Nordic Journal of Surveying and Real Estate Research 2:2 (2005) 77-98
submitted on 20 June 2005
revised on 15 September 2005
accepted on 08 December 2005

NGOS – The Nordic Geodetic Observing System

Markku Poutanen [1], Per Knudsen [2], Mikael Lilje [3],
Torbjørn Nørbech [4], Hans-Peter Plag [5], Hans-Georg Scherneck [6]

[1] Finnish Geodetic Institute, Geodeetinrinne 2, 02430 Masala, Finland
Markku.Poutanen@fgi.fi
[2] Danish National Space Center
[3] National Land Survey of Sweden
[4] Norwegian Mapping Authority
[5] University of Nevada, USA
[6] Onsala Space Observatory, Sweden

Abstract. *The Nordic Geodetic Observing System (NGOS) integrates fundamental geodetic techniques for the long-term observation of Earth system parameters that are important in the context of change in and on our planet. The NGOS is an infrastructure for geodetic observations required for a wide range of scientific and practical applications both in the Nordic region and on global level. For the Nordic countries, a main focus will be on crustal motion, dynamics of glaciated areas and sea level.*

The new structure of the International Association of Geodesy (IAG) beyond 2000 defines projects as entities of coordinated long-term activities. At the XXIII General Assembly of the IUGG in Sapporo, Japan, July 2003, the Global Geodetic Observing System (GGOS) has been established as such a project. Eventually, GGOS will contribute to large international observation and science programs.

The Nordic Geodetic Commission established a Task Force in 2002 with the mission to prepare a document providing the definition and draft for the implementation of the NGOS. The NGOS is proposed as a system that will constitute the regional implementation of the observational network required to realise GGOS. In this paper we describe the plans and current status of the NGOS, give a review on the use of geodetic observations for scientific and non-scientific applications, and specify the requirements in terms of accuracy and spatial and temporal resolution.

Keywords: *geodetic observing system, geodetic observations, reference frames*

1. Introduction

The three pillars of geodesy according to Bruns as stated in the 19th century are geometrical geodesy (constructing the terrestrial polyhedron), astronomical geodesy (tracing the motion of the polyhedron in inertial space) and gravimetry (deriving gravity potential or height differences between the points of the polyhedron). This concept is still valid for modern geodesy, although the resolving power of the primary parameters has moved to the parts per billion level, and many more processes can be studied at this level.

The space-based technologies allow us now to determine positions in a globally coherent and highly accurate reference frame. These techniques are changing surveying and geodesy completely, not only with respect to the technology used but also with respect to the underlying principles. Key variables of the Earth system such as the movements of the tectonic plates, land movement, Earth rotation, changes in the gravity field, and sea level changes are now observable in a globally consistent reference frame. There is an increasing demand for accurate geodetic observations for many scientific and non-scientific applications. However, the accuracy level achieved reveals inconsistencies between the global reference frame and the regional and national frames established for practical use.

In the Nordic area, recently differences between the national frames have been detected that hamper a full exploitation of the new technologies and methodologies in society. At the same time, the need for common vertical and horizontal reference frames across national boundaries is emerging. Thus, on Nordic as well as on European level, considerable efforts are under way to establish common reference frames.

Over the last three decades global monitoring has emerged as a prerequisite for understanding the impact of mankind on the Earth system and for devising actions to mitigate the predicted changes. Recognising this need for global monitoring, three Global Observing Systems (G3OS) for Climate (GCOS), Terrestrial (GTOS) and Ocean (GOOS) were initiated and partly established under the United Nations Environmental Programme's (UNEP) Earth Watch activities (see http://earthwatch.unep.net).

The regional system aligns with international efforts such as the Global Observing Systems and adheres to the Integrated Global Observing Strategy (IGOS, see http://www.eohandbock.com/igosp/ and the documents available there). However, Plag (2000) pointed out that none of these observing systems includes a geodetic component or is directly connected to the extensive global geodetic observing networks established over the last decade. Thus, until very recently, the fundamental role of geodesy as the backbone for all Earth observation was not formally acknowledged in the frame of global Earth observations.

During the last two years, the establishment of the Global Earth Observation System of Systems (GEOSS, see GEO, 2005a, b) has dramatically changed the landscape of global Earth observation. IAG was actively involved in the development of the GEOSS Implementation plan, and the fundamental role of geodesy as the provider of the global reference frame and important observations of the Earth's shape, gravity field and rotation is widely acknowledged.

The new structure of the International Association of Geodesy (IAG) beyond 2000 defines projects as entities of coordinated long-term activities (Beutler et al., 2000a, 200b). At the XXIII General Assembly of the IUGG in Sapporo, Japan, July 2003, the Integrated Global Geodetic Observing System (IGGOS, see Rummel et al., 2001; Beutler et al, 2003) has been established as such a project. Since that time the name was changed to Global Geodetic Observing System, GGOS. Eventually, GGOS will contribute to large international observation and science programs.

The central objectives of the GGOS are (Rummel, 2000)

1. to provide a well-defined and reproducible global terrestrial frame,
2. to analyse the integral effect on Earth rotation of all angular momentum exchange inside the Earth, between land, ice, hydrosphere and atmosphere, and between the Earth, Sun, Moon, and planets,
3. to establish the geometric shape of the Earth's surface (solid earth, ice and oceans), globally or regionally, and its temporal variations, whether they are horizontal or vertical, secular, periodical or sudden, and also
4. to study the Earth's gravity field – stationary and time-variable – mass balance, fluxes and circulation.

Thus, GGOS integrates the reference frame with the three main areas of geodesy, shape (and kinematics), rotation, and gravity field. The aim of GGOS is to contribute geodetic observations of relevant Earth system parameters to global earth observation programs like the three Global Observing Systems (G3OS, see http://earthwatch.unep.net/data/g30s.php) and thus to support major research programmes such as the World Climate Research Program (WCRP, see http://www.wmo.ch/web/wcrp/wcrp-home.html), and the International Geosphere Biosphere Program (IGBP, see http://www.igbp.kva.se/).

Large parts of the physical observing network of the GGOS are already in place through the efforts of the national mapping authorities and other institutions involved in operational monitoring. These networks are contributing to the maintenance of the International Celestial and Terrestrial Reference Frames (ICRF and ITRF). However, the observing networks are mainly organised as single-technique networks and services. The creation of GGOS provides the frame to integrate the services into a comprehensive geodetic observing system. GGOS also provides the direction for further development of the geodetic networks operated by the national mapping authorities.

Over the last four years, the European Commission and the European Space Agency have jointly proposed a programme for *Global Monitoring for Environment and Security* (GMES). The information delivered by GMES is to serve three main themes, namely

- meeting Europe's environmental obligations, i.e. to contribute to the definition, implementation and verification of environmental policies, national regulations and international conventions;
- supporting sustainable development both within the EU and globally;
- contributing to the security of citizens both within Europe and globally by providing the information support to decision-makers and to operational actors

(see the *GMES Final Initial Period Report*, available on http://www.gmes.info). The needs of GMES in terms of observational infrastructure as well as data management and information system can be expected to be a major driver for the development of observation networks and applications over the next decade.

In parallel and in response to the international developments, geodesists in the Nordic countries have worked towards the definition of an integrated geodetic observing system in the Nordic countries. The *Nordic Geodetic Commission* (NKG) has recognised the necessity for contributions to global geodetic networks as well as regional homogenisation and standardisation and promoted these in the Nordic region. Responding to the international development in Earth observation, since 1998 NKG working groups have discussed the rationale and objectives as well as the potential applications of a *Nordic Geodetic Observing System* (NGOS).

In 2002, the NKG presidium set up a Task Force with the mission to prepare a document providing the definition and draft for the implementation of the Nordic Geodetic Observing System. The authors of this paper were nominated to prepare the plan and the present document. The full document of the NGOS Task Force can be found in the web pages of the NKG, http://www.nkg.fi.

2. Application of geodetic observations

A global geodetic observing system provides the infrastructure and observations to determine and maintain an accurate and stable global terrestrial reference frame, and delivers observations of the changes in the geometry and rotation of the solid Earth as well as changes in the Earth's gravity field. Such a reference frame is a necessary prerequisite for all Earth observation and monitoring both from space and ground-based. Moreover, in order to detect slow changes in the Earth system, the long-term stability of the reference frame is crucial.

Today, the International Terrestrial Reference Frame (ITRF) is the most accurate global frame available. The ITRF is maintained on the basis of a mix of space-geodetic techniques through international cooperation. Each of these techniques contributes in a specific way to the determination of the ITRF. Modern national and regional reference frames are today based on space-geodetic techniques. The geodetic observations from permanent networks are fundamental for the definition and maintenance of these reference frames.

The geodetic observations not only provide the reference frame required for long-term Earth observations but also information related to displacements and strain of the Earth surface caused by tectonic and seismogenic processes, man-induced subsidence and motion of man-made infrastructure.

New gravity satellites CHAMP, GRACE and GOCE will provide us information on the Earth's gravity field which eventually will enable a precise realisation of a global vertical datum but also allows us to monitor the gravity changes. Both these will have a major impact on monitoring the global change.

Changes in the Earth's geometry, gravity field and rotation are caused by mass movements and dynamical processes in the Earth system. Consequently, observations of these quantities provide a means to monitor the dynamics of the Earth system and associated mass movements, such as fluxes in the hydrological cycle including ocean circulation, ground water storage, terrestrial surface flows, sea level changes and ice changes.

2.1 Positioning, changes in positions, and displacements

In maintaining the reference frames and monitoring different aspects of the Earth system, GPS augmented with the products of the IGS (International GNSS Service) has served both as the primary measuring device as well as a tool to position sensors with unprecedented accuracy. Ten years of experience have shown that requirements are of the order of better than 1 cm in daily or sub-daily positions and better than 1 mm/yr in secular stability.

On a global scale, monitoring the surface kinematics through the global ITRF network and particularly the densest component, i.e. the IGS network of tracking sites, has contributed significantly to improvements of the global plate motion model. Additional improvements of the models for the horizontal plate motion can be expected mainly through better coverage of the Earth surface with continuous GPS (CGPS) sites and also other space-geodetic stations. Accuracy requirements are of the order of 1 mm/yr or better.

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. Most of the Fennoscandian uplift, however, can be reconstructed to better than 1 mm/yr due to repeated precise levelling over the last 100 years, and current CGPS networks.

In the BIFROST project (see e.g. Scherneck et al., 1998, Milne et al., 2001, Johansson et al., 2002), both the vertical and horizontal post-glacial rebound signal could be detected in long (> five years) CGPS time series of a regional network. Significant differences of model predictions due to differences in the Earth and ice models used to compute the present-day kinematics are of the order of 1 mm/yr and < 0.5 mm/yr in the vertical and horizontal components, respectively. This sets the requirements for the observational accuracy in order to contribute to the validation of the different models.

On seasonal and sub-seasonal time scales, the changes in the shape of the Earth as observed by the global geodetic networks, particularly the IGS network, have been used to extract the signal due to surface loading. Examples are Van Dam and Herring (1994) and Van Dam et al. (1994), who detected the air pressure loading signal in VLBI and CGPS, respectively, and Van Dam et al. (2001), who found evidence of the continental water loading in CGPS. Differences are on the 5 mm level for the vertical component of daily coordinates, and in order to contribute to a validation of the loading models, this sets a requirement for the precision of daily coordinates (e.g. Poutanen et al., 2005).

In tectonic regions such as the active plate boundaries a major contribution to the displacements of the Earth's surface is due to strain induced by the tectonic processes. Most of the global deformation zones are associated with plate boundaries, but in some cases they extend far into the plates and their actual extension remains uncertain.

In the Nordic countries, areas likely to be affected by seismogenic displacements are South western Norway (including a wide off-shore region), Iceland and Svalbard. Earthquakes in the off-shore region adjacent to South-west Norway can affect the security of oil-platforms. Human activities such as ground-water and oil exploitation can also induce non-linear motion, particularly in the vertical component. No models exist currently to predict such movements.

Increasingly, GNSS and IGS products are used to monitor the motion and stability of large infrastructure such as oil platforms, reservoir dams and bridges. Typical applications include the monitoring of short-term stability in order to detect in a timely manner instabilities or unwanted motion, and monitoring the long-term stability in order to determine long-term trends. Experience with oil platforms shows that user requirements for monitoring of such infrastructure are of the order of less than 1 cm for sub-daily to daily positions available with a latency of a few days, 2-3 mm on monthly to seasonal time scales, and 1 mm/yr for long-term stability (Plag, 2004).

Similar requirements apply to reservoir dams and large bridges; however, here the tolerable latency may be much lower. In the absence of a local stable reference frame, the global network of IGS tracking stations can be used as reference. In most applications, time series of daily coordinates determined by ppp (precise point positioning) provide the basis to compute the relevant parameters such as velocities. A key limitation for monitoring infrastructure at points far away from a stable reference point is the temporal stability of the global reference frame.

Decontamination of the coordinate time series for the so-called Common Mode Errors (CME) prior to the analysis of the time series is a crucial issue. For that, the regional network of tracking stations provides the observational basis.

Highly accurate positioning of sensors for e.g. airborne gravity, laser scanning or photogrammetry, and hydrographic surveys requires positions with high temporal resolution (down to 1 second) and sub-decimetre in position. They also require a high long-term stability as measurements are carried out over long time intervals (even decades) and should be interconnectable without loss of accuracy. Hydrographic surveys on, for example, oilfields require an accuracy of 5 cm over a time span of up to 50 years, which is equivalent to a long-term stability of 1 mm/yr.

For the most demanding land surveying tasks such as determination of real estate boundaries in densely populated areas (with high values of real estate) or mapping of underground cables and pipelines in cities, accuracy requirements are of the order of 5 cm with low latency. The cost of surveys strongly depends on the time needed to achieve this accuracy and the integrity and availability of the system. Having access to a reliable position in near-real time would greatly ease the surveying tasks and reduce the costs.

For most surveying tasks, it is crucial to be able to relate (time dependent) coordinates given in the global reference frame to (time fixed) coordinates in the national reference frame. In order to transform *ad hoc* coordinates in ITRF to national coordinates, a detailed knowledge of the velocity field of the Earth surface with accuracy better than 1 mm/yr is required. An error of 1 mm/yr already introduces an error of 1 cm in *ad hoc* positions over 10 years. In some regions, plate tectonic models provide a first order approximation to the horizontal velocity field. However, in many regions intra-plate deformations exceeding the 1 mm/yr level require more detailed (empirical) models. For the height component, even first order models are missing, except for post-glacial rebound in and around the formerly glaciated areas.

In summary and based on the allowable latency, we can identify three main groups of high accuracy applications requiring or benefiting from *ad hoc* positioning:

- Real time positioning: For these applications, the most extreme accuracy requirements are expected to be considerably lower than 10 cm and in some case even below 1 cm. Some real time applications will require high integrity (e.g. process control) and high update rates.
- Near-real time positioning and other near-real time applications. Here, accuracy requirements will be close to 1 cm in most of these applications (monitoring of infrastructure, meteorological applications) while other applications will require less accuracy (e.g. of the order of 5 cm) but higher integrity (e.g. land surveying).
- Post-processing with extreme requirements: Most of these applications can accept latency but will require accuracy at the 1 cm level for daily coordinates and a few millimetres on intra-annual time scales. For long-term monitoring tasks, 1 mm/yr in stability seems to be a critical boundary both for scientific and non-scientific tasks. Some applications such as the study of climate-induced sea level changes and surface load-induced displacement may require stabilities significantly better than 1 mm/yr. This number also applies to collection of geo-databases, which are to be maintained over time scales of several decades.

2.2 Earth rotation

The NGOS as a regional effort offers a high-quality capability contributing to global monitoring of earth rotation, primarily with VLBI. The aim is sub-millimeter stability and calls for corresponding stability monitoring. The methods are, besides co-location of techniques, regional footprinting in e.g. GPS networks. This is an essential requirement in order to achieve the necessary consistency of reference frames.

Earth rotation monitoring is carried out in sparse networks. The stability of the participating stations plays a key role. Future demands of site stability will probably range below 0.1 mm (horizontal standard deviation). Emphasis is therefore given to a few well-co-located stations which can be followed up with local footprint studies under long time. The three stations Ny Ålesund, Metsähovi and Onsala continue to be important international resources. Co-located GNSS stations will help to improve the short-term resolution of EOP time series, but VLBI is the only technique available that is capable to link the terrestrial reference frame to the celestial frame on a routine basis.

Earth orientation parameters are key parameters for global reference frames. The need for continuous monitoring and rapid solutions is likely to increase somewhat. Continuous monitoring is already implemented on a global scale; however, the increasing need for higher accuracy will probably call for a somewhat larger number of stations in simultaneous networks.

Scientific results that draw from the high stability and resolution of Earth orientation parameters estimated from VLBI have amongst others demonstrated that climate-related processes, especially the El Niño phenomenon in the Pacific, leave discernible fingerprints in earth rotation variations. This area has high potential for further discoveries. With the increasing length of time series and settling of uncertainties at still better levels more subtle changes in the atmospheric-oceanic angular momentum budget and effects of atmospheric and oceanic torques on nutation and polar motion can probably be observed.

2.3 Gravity and its changes

National reference networks have been maintained with relative gravimetric measurements. There have been only a limited number of absolute gravity points. The situation is changing now, mainly because our capacity to make absolute measurements has been improved. We are moving toward the situation where the primary reference network is maintained by absolute measurements and the sites are common with those of other techniques, e.g. permanent GPS stations.

Measuring the secular change of gravity in a gravimetric network of permanent stations over long periods of time affords a unique method to monitor large-scale mass movements. Of particular interest in our area is the phenomenon of postglacial rebound. Combining gravity change with surface displacement promises an aid to discerning ice load related effects from earth structure. In order to resolve models of mass redistribution in glacial isostatic rebound models, gravity change needs to be determined at 1 to 2 nm/s^2/yr reproducibility. This aim can be met with repeated absolute gravity campaigns that encompass a time frame of at least one, but preferably three decades. The spatial scale of the phenomenon, varying conditions due to land-sea distribution, and unknown variations in the ice unloading history argue in favour of a large-scale network that encompasses the entire uplift area. Larson and van Dam (2000) suggest that 5 nm/s^2/yr uncertainty can indeed be obtained from five annual campaigns.

Temporally sparse measurements of gravity change in networks using absolute instruments are notoriously susceptible to transient gravity variations. Temporally dense sampling of gravity field variations at a limited number of stations provides means of identifying the different processes that are involved and of improving existing models. Measurements with modern instruments like superconducting gravimeters and ancillary monitoring of environmental parameters like ground water, rain, snow, lake and sea levels constitute an ongoing research effort, partly in its own right and partly in direct support of the absolute gravity network. The studies are also relevant to observable variations of geodetic position in the space geodesy network. Consistency is required at the 0.1 nm/s^2 level, and this is still a challenge at seasonal to inter-annual periods. Superconducting gravimeters form thus desirable equipment to maintain at co-location stations (Virtanen, 2006).

Superconducting gravimeters are very sensitive instruments able to monitor gravity changes. However, they have no absolute scale of their own, and due to (unknown) drift, there is a need to control them with regular absolute measurements at the same site. In the Nordic area, one needs to ensure that the existing superconducting gravimeter (currently only one) has an adequate tie to the frame measured by absolute gravimeters.

Satellite gravity missions such as the ongoing Gravity Recovery and Climate Experiment (GRACE) and the upcoming Gravity Field and Steady-State Ocean Circulation Mission GOCE, map the Earth gravity field with high accuracy almost globally. For calibration and validation of the data a-priori information about the gravity field is needed at least in some regions. In those regions which may have the extent comparable to the Nordic region, information about the spatial characteristics of the gravity field can be compiled using terrestrial measurements combined with airborne and ship borne surveys. Absolute gravity is essential as fundamental information to define the level as well as to calibrate and validate the relative gravity data. Hereby, errors in the standards and discrepancies between different regions can be avoided and this helps secure the success of the satellite missions.

The use of data of the gravity satellites CHAMP, GRACE and GOCE will eventually produce a global geoid model, the accuracy of which is better than a couple of centimetres. This enables creation of vertical datums anywhere globally which are consistent within the geoid model accuracy. Realisation of W_0 will be possible using the same GPS measurements or utilising local or global permanent GPS networks.

2.4 Geoid

The geoid is an equipotential surface associated with the Earth’s gravity field. The shape of the geoid, i.e. its spatial variations, depends on the mass distribution within the Earth that causes the geoid to depart up to 120 meters from the reference ellipsoid. Consequently, the geoid is an important surface to consider when the shape of the Earth is described. Furthermore, the geoid as an equilibrium surface defines the reference for physical processes such as mass movements.

Determination of the geoid has traditionally required information about the gravity field. Such information is acquired through gravity surveys on land and over the ocean, where variations in the gravimetric acceleration are measured with high accuracy. Recent developments in airborne surveying have made the collection of data more efficient.

With the increased use of satellite navigation tools (such as GPS) in surveying, accurate information about the geoid has become essential. Satellite positioning is carried out with respect to a global reference frame and the height is referring to the ellipsoid. To convert those ellipsoidal heights to orthometric heights a geoid model is needed. To obtain heights in a national height reference system the geoid may be fitted to the national reference, e.g. mean sea level.

At sea an undisturbed ocean surface would coincide with the geoid. However, different temperatures and salinities cause inhomogeneities in the density of the ocean water. Furthermore, atmospheric forces such as wind and air pressure act on the ocean and cause its surface to depart from the geoid. In ocean science the difference between the ocean surface and the geoid (called the dynamic topography) is important for studies of the dynamics of the ocean, its currents and heat transport. An accurate geoid is required to study the changes in the currents and the heat transport and their role in climate studies.

On the surface of the solid earth the movements of water and ice naturally depend on the gravity. In the Earth’s interior movements of mass are caused by the variations in the gravity potential field combined with the visco-elastic properties of the earth materials. The postglacial rebound in the Nordic region, where the crust in the central part of the region moves up by 1 cm per year, is such a phenomenon.

As surveying on land by levelling etc. is carried out with respect to the geoid, positioning and navigation by gyros in Inertial Navigation Systems refer to the geoid, or more correctly to the gravimetric equipotential surface, of which the geoid is one. Gyros react to changes in position through the accelerations including changes in the gravimetric accelerations.

Precise positioning of satellites has become very important, as the satellite technology has developed. Communication satellites and other satellites that are fixed in the equatorial plane at a specific position with respect to the rotating Earth need to be launched and put into orbit very accurately to keep their positions. The success of the global navigation satellite systems depends on how well the positions of the navigation satellites are known. Furthermore, the increasing number of environmental as well as scientific satellite missions increases the demands for accurate geoid models that are needed to compute the positions of the satellites accurately.

2.5 Combination of observations

Space-based segments can remotely observe several key quantities (global ocean surface, ice surface, gravity field at long- and medium-range spherical harmonic degree), while ground-based observations are sensitive to the situation at a very local scale.

Global navigation satellite systems (GNSS) such as GPS, are well suited for measuring the positions of single points in a global reference system. To obtain high accuracies (better than one centimetre) observations need to be acquired continuously on a permanent basis. Other space techniques, especially VLBI and SLR, give positions with a higher accuracy.

Classical techniques such as trilateration and levelling can be used for measuring precise relative positions which after repeated measurements can give local displacements and deformations. Precise levelling is used to determine accurate changes in height to recover local land uplift and subsidence. Land uplift and subsidence relative to mean sea level may be measured using tide gauges. The three techniques, however, measure vertical displacements in three different systems, i.e. relative to the ellipsoid, relative to the geoid, and relative to the mean sea level.

The Earth's rotation is studied using coordinate time series from space techniques as VLBI, SLR and GNSS. Accurate gravity variations from superconducting gravimeters are also used. The determination of earth rotation parameters needs a global coverage of stations.

The determination of the gravity field including the geoid is based on measurements of the accelerations obtained by gravimeters. Absolute gravimeters measure the gravity with a high accuracy using a free fall principle. Spring gravimeters are used for the spatial densification of the gravity that is required for the computation of the geoid. Spring gravimeters can also be used for collecting time series for studies of e.g. earth tides and loading. To study the details of the dynamics of the earth the gravity need to be measured by superconducting gravimeters.

Glacial isostatic adjustment (GIA) is an good illustration of a geodynamic problem where coordinated multi-component geodetic observations are essential. The dynamics of the GIA problem is constituted by a planet that has a specific rheology, guiding the response to surface loading. This problem is under study at various levels of complexity. Assumptions are needed about the temporal evolution of the load, where the exact history of glacial load over time and space is the least well-known.

In order for earth models to develop in more detail, a rich data base of coordinated measurements are needed. Consistency of the reference system and compatibility in special and temporal sampling (array density, sampling interval, sampling duration) is also required. Model solutions will draw benefits from the combination of some or all observables.

Today we are beginning to retrieve fully 3-D surface motion at 0.1 (0.05) mm/yr resolution, sea level change below 0.2 mm/yr, while gravity changes are monitored at a μGal/yr level with absolute or relative gravimeters. To mitigate this shortcoming the Nordic absolute gravimetry plan has been launched and several institutes have already increased their level of activity.

Leaving the example of glacial isostasy and turning to a more general scope of applications, the major obstacle for data combinations across all time scales is that the components of the systems have different sampling schemes. For a foreseeable future it is unrealistic to expect permanent absolute gravimeter installations for much tighter than annual campaign schemes. To overcome the drawback the preferred method would be to start and install recording gravimeters (remotely controlled, emphasis on low instrumental drift) at some of the absolute gravity sites.

A well-established, accurate and stable reference is essential for the determination of the changes described above. The realisation and maintenance of the terrestrial reference frame is carried out by means of a global or regional cluster of fiducial points with precise positions relative to some external reference associated with them. The reference frame for gravity is established and maintained using a global or regional cluster of absolute gravity measurements combined with relative measurements.

3. The Nordic Geodetic Observing System

3.1 Objectives of NGOS

NGOS aims to provide geodetic observations for the Nordic area that are of sufficient quantity and quality to serve most of the needs of global Earth observation as well as practical and scientific applications in the region. In particular, NGOS

- will contribute to the GGOS and the IAG Services
- will contribute to global Earth observation systems such as the G3OS, GLOSS,
- will contribute to European activities such as EUREF, ECGN, EuroGOOS, and ESEAS,
- will support the European GMES,
- will provide the reference frames for the Nordic countries, and the region as well as contribute to the global ones,
- will support scientific projects related to the geodynamics of the Nordic area,
- will provide ground-truth for satellite missions.

NGOS is envisaged to provide the necessary observations to determine

- geodetic positions and to infer the kinematics of the Earth surface,
- gravity and its temporal changes, and
- Earth rotation and its temporal changes.

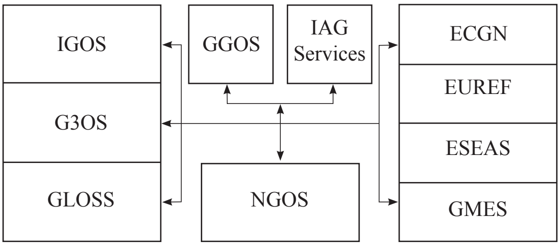

Figure 1. *Relations of NGOS to other activities. (abbreviations are as follows: ECGN = European Combined Geodetic Network; ESEAS = European Sea-Level Service; EUREF = Reference frame subcommission for Europe; G3OS = Global Observing Systems; GGOS = Global Geodetic Observing System; GMES = Global Monitoring for Environment and Security; IAG = International Association of Geodesy; IGOS = Integrated Global Observing Strategy; NGOS = Nordic Geodetic Observing System)*

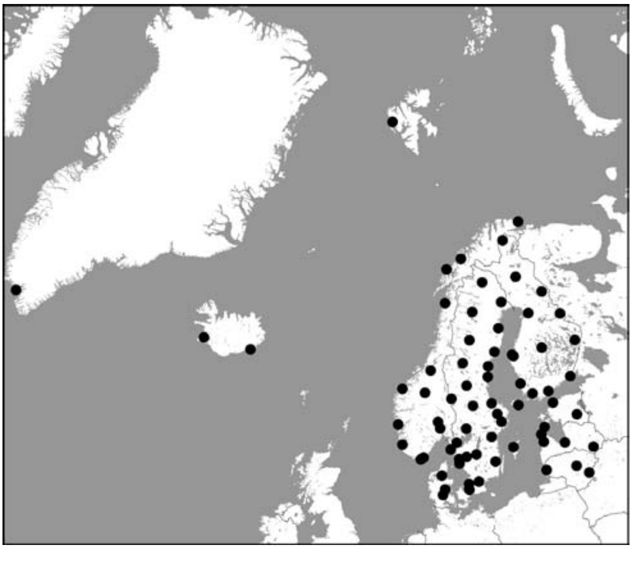

Figure 2. *The geographical area covered by the NGOS and proposed NGOS stations.*

To a large extent, these objectives agree with the goals of GGOS. Taking into account the specific phenomena of the region, NGOS will, however, have a particular focus on geodynamics. Particular focus will be the long-term stability in the observing system, homogeneity in time, and a sufficient capacity to perform its tasks also in the future. These data will allow us to address most of the practical and scientific problems discussed in Section 2.

The geographic extent of NGOS is currently defined as the Nordic countries, including Greenland and Svalbard. However, it is recommended that the geographical region is extended to include also the area of Baltic States. This covers the area of the ice-covered part of the Northern Europe during the last ice age, and therefore the common geophysical interest.

3.2 Components and requirements of the NGOS

Only the ground components of the geodetic observation techniques and infrastructures are considered in NGOS. Densification, e.g. in special target areas such as glaciers, tectonically active structures, or near tide gauges, can be accomplished using remote sensing techniques, such as space and airborne radar and laser systems. Sea level can be monitored using satellite altimetry. The large scales of the gravity field and its changes are studied using observations of the motions of satellites by SLR and GPS or by dedicated gravity satellite missions. NGOS will support the space and airborne techniques though they are not included in NGOS.

In the frame of the global observing systems much of the focus has been on the requirements of an observation system providing a comprehensive monitoring of the Earth system. The emerging ideas have been compiled in the strategy document of IGOS. Most importantly, the IGOS emphasises the transition from research to operational observing systems. This is justified by the requirements for Earth system observations derived from the nature of the processes in the Earth system.

A key requirement for sustainable monitoring, which is the overall goal of the observing systems, is that it is long-term and homogeneous in time. This requirement can only be met by operational observation systems. Moreover, IGOS requests the monitoring to be multi-parameter, global and integrated.

Another focus of IGOS is on the data archives. Here, it is stated that data archives resulting from Earth observing systems must be integrated, quality-controlled, homogeneous, consistent, and last but not least accessible. The last point cannot be overemphasised, and currently research in many areas is hampered by difficulties in accessing relevant databases.

The practical implications of these requirements are demanding and not easily fulfilled. For example, long-term operation can often not be guaranteed due to shifting political priorities and changing economical conditions. The changing environment (e.g. urbanisation) easily introduces artificial effects around ground-based components or destroys the conditions required for observations. Technological developments provide another challenge for the long-term stability.

Table 1. *Summary of techniques considered in NGOS.*

Technique	Objective	Accuracy	Component(s)
VLBI	Point positioning relative to space	0.001 ppb 0.1 mas	Surface displacement Earth rotation Reference frame
SLR	Point positioning relative to many satellites	< 1 cm (range) 1-2 cm	Surface displacement Earth rotation Reference frame
GNSS	Point positioning relative to a satellite system	E: 1-2 cm [*)] C: 1-2 mm	Surface displacement Reference frame
DORIS	Point positioning relative to satellites	1-5 cm	Surface displacement Reference frame
Levelling	Height differences of points relative to the geoid	< 1 mm/km^{½}	Surface displacement Reference frame
Tide gauges	Height of points relative to sea level	E: 10 cm C: 1 cm	Surface displacement Reference frame
Absolute gravimeters	Absolute gravimetric accelerations	2-3 µGal	Surface displacement Earth rotation, Gravity Reference frame
Superconducting gravimeters	Relative gravimetric accelerations	0.1 µGal (< 1 nGal periods)	Surface displacement Earth rotation, Gravity Reference frame
Spring gravimeters	Relative gravimetric accelerations	2-3 µGal	Gravity Reference frame

[*)] *E means episodical and C continuous measurements*

To be homogeneous in time, the operational networks need careful planning to avoid too many changes in the operational routines, spatial distribution, and also to guarantee the continuous observations of the network. Multi-parameter requires often cross-discipline, even cross domain coordination and the organisational structures are mostly not available. This may lead also to difficulties in data archiving and delivery. Data are either not freely available or it is distributed between several institutions or organisations, and the customer using data needs to contact all of them to obtain the whole data set.

In order to achieve integration of techniques, two types of objectives must be fulfilled. The components of such a system need to interact and be compatible within its own structure. The routines and techniques used must comply to the international standards. The integration should bring about a set of stations that are monitored by an adequate number of different techniques, and a few fundamental stations where as many techniques as possible are represented. Therefore the system needs to follow closely (and help develop or influence directions of) the inter-technical developments coordinated by the IERS. The individual techniques that are included need to follow closely (and help develop or influence directions of) the corresponding services (IGS, IVL, ILRS, IGeS).

NGOS is planned to be a regional implementation of GGOS. Hereby, NGOS is related to the international geodetic cooperation work in the IAG and its associated services. Those services are summarised in Table 2. Furthermore, the activities should be coordinated with other international services outside IAG such as PSMSL, and with some European services such as ESEAS. Such services are also summarised in Table 2.

Concerning spatial variations of gravity and its temporal changes, we propose to concentrate on the use of modern, absolute gravimeters. See the NGOS/Absolute Gravimetry plan (Scherneck et al., 2002) and "Draft plan for absolute gravity campaigns in the Fennoscandian land uplift area" by Mäkinen et al (2003). There is a plan for absolute gravity measurements in the Nordic area, as a co-operation of Kort- og Matrikelstyrelsen, the Finnish Geodetic Institute, Statens Kartverk, Lantmäteriverket, Onsala Space Observatory, Norwegian University of Life Sciences in Aas, University of Hannover and Bundesamt für Kartographie und Geodäsie, as described in Mäkinen et al 2003.

Some of the NGOS sites are close to the tide gauges, or even at the tide gauge. We encourage the availability of tide gauge data; however, at the same time we are aware of the limitations of that in some countries. However, for global change studies, combination of tide gauge time series with GPS and gravity time series is a necessity. We note the work of ESEAS (see e.g. Plag, 2002) and TIGA (see e.g. Schöne, 2001) in this respect.

We also emphasize the importance of geoid determination. By nature, it is not limited to the NGOS stations or NGOS plan, but the geoid is increasingly used in height determination. In the future, the new gravity satellite missions, especially GRACE and GOCE will give their contribution also to the Nordic geoid models.

Table 2. *Components and associated services*

Components	IAG service(s)	Other service(s)
Surface displacement	IVS, ILRS, IGS, IDS, TIGA, WEGENER	PSMSL, ESEAS
Earth rotation	IERS	
Gravity	BGI, IGeS, ICET	
Reference frame	EUREF	

3.3 Current situation in the Nordic area

NKG has tried to act as a platform for sharing the knowledge concerning construction of various geodetic networks and in co-operation of geodetic campaigns. However, it has ultimately always been the responsibility of an individual country to implement the work in practice. The Nordic countries have historically been building up their geodetic networks quite independently. There has been only a limited amount of co-operation between the countries or techniques. Inside the countries even collaboration between organisations has not been optimal. Tide gauges are typical examples, because institutions taking care of them are generally outside of the geodetic community.

In each country there are networks of permanent GNSS stations which are partly operated by the national geodetic authorities. The co-ordination concerning e.g. location, construction, facilities and products was not optimal when the stations were built. This means e.g. that the stations have different monumentation, have different types of equipment, produce slightly different products and possibly are not optimally spread over the Nordic Area. However, the basic observables are the same at all stations, thus allowing e.g. the common Nordic computation of the EPN block, or the collaboration in the projects like BIFROST.

The Finnish Geodetic Institute has been active in absolute gravimetry and has been performing measurements on stations over the Nordic Area for many years. Groups from USA and Germany have also made absolute gravity measurements in the Nordic Area. The current NGOS AG plan clearly demonstrates the current co-operation in this field. Since 2003, also the Norwegian University of Life Sciences in Aas, has an absolute gravimeter which is a substantial contribution to the resources. Most of the measurements in Finland and Sweden have been performed at stations with other geodetic techniques, such as permanent GNSS stations and/or tide gauges.

There is a superconducting gravimeter at Metsähovi and Ny-Ålesund. These two stations and additionally Onsala are also equipped with a geodetic VLBI. These three stations are internationally important fundamental resources since several specific techniques are collocated at these stations. Metsähovi has additionally co-located two other space geodetic equipments, namely the SLR and DORIS. Since 1978 Metsähovi has participated in the SLR programmes, and is currently the Northernmost SLR station. Stations for geodetic VLBI and SLR contribute to the work of IVS and ILRS which are IAG services.

GNSS data of some Nordic stations are used in IGS, but a wider selection of Nordic GNSS stations belong to the EPN, the European Permanent GPS Network, coordinated by EUREF. EUREF has during the last decade become active concerning European co-operation and examples of this are:

- the European reference frame ETRS89
- the European Network of permanent GNSS stations EPN
- the European vertical network EUVN
- the European height network UELN and the height system EVRS 2000
- ECGN

The Nordic countries have adopted national ETRS89-realisations as their national reference systems. NKG is responsible for one of the EPN analysis centres and the responsible organisation is currently the National Land Survey of Sweden. NKG has urged the countries for Nordic co-operation concerning the Nordic height systems. The joint Nordic adjustment of the levelling networks is headed towards a common vertical datum in the area. NGOS is in line with these initiatives towards Nordic co-operation concerning the national geodetic networks and geodetic stations.

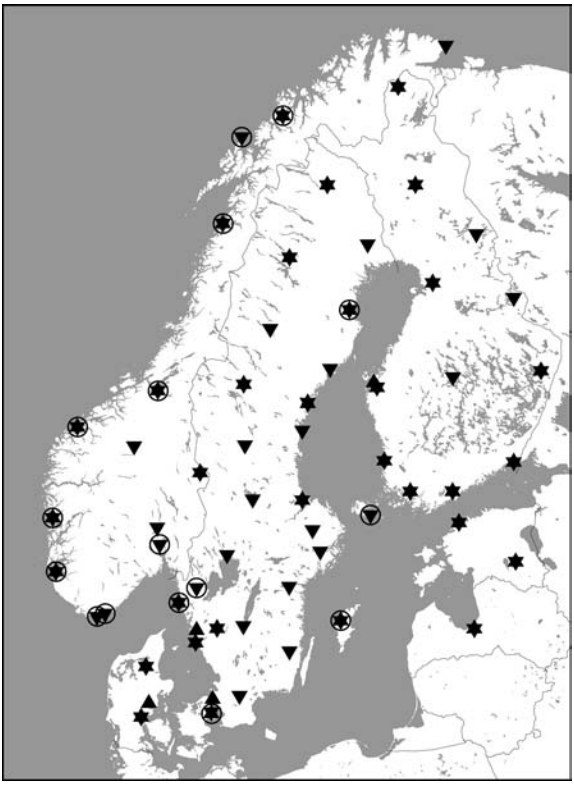

Figure 3. *NGOS plan. Absolute gravity points (triangles), Nordic permanent GPS network (upside down triangles) and tide gauges (circles). All absolute gravity points are occupied with a GNSS instrument.*

Products of the NGOS, data access and archives are to be defined. Geodetic data are spread between the various countries and organisations and are also in various formats. Very little has been done in standardisation of data archives as well as in assuring the access to data. Different policies in the countries concerning accessibility to data due to pricing policies have complicated this issue.

The characteristics of the NGOS, and NKG behind it, do not imply a common data archive covering all data and products of the NGOS. The role of NGOS data policy should be co-operative, utilising current infrastructure also in data policy and archiving. There already exist working examples of products and data archiving, including the Nordic permanent GPS network, levelling data bank and gravity data. At least as a first step, an NGOS data base is needed to list the existing data, describe how to access it, and possibly give some auxiliary information concerning the use of data and products. It is the responsibility of individual institutions to maintain the data bases, possibly making a common agreement on data exchange and use, and also the data delivering policy is a national decision.

Details including the NGOS data archiving and products are to be agreed in NKG. Some examples are given above, including the permanent GPS network and absolute gravimetry. Moreover, data gaps, both temporal and spatial, are to be defined and pointed out in future plans when NGOS is developed.

4. Relations between NGOS and other on-going activities

The IAG Subcommission for Europe of the Commission X Global and Regional Networks (EUREF) and of the International Geoid and Gravity Commission (IGGC) agreed to develop an integrated geodetic network for Europe. A proposal for the development of a European Combined Geodetic Network (ECGN) has been submitted (Ihde 2003) and the First Call to participate in ECGN has been replied to e.g. by all Nordic countries.

The ECGN is considered as a European contribution to the GGOS. However, the ECGN also constitutes an independent component of its own. The primary concern of the project consists in connecting the height component with the gravity determination while allowing for measuring data that are acquired in the European coastal regions and above adjacent seas. As described in Ihde (2003), “the planned activities on ECGN aim to link the spatial reference system with gravity field related parameters in order to contribute to a consistent description of the general processes of the system Earth. These processes shall be kinematically integrated into a combined monitoring system of position and gravity. Products of the satellite gravity field missions will be combined with the data of the integrated geodetic terrestrial reference frame.”

The European spatial reference system realized by the EPN (European Permanent GPS Network) is based on global systems. Consequently, the entire ECGN project must be seen in the global context. The work on the integrated kinematic network must be understood as a European contribution to a global integrated geodetic network, as an essential part of GGOS. EUREF supports with the ECGN activities also an improvement of the European height reference system for scientific work and for the supply of relevant data to European authorities and institutions.

5. Conclusion

We have described the general principles to select the points for the NGOS. The final selection of the points depends on the resources available for maintaining and measuring the sites. We may begin with the sites proposed for the ECGN, supplemented by the most probable sites for absolute gravimetry. One should emphasize the multi-technique approach, and put the priority according to that. We expect that during the discussions to be held in the near future we are able to fix the core set of the NGOS stations. The work of the Task Force will continue, because the Presidium of the NKG gave a new task to find out the existing infrastructures and data archives, prepare a status report and recommendations for the practical implementation of the NGOS. We also propose that the work on the NGOS on the practical level will be continued in the NKG Geodynamics Working Group.

Acknowledgements

This report is a combined effort of a great many people. In March 2003 the NKG Presidium appointed the following members of the Task Force "Nordic Geodetic Observing System (NGOS)": Markku Poutanen (chairman), Per Knudsen, Mikael Lilje, Hans-Peter Plag, and Hans-Georg Scherneck. In 2004 Torbjørn Nørbech replaced H.-P.P. in the group. Most of the text here is based on the material compiled and written by the chairman of the NKG Geodynamics Working Group, H.-G. Scherneck and Hans-Peter Plag. The text was discussed and modified during the mutual meetings of the Task Force. Some earlier versions of text have been additionally contributed by R. Forsberg, B.R. Pettersen, D. Solheim, J. Mäkinen, M. Vermeer and many more Nordic colleagues not mentioned here. We like to express our sincere thanks to those who have helped us to prepare the document.

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