be established with the operators of the various GPS sensor networks and with the relevant data processing centres. Thus, it is essential that the operational liaison group is strongly supported and financed. with a suitable contract placed on the member responsible for organizing this activity.

C.4 Work breakdown

C.4.1 Programme management

The PM will be responsible for the management of the programme and the three expert teams. A web site plus an FTP server will facilitate communication between participants. The PM will organize the half yearly plenary meetings. The PM will provide the necessary support for the expert meetings to be held. The PM will in all case cooperate with the local organizer of the meetings.

Thus, the PM has to perform the following tasks.

- Set up working and reporting procedures
- Monitor the progress, initiate corrective actions as necessary
- Preparation of meetings, administration for the meetings, minutes, etc. (in liaison with EUMETNET CO)
- Function of a web site for publicity and project documents
- Management of the project budget
- To supervise liaison with the GPS sensing community
- To liaise with bodies like WMO, and the user community
- Delivery of the final report

C.4.2 Operational liaison group for GPS water vapour

At the moment a few NMS have agreements with national GPS operators that can be expected to continue for several years in operational mode, but many countries have not yet established a long-term agreement. Data processing centres are currently supported by research funding and up to now are not in a position to assume the permanent responsibility for processing data on a European scale, or the costs which are associated with such a service.

Thus this group should have the following tasks.

- Agree an operational processing policy for a European scale regional network using data from sensor sites where raw GPS data are freely available.
- Agree an operational processing policy for data from national GPS sites where the real time GPS data cannot be made freely available on a European scale.
- Review options for the rapid provision of satellite orbits and clock offsets for use in the real time processing centres, and implement collaboration with the relevant agencies as considered necessary.
- Identify possibilities for collaboration with other GPS meteorology programmes, such as the EUMETSAT METOP GRAS SAF.
- Identify what services meteorologists can provide to the GPS sensing community, which may mitigate the operational costs of the GPS sensing network.
- Develop policies where facilities associated with the deployment of surface GPS sensors (e.g. sensor sites, communications) can be shared between meteorologists and the GPS operators, thus reducing costs to meteorologists.
- Monitor and report on the progress in developing the GPS water vapour sensing network.
- Agree a method of identifying sensor sites unambiguously, acceptable to both geodetic and meteorological communities (which use different naming conventions).
- Provide support for the establishment of operational data processing centres, especially in areas where the network coverage is currently poor.
- Provide recommendations for design of GPS networks for regional NWP.
- Agree with EUCOS a plan for long term financial and administrative support of the GPS water vapour network.

C.4.3 Expert team on data processing and standards

Within the COST 716 experiment, various methods of data processing were being used with varying degrees of operational stability. This expert team should work to identify the necessary standards for operational and climate products. Therefore it is necessary to:

- Update user requirements for processed data, particularly in the light of ongoing data assimilation experiments, identifying errors that might be harmful to successful operations
- Develop/update the monitoring and reporting practices for feedback to GPS data processing centres and GPS stations operators as necessary.
- Report on progress in the development of near real time processing of total zenith delay
- Report on the success and errors of various data processing techniques, and recommend those methods considered sufficiently reliable to meet the accepted data requirements.
- Investigate new developments to optimize data quality for climate use.
- Support the implementation of an operational data hub and quality evaluation centres (both for raw GPS measurements and for the meteorological output). This operational monitoring will have active feedback to the various processing centres and network operators in order to sustain data quality.

C.4.4 Expert team on promoting the use of GPS water measurements

Within COST 716 the data processing centres have been disappointed by the relatively slow response of operational meteorologists in using the measurements provided. Some users require a deeper evaluation of the usefulness of the GPS water measurements before committing to significant financial support for operations. Thus, the expert team needs to take on the following responsibilities.

- Support the development of improved data displays for results from the European networks.
- Develop documentation that introduces meteorologists to GPS water vapour measurements , origin of errors, and examples of the use of observations for meteorological operations and research.
- Review progress with data assimilation techniques suited to improve the use of GPS water measurements in numerical weather prediction and the results of associated observing system experiments.
- Report on the developments of the use of real time measurements in nowcasting and real time forecast verification.
- Report on the use of GPS measurements as a component of future meteorological Integrated Observing Systems.

C.5 Financial costs per year

Based on 85,000 Euros for 1 person for a year.

Project manager per year 0.75	64k
Liaison group meetings	15k
Expert team meetings	10k
Contract to support hub/central processing	30k
Project travel	10k
Total	129k

C.6 Time table

The programme is planned to start on March 1st, 2005 and to last for 4 years. Four years is recommended to allow transfer of data processing and data collection responsibilities from COST 716 and TOUGH. It should also allow time for the development of a plan for EUCOS involvement in the long-term operations of the GPS water vapour network.

Plenary meetings at 6 month intervals.

Operational liaison group first meeting in spring 2005. And at regular intervals afterwards, possibly integrated with the plenary meetings.

Expert teams, maximum number of meetings once per year, unless PM decides otherwise.

Table C.1: Project time table

Subject	**Start**	**End**	**Y1**	**Y2**	**Y3**	**Y4**
Formation of the liaison and expert groups	00	03	🟩			
Liaison group	03	48	🟩	🟩	🟩	🟩
Expert team on data processing	03	48	🟩	🟩	🟩	🟩
Expert team on meteorological use of GPS data	03	48	🟩	🟩	🟩	🟩
Setup of hub for GPS meteorological data	00	12	🟩			
Continuous running of hub + archive	12	48		🟩	🟩	🟩
Quality measurement / reporting setup	00	12	🟩			
Quality measurement / reporting working	13	24		🟩		
Quality measurement / reporting automated, NRT	25	48			🟩	🟩
Agreement with EUREF on use/processing of EUREF data	03	12	🟩			
Agreement on processing policy for other "free" data	03	12	🟩			
Agreement on processing for national data not available internationally	03	24	🟩	🟩		
Develop policies for common facilities (meteorology + GPS)	03	48	🟩	🟩	🟩	🟩
Agree on method for identification of GPS sites	03	24	🟩	🟩		
Discussions with EUCOS on long term running of operational ground based GPS network	24	48			🟩	🟩
Support (know-how) for establishment of operational processing centres	24	48			🟩	🟩
Update user requirements	03	48	🟩	🟩	🟩	🟩
Monitor quality of different processing techniques. Identify superior methods.	03	48	🟩	🟩	🟩	🟩
Investigate processing strategy for climate use	18	48		🟩	🟩	🟩
Report on progress in real time processing	18	48		🟩	🟩	🟩
Support displays of data from European GPS network	03	48	🟩	🟩	🟩	🟩
Make introduction documentation regarding use of GPS data in meteorology	03	48	🟩	🟩	🟩	🟩
Review progress with data assimilation of GPS data in NWP	12	48		🟩	🟩	🟩
Report on progress in use of GPS data in nowcasting and real time forecast verification	12	48		🟩	🟩	🟩
Report on the use of GPS measurements as part of future Integrated Observing System	36	48				🟩
Identify meteorological data of value to GPS community	03	24	🟩	🟩		
Identify other services the meteorological community can provide the GPS community	03	24	🟩	🟩		

C.6.1 Milestones

Year 1

- Successful setup of liaison group and the two expert groups and first year reports from those.
- Successful setup of hub to receive GPS meteorological data, distribute them and archive them.
- Start of quality measurement/report facility.
- An agreement with EUREF about the use of EUREF GPS data.
- Recommendations for design of regional/national GPS networks for water vapour determination.

Year 2

- Formal arrangements with national organisations assuring delivery of GPS meteorological data to hub for a multi-year period. Either via NMS or directly with E-GVAP.
- Operation of quality measurement/report facility. Quality measured against NWP, radiosonde and other available meteorological data. Reporting quarterly.
- Workshop on the production and use of GPS data (possibly in connection with project meeting).

Year 3

- Formal arrangement with facility which can process “raw” GPS data which might become available in Europe, but are not processed already by current GPS processing centres for whatever reason.
- Functioning automated real time quality control of GPS meteorological data against GPS meteorological data from nearby GPS stations, other GPS networks with common stations, and against NWP data and other meteorological observations. Automated near real time feedback to owners of problematic stations and processing centres processing the station(s) in question. Periodic feedback to all involved parties.
- Organised support for expansion of network in regions with poor coverage, and for more GPS sites collocated with radiosonde sites, airport (AMDAR), and other meteorological sites.

Year 4

- Ongoing processing of ground based GPS data from an increasing European GPS network.
- Review of processing, utilisation, and impact of ground based GPS data at European meteorological services.
- A review/discussion of the future route for European ground based GPS observations for meteorology.

Appendix D

List of Publications

D.1 Papers and reports inspired or motivated by COST Action 716

Baker, H.C., A.H. Dodson, N.T. Penna, M. Higgins D. Offiler, Ground-based GPS water vapour estimation for meteorological forecasting, *J. of Atmospheric & Solar-Terrestrial Physics*, **63**, 1305–1314, 2001.

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D.2 Special journal issues/volumes relevant to COST Action 716

The proceedings from the first workshop in Oslo were published in a special issue of *Physics and Chemistry of the Earth, Part A: Solid Earth and Geodesy*, Vol. 26, Issues 6–8, pp. 369–652, 2001. In total 26 papers from the workshop were accepted for publication. In addition, the *“Book of Abstracts”* is available in electronic form and can be downloaded form the workshop web site: `http://www.gdiv.statkart.no/cost716/`.

The second workshop *Exploitation of Ground-Based GPS for Meteorology* was held at Geo Forschungs-Zentrum (GFZ) in Potsdam Germany in January 28–29, 2002. The results from the second workshop were published as summary papers distributed at the workshop. These are available at the workshop web page: `http://op.gfz-potsdam.de/D1/COST716`.

The workshop on GPS Meteorology in Japan during January 14–17 2003 is documented in *Proc. International Workshop on GPS Meteorology* and included many contributions from the COST 716 community. Papers are available at: `http://dbx.cr.chiba-u.jp/Gps_Met/gpsmet/index.html`. Many presentations from the workshop were extended and published in a special issue of the *Journal of the Meteorological Society of Japan* Vol. 82, No. 1B (March 2004).

At the beginning of the action also a flyer was produced in order to spread information about the collaboration between geodetic and meteorological communities in Europe. It can be downloaded form the home page of the action.