Determination and Maintenance of Navigation Systems Reference Frames: The EGNOS Example

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ABSTRACT

Satellite-Based Augmentation Systems like the *European Geostationary Navigation Overlay Service (*EGNOS) provide users with data allowing them to accurately determine their position and integrity parameters. In EGNOS, the GPS and GLONASS observations monitored by *Ranging and Integrity Monitoring Station*s (RIMS) are transferred to *Central Processing Facilities* (CPFs) which compute the correction and integrity data. This information is then transmitted to EGNOS users via geostationary satellites. In order to perform the computations, the EGNOS CPFs need accurate and reliable coordinates of the RIMS antennas in a global reference frame with an accuracy of 5 cm. These RIMS coordinates determine the EGNOS reference frame, and users who determine coordinates with the help of EGNOS will get these coordinates in this EGNOS reference frame. Therefore, a key issue is the proper alignment of the EGNOS reference frame with the reference frame(s) commonly used by main EGNOS user groups. Considering aviation as one of the main applications of EGNOS, it is noted here that the ICAO SARPS mandatorily require coordinates to be referred to WGS84. Today, WGS84 as realized by GPS is aligned to the more accurate *International Terrestrial Reference Frame* (ITRF), and therefore, coordinates with an accuracy of 5 cm in ITRF imply the same accuracy in WGS84. In order to maintain the 5 cm accuracy over time, the RIMS coordinates need to be time-dependent, thus necessitating frequent updates during the anticipated EGNOS lifetime of 15 years. Since EGNOS is a safety-critical element to be used in civil aviation, integrity is a key requirement including also the RIMS coordinates, which have to be associated with a high level of confidence. To meet these requirements, initial geodetic coordinates for 34 EGNOS RIMS were determined in ITRF2000 through dedicated GPS field campaigns. Aligning the EGNOS reference frame to ITRF2000 ensures also a close alignment to WGS84. Reliability of the initial coordinates and their accuracy estimates was achieved through three independent analyses of the observations. The comparison of the independent solutions showed that the accuracy of the mean coordinates is better than 5 cm with respect to ITRF2000. A velocity model for each RIMS station was determined on the basis of *a priori* information. Maintenance of the coordinates uses the so-called RIMS method, which utilizes the RIMS observations themselves. Three independent analyses of the RIMS observations ensure integrity of the observed coordinates, which are compare to predicted coordinates. The predicted coordinates are computed from the initial coordinates and the velocity model. Only in a few cases, significant deviations between predicted and observed coordinates were detected, which in all cases were due to post-survey changes at the RIMS.

1 INTRODUCTION

The *European Geostationary Navigation Overlay Service* (EGNOS) is the European regional *Satellite Based Augmentation System* (SBAS) for the *Global Positioning System* (GPS) and the *Global Navigation Satellite System* (GLONASS). EGNOS aims to enhance performance of these two *Global Navigation Satellite Systems* (GNSS) over Europe for navigation and other applications, including time and frequency transfer and geodetic applications. The *Ranging and Integrity Monitoring Stations* (RIMS) perform GPS and GLONASS measurements and transfer the observations to the EGNOS *Central Processing Facilities* (CPFs). There, corrections and integrity parameters are computed which are broadcast to users via geostationary satellites. In order to perform the computations, the EGNOS CPFs need accurate and reliable coordinates of the RIMS antennas in a global reference frame with an accuracy of 5 cm. These geodetic coordinates of the RIMS, which are inputed as *a priori* information in the computation of the corrections determine the EGNOS reference frame. Coordinates determined based on EGNOS corrections are given in this EGNOS reference frame. Therefore, the explicit knowledge of the reference frame of EGNOS is a key issue for EGNOS users. In order to ensure that EGNOS coordinates are consistent with the reference frame used for the main applications of EGNOS, the EGNOS reference frame needs to be aligned to the user reference frame or transformations need to be readily available.

Consequently, the operation of EGNOS requires accurate and reliable ground station antenna coordinates in a well defined global geodetic reference frame. The most accurate global reference frame available today is the *International*

Terrestrial Reference Frame (ITRF, see e.g. [1]). A major application of EGNOS is in civil aviation. The *Standards And Recommended Practices* (SARPS) of the *International Civil Aviation Organization* (ICAO) in Annex 15 mandatorily require coordinates to be referred to the *World Geodetic System 1984* (WGS84). Today the most recent WGS84 realization through GPS is fully aligned to the most recent version of ITRF with an accuracy of about 1-2 cm [2], where the latter provides a much higher accuracy than WGS84 itself. Considering an accuracy of 5 cm, ITRF coordinates therefore can be considered to be equivalent to coordinates in the most recent WGS84 realization. Moreover, in order to ensure interoperability, the European Union and the government of the USA recently agreed to align the reference frames of GPS and the future Galileo system as closely as possible to the ITRS [3], which implies that the reference frames of these two systems will be closely agreeing with the latest ITRF version. Therefore, below we consider ITRF and WGS84 as equivalent and refer to ITRF whenever cm-accuracy is required. Aligning the EGNOS reference frame to ITRF not only ensures the most accurate alignment to WGS84. In addition, transformations from ITRF to most national or regional reference frames (such as EUREF89 in Europe and SNARF in North America) are readily available.

EGNOS is aimed for a long operation period of at least 15 years. The use of EGNOS for safety critical applications in civil aviation implies that the stated requirements on accuracy, continuity and integrity have to be met not only during the implementation and validation phases but also throughout the operational life of EGNOS. These requirements include the accuracy of the RIMS reference coordinates. Moreover, it is likely that during the EGNOS lifetime, RIMS antenna positions may have to be changed due to operational or maintenance constraints, and new RIMS locations may have to be added to the EGNOS network.

Coordinates given in ITRF are time-dependent. Points on the Earth's surface exhibit horizontal velocities with respect to ITRF of the order of several centimeters per year, depending on which tectonic plate a point is located. In order to maintain the RIMS coordinates with an accuracy of 5 cm, the RIMS reference coordinates have to be time-dependent, too. Thus, frequent updates of the reference coordinates are necessary. The required frequency for updates of coordinates of a given station depends primarily on the velocity of this station in the global reference frame as well as the accuracy requirements for the coordinates.

The EGNOS project initially anticipated the deployment of a network of 40 ground sites (34 RIMS sites and 6 *Navigation Land Earth Stations*, NLES). Each RIMS site was planned to be equipped with one to three stations. These sites were anticipated to be established in three main batches, and geodetic reference coordinates were requested to be available at the end of each batch. This requirement excluded a simultaneous survey of all sites with space-geodetic techniques as a viable approach to the determination of the geodetic reference coordinates.

At each RIMS site, coordinates were required for reference points at up to two RIMS antennas (RIMS A and RIMS B). Moreover, coordinates of an additional eccentric point not too far away from the two RIMS stations were to be determined for redundancy reasons. A detailed comparison of different methods for the determination of highly accurate coordinates of a reference point in a global reference frame led to the methodology described in Section 2. The chosen methodology ensured the reliability of coordinates and associated uncertainties as well as a globally homogeneous accuracy of the resulting coordinates. Taking into account the specific situation and requirements at the RIMS sites, the overall methodology for the initial field survey of a RIMS site is then outlined in Section 3, and the GPS analysis procedure is detailed in Section 4. The results of the field surveys carried out at a total of 35 RIMS and NLES sites are discussed in Section 5 focusing particularly on the accuracy of the reference coordinates. In Section 6, we discuss the approach to maintain the coordinate accuracy throughout the lifetime of EGNOS, making use of the discussion of methodologies in Section 2. Certification of EGNOS will also imply a certification of the methodology used to determine the reference coordinates. Therefore, in Section 7 we summarize the main requirements for certifiability and comment on the international situation with respect to regulation authorities in geodesy. Finally, in Section 8 we summarize the main results and conclusions of this study.

2 METHODOLOGY FOR POINT POSITIONING

GNSS, in particular GPS, is the state-of-the-art technique for the determination of coordinates in a global reference frame. Combined with the *Satellite Orbits and Clocks* (SOC) and the *Earth Rotation Parameters* (ERP) provided by the *International GNSS Service* (IGS), GPS observations of a duration of a day or more allow the determination of single-point coordinates in ITRF with an accuracy on the 1 cm level anywhere on the globe. In a considerable international effort, the IGS has established a global network of permanent and *continuously operating GPS* (CGPS) stations, which today consists of about 400 stations. Utilizing the observations of this global network of tracking stations, the IGS provides continuously highly accurate SOCs for all GPS and GLONASS satellites in the most recent ITRF (presently ITRF2005, see [4]; and at the time of the EGNOS RIMS deployment, ITRF2000, see [2]). Positioning based on IGS SOCs consequently results in coordinates given in the most recent ITRF.

Combining observations from one or several stations in the IGS network with the products of IGS or one of the IGS *Analysis Centers* (ACs), coordinates of new points can be determined relative to the stations in the permanent IGS network. Moreover, using the method of *Precise Point Positioning* (PPP, [5]), single point coordinates can be determined using only the SOC and ERP as provided by IGS or an AC. The accuracy level of the resulting coordinates depends mainly on the quality of the global products used in the data analysis and can be expected to be spatially homogeneous. An accuracy better than 3-5 cm can be achieved by selecting a sufficiently long observation time (see e.g. [6], [7], for examples). Therefore, it was not necessary to observe the new RIMS sites or subsets of these simultaneously. Consequently, field surveys could be scheduled according to a tight and evolving deployment schedule.

Three main types of analysis strategies are most widely used for the analysis of GPS observations (Table 1), with each of these being affected by error sources in different ways. Applying different strategies to the observations therefore can help to improve the accuracy of the coordinates and particularly the reliability of associated error estimates.

PPP involves observations from a single station, only, but requires as *a priori* information precise SOCs determined in an analysis of a global tracking network. The reference frame for PPP is determined by the global products of SOCs and ERP, which are kept fixed in PPP. Such SOCs are provided by IGS in a specific frame which differs from ITRF [8],[9],[10] by a slow motion of its origin of the order of 1-2 mm/yr. The frame of the IGS SOC is constrained by approximately 100 fiducial stations selected from the global IGS network. The *Jet Propulsion Laboratory* (JPL) provides fiducial-free orbits as well as transformations for these orbits to the most recent ITRF, with the transformation parameters being determined on the basis of approximately 100 fiducial stations. PPP results in single point coordinates with a well defined and spatially rather homogeneous accuracy. Moreover, processing is rather fast. In some cases the PPP results are less sensitive to any station-dependent effect at individual stations in the permanent network. A disadvantage of PPP is that errors in the SOCs will be propagated into the solution.

Ideally, a *Global Network Solution* (GNS) requires a homogeneous geometric distribution of satellite-tracking stations. In a free network solution loose constraints are put on the coordinates of all sites. An additional requirement is that the first-order Stokes coefficients are zero, which ensures that the frame has its origin in the center of mass as sensed by the satellite motion and the frame is rotated around this center of mass. The main advantage of the free network solution is that it is independent of errors in the *a priori* station coordinates. The data span chosen for a GNS normally is longer than 24 hours.

A *Regional Network Solution* (RNS) requires precise SOCs determined in a GNS, which can be collected from either IGS or one of the IGS ACs. These predetermined SOCs can be further improved for the region under consideration. In a RNS, GPS data can be processed as undifferenced or differenced (single, double, or triple) measurements.

A GNS or RNS with the coordinates of the reference stations constrained to their ITRF values will provide an independent solution, which can be cross-check against each other or a PPP solution in order to assess the overall reliability of the analysis. The accuracy of the coordinates with respect to ITRF at the central epoch of observation, t_C, depends on (i) the duration of the observations at the point, (ii) the accuracy of the SOCs, and (iii) particularly for PPP, the ability to correct the coordinates for so-called *Common Mode Variations* (CMVs). For sites with reasonable GPS conditions, the day-to-day variations of the daily coordinate estimates in a consistent global reference frame are of the order of $\pm$1.5 cm or less for the vertical component and about 1/3 of that for the horizontal components. Thus, an observation span of 24 hours will provide a precision of better than 3 cm. However, in order to increase reliability, an

Table 1: Characteristics of different GPS analysis strategies. Modified from [11].

No.	***Acr.***	***Description***	***Input***	***Comment/error sources***
1	PPP	Precise Point Positioning	IGS or JPL SOCs	Strongly affected by CMVs
2	GNS	Global Network Solution	Data from a global subset of the IGS station network	Require a homogeneous global network
3	RNS	Regional Network Solution	IGS or JPL SOCs, data from regional subset of the IGS station network	Network dependent

observation span of two or more full days is necessary.

IGS and JPL precise SOCs are of high accuracy and long-term stability. On daily time scales, their contribution to the overall error budget of the point coordinates is on the level of a few millimeters. On time scales of several days to weeks, the orbits exhibit errors with long spatial wave length introducing CMVs in the coordinates with amplitudes of several millimeters. Besides errors in SOCs, CMVs are also caused by errors in the local ionospheric and tropospheric corrections and an incomplete station motion model used in the analysis.

For PPP, CMVs may be the most critical factor in terms of accuracy of the coordinates. However, many of these errors show a long-periodic regional variation. Therefore, using a regional network of permanently tracking reference stations, common temporal and spatial variations of the network can be determined. Although a number of different filter methods have been proposed to eliminate CMVs from GPS solutions and to improve the internal precision of the solutions (see e.g., [12] and the references therein), all these methods have the disadvantage of reducing the link of the filtered solution to the global reference frame. For the determination of the EGNOS reference coordinates, precision is not the main goal, and the accuracy with respect to the global reference frame should be compromised in favor of a higher internal precision of the solution.

3 FIELD SURVEY OF THE RIMS SITES

Despite some differences between the individual RIMS stations due to different designs of monuments and masts, two reference points were defined for each RIMS station. In this way, the results of the field survey could be presented in a standardized way. This standardization is also of benefit for the use of the reference coordinates as well as their maintenance. The two points are the *Center of Mast at Ground Level* (CMGL) and the *Center of Hole in Top Plate at top level* (CHTP). In Figure 1, these two points are shown for an idealized RIMS station. The CMGL is the fundamental reference point. The location of the CMGL depends solely on features that may be considered permanent for this purpose. In particular, the location does not depend on the properties of the mast, and therefore should not be affected if the mast is modified or replaced (as long as the mast remains centered around the CMGL). The reference point for the RIMS/NLES antenna is the CHTP, and the coordinates of the CHTP are the reference coordinates used in the EGNOS computations. The CHTP is dependent on the mast; hence the position of the respective CHTP changes whenever a mast is modified or replaced. Thus, a new local tie vector between the CMGL and the CHTP has to be determined after any changes at a station affecting the mast.

The primary goal of the field survey was to determine accurate coordinates for the CMGL. Where possible, the local tie vector between CMGL and CHTP was to be determined, too. The actual survey was carried out using GPS. Therefore, the GPS *Antenna Reference Point* (ARP) entered into the picture as a third point (Figure 1).

As mentioned in the Introduction, the field surveys were carried out depending on the deployment schedule of the RIMS and NLES stations. The conditions at the sites and the individual stations at the time of the survey were variable: At some sites, no RIMS/NLES masts were installed, while at others, the RIMS/NLES antennas were already in place. At some stations, the CMGL was physically accessible and could be marked permanently, while in other cases, the CMGL was covered by the existing mast and thus could not be marked. In these latter cases, other features were selected, from which the CMGL could be determined unanimously, such as the screws used to fix the mast to its foundation (Figure 2).

At stations where the mast was already present, the GPS antenna was attached directly to the top plate of the mast. In most of these cases, a standard adapter was used for this attachment, resulting in a predetermined eccentricity vector between CHTP and ARP. At these sites, the eccentricity vector between CMGL and CHTP was measured. At stations with no mast in place, a tripod was used to emplace the GPS antenna above the anticipated future CMGL, and the eccentricity vector between CMGL and ARP was measured. In the rare cases where the location of the CMGL was not known at the time of the survey or the tripod could not be placed over it, one or several eccentric sites were established and denoted as “MARK”. In these cases, the eccentricity vector between MARK and ARP was determined.

The equipment used for measuring eccentricity vectors included carefully calibrated theodolites, tape measures, and compasses. Classical geodetic techniques based on measurements of angles and distances were used to determined the position of the ARP relative to the reference point (CMGL or MARK) with high accuracy (on the level of 1 to 5 mm). The orientation of horizontal offsets (of the order of a few centimeters) were determined with a compass.

Each reference point was identified by a four-character identification, analogous to IGS station identification. In order to avoid conflicts with the identifications of IGS stations, the first character was chosen to be the digit '0' for all RIMS station points. The next two characters indicated the station name, while the last digit was used to distinguish the

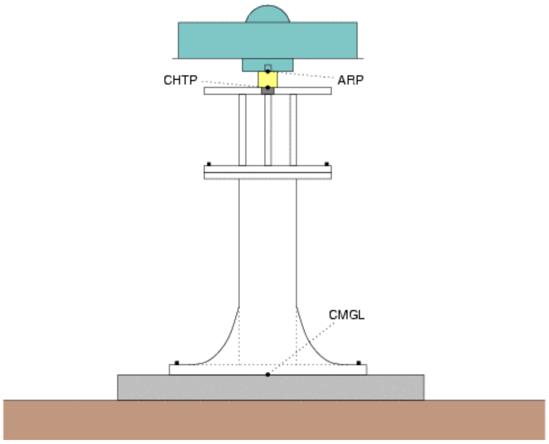

Figure 1: *Schematic location of the reference points at a RIMS site.* CMGL: *Center of Mast at Ground Level*; CHTP: *Center of Hole in Top Plate at top level*; ARP: *Antenna Reference Point*. From [11].

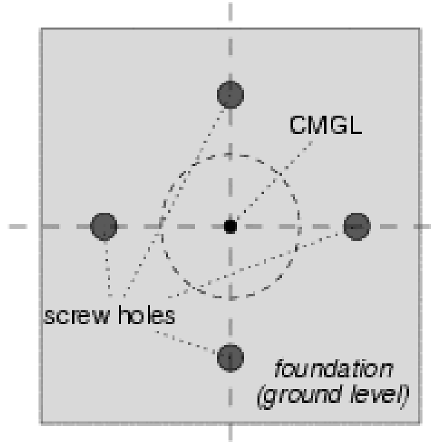

Figure 2: *Determination of CMGL based on its surrounding screw holes.*

different stations at one site. The last digit was assigned based on *a priori* information of the designation of a site, with '1' and '2' denoting a RIMS/NLES station, '3' an eccentric reference point, and '4' a second eccentric reference point or a third RIMS/NLES station. However, at some sites, the station designation changed subsequently, or the *a priori* information turned out to be incorrect.

Based on the considerations reported above, general specifications for the site surveys were derived, which were followed by all surveyors (Box 1). In particular, a site survey comprised a GPS campaign of at least two full days duration with simultaneous measurements on all reference points at a site. This allowed the determination of highly accurate vectors between the reference points at a site, which are of use for later checks of the station stability. The GPS receivers had to be of geodetic quality, which at the time of the surveys was equivalent to dual-frequency receivers with Choke Ring antenna.

4 GPS ANALYSES

Based on the discussion summarized in Section 2, specifications for the reference frame, the analysis strategy, and the coordinates were set up (Box 2). For point coordinates it is difficult to say what are the true values in a global reference frame. Therefore, a single analysis normally only result in estimates of precision. Comparison of point coordinates computed from the same data using different software packages and independent strategies appears to be areasonable test of the accuracy of the solution. In order to decide on the more likely coordinates in case of significant discrepancies, at least three independent solutions are required. The precision of the individual estimates depends

EGNOS-COR-FC-001: Observation tool: All geodetic reference point coordinates shall be determined using GPS.

EGNOS-COR-FC-002: Local site network: At each site, one location per RIMS antenna (up to two antennas per site) plus one eccentric marker shall be observed.

EGNOS-COR-FC-003: Marking: Each observed location shall be clearly and permanently marked or referred to a uniquely identifiable location. Each marker has to be numbered.

EGNOS-COR-FC-004: Station log: All observation activities shall be logged, in particular observing dates and times, marker locations and potential offsets between the marker and the observing station.

EGNOS-COR-FC-005: Observation tools: The observations shall be carried out with dual-frequency geodetic GPS receivers equipped with Choke Ring antenna. All measurements shall be carried out with receivers and antennas of identical type.

EGNOS-COR-FC-006: Calibration: All observation tools shall be calibrated before and after field surveys.

EGNOS-COR-FC-007: Duration of observation: Each individual observation with one receiver/antenna pair shall at least cover two full days from midnight to midnight. Each location will be observed for a total of at least 48 hours.

Box 1: *High-level functional requirements for the field survey at the RIMS sites.* Modified from [11].

significantly on the observation span of the GPS measurements. For reliability reasons and in order to ensure an accuracy of the final coordinates of better than 5 cm, the minimum observation window was set to 48 hours.

The GPS observations were processed by three different institutions with each of them using different software packages and analysis strategies (Table 2). Prior to the analysis, the GPS observations were scrutinized for any potential effects due to local environmental conditions (multipaths, interference, etc.). Common input files for each analysis were the station log files and the daily RINEX files. Program parameters and additional information like ocean loading, atmospheric mapping, and elevation cut-off were not homogenized between the groups, while the choice of stations for reference frame fixing depended on the different analysis strategies. In order to detect potential errors,

EGNOS-COR-RNC-001: Number of processing methods and reliability of coordinates: All point coordinates shall be determined with at least three independent processing strategies and softwares. The reliability of the accuracy estimates for the recommended geodetic survey method shall be demonstrated on the basis of the results from at least three independent estimates of the coordinates.

EGNOS-COR-RNC-002: Reference frame: The solution of the RIMS coordinates shall be provided in ITRF2000.

EGNOS-COR-RNC-003: Data: Complementary data and input information used in each individual analysis shall be stored and delivered together with the results (e.g. IGS RINEX or orbit files, ERP, etc.).

EGNOS-COR-RNC-004: Intercomparison of result: The combination of the independent solutions shall allow to detect and remove from the final product any solution showing a significant deviation from the other two.

EGNOS-COR-RNC-005: Final product: A unique set of RIMS coordinates shall be provided, as a result of the combination of the independent analysis results.

EGNOS-COR-RNC-006: Site report and certifiability: In order to fulfill the requirements for certifiability, the surveyors shall produce a report for each site with at least the following contents:

1) Name/number of the project
2) the main task of the survey
3) persons who carried out the survey
4) instruments used in the survey
5) description of the survey method used
6) name or description of computer program(s) used
7) list of coordinates and estimated accuracy for identified points, and reference frame used
8) a description of each point for which position is computed, containing:
    - identification number
    - a photo where reference markers are shown
    - a map where the point is marked
    - anything else necessary for identifying and access the point
9) documentation of calibration and control of the equipment used in the survey.

Box 2: *EGNOS RIMS and NLES Coordinate requirements.* Note that the requirements, in particular EGNOS-COR-RNC-006, also ensure that the coordinates meet the conditions posed by a potential certification of EGNOS. Modified from [11].

Table 2: *Overview of the three independent GPS analyses.*

No.	***Instiution***	***Package***	***Strategy***	***SOC/ERP***	***Comment***
1	NMA	GIPSY/OASIS-II	PPP	JPL	Free solutions were transformed to ITRF2000 using the daily seven-parameter transformations provided by JPL
2	OSO	GAMIT/GLOBK	GNS	SOPAC	Approach with double differencing. Coordinates of about 30 globally distributed stations constrained to ITRF2000 coordinates. Solution included corrections for orbits and the station coordinates, as well as a transformation (rotation and translation) of the free solution to the ITRF2000 frame.
3	GMV	BAHN	RNS	GPS broadcast	Precise SOCs and ERPs were computed as part of the solution, which was aligned to ITRF2000 using a network of more than 20 IGS stations.

each institution also interpreted the antenna type information in the station log files and determined the vector from the antenna phase center to ARP individually. As output, each group produced files with daily coordinates. Thus, for each point the processing resulted in three sets of daily coordinates, which are affected differently by various error sources. After the processing, parameters like accepted and rejected samples, post-fit phase and range residuals were utilized to assess the quality of the solution and the local micro-GPS conditions at each antenna location. The final step was the combination of these solution to derive the final point coordinates and reliable accuracy estimates.

5 ACCURACY OF COORDINATES

For a given individual solution, the precision of the point coordinates was assessed on the basis of the repeatability of the daily coordinates. For most solutions, daily repeatability was on the order of 1.5 cm for the vertical component and less than 1 cm for the horizontal components. The official coordinates were computed as the average of the three individual solutions. The accuracy of these official coordinates was estimated on the basis of deviations between the three individual solutions. The comparison of the independent solutions also allowed the detection of any solution showing significant deviation from the two other solutions. In a few cases, such outliers were not included in the final solution.

The basis for the intercomparison were the deviations of the individual solutions from the mean of the three solutions. For the north component, the OSO and NMA solutions agree on a level better than 1 cm, with only one exceptions. The GMV solution displays a systematic deviation from the two other solutions of 1 to 2 cm. For the east component, agreement of all three solutions was found to be very good and deviations of the individual solutions from the mean were on the 1 cm level, with the exception of very few sites. For the vertical component, agreement was on the 2 to 3 cm level with no systematic offset of any of the solutions.

Most of the deviations for the horizontal components are most likely due to differences in the fixing of the reference frame to ITRF2000. The cause of the systematic deviation in the north component of the GMV solution from the two other solutions is not clear, but minor difference, for example, in the implementation of the IERS Conventions [13][14] or the selection of stations for the alignment of the solutions to ITRF2000 can easily explain such a deviation. The deviations in the vertical are caused by a combined effect of different treatment of the troposphere, cut-off elevations and ocean tidal loading, as well as different effects of an incomplete station motion model, ionospheric errors and errors of the SOCs on the three analysis strategies. The station motion model is incomplete particularly with respect to surface loading, where atmospheric loading can introduce day-to-day variations on the order of ± 1 cm. These variations affect PPP results fully while in a RNS and GNS solutions, they are strongly reduced.

6 UPDATING OF RIMS REFERENCE COORDINATES

In order to keep the reference coordinates within the predefined accuracy with respect to the global reference frame, frequent updates of the RIMS reference coordinates are necessary. Updates may be scheduled in order to account for the nearly linear velocity expected for each site with respect to the global reference frame or they may be necessary on demand in order to account for non-linear motion (including rapid offsets).

The accuracy of point coordinates at the central time of measurement t_C depends on the three main factors discussed in Section 2. Without new measurements, the accuracy at any other reference epoch t_R different from t_C depends on the ability to model time-dependent changes in the coordinates. For that, the three-dimensional velocity vector of the point needs to be known. In general, this velocity vector is a non-linear function of time.

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. Earthquakes may lead to displacements of several meters over larger areas within a few seconds with the associated displacement field extending for several hundred kilometers. Seismic waves 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 tidal periods 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 approx. 14 months). Post-glacial rebound leads to secular vertical motion of up to 15 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. Human activities such as groundwater and oil extraction can induce surface motion with vertical velocities of several cm/year.

Most of the motion at shorter time scales can be modeled with high accuracy in a station motion model [14]. At most stations, the remaining motion is mostly secular and can be described by a constant velocity. However, in tectonically active regions, non-linear, transient motion can occur that is not captured by such a linear model.

A model for the secular motion (with constant velocity) of the EGNOS sites was set up on the basis of all available information from plate tectonic models and nearby observations from CGPS sites. The model given in Figure 3 predicts horizontal velocities of up to 3 cm/yr, while predicted vertical velocities (not shown) reach 1 cm/yr. Depending on the available information, the uncertainties in the velocities may be as large as ±5 mm/yr. The EGNOS velocity model was use to refer all coordinates to a common reference epoch.

In order to keep the coordinates well within the accuracy limits, the coordinates should be updated whenever they have changed about half of the pre-defined accuracy. Thus, the 5 cm accuracy requirement appears to be compatible with an update interval of six to twelve months. For sites on stable parts of the tectonic plates, updated coordinates can be predicted from the velocity model with high reliability. However, several of the EGNOS sites are in tectonically active areas and in particular at these sites update values for the coordinates can only be determined with sufficient accuracy from a geodetic monitoring of the reference sites. For this, the so-called RIMS-method was proposed, which would use the RIMS observations themselves in a geodetic analysis with the goal to determine highly accurate RIMS antenna coordinates.

In a detailed analysis of RIMS observations it was demonstrated that the EGNOS antennas and receivers are of geodetic quality (Johansson, 2005, person. communication). Through a comparison of coordinates determined from RIMS observations to those predicted from the initial coordinates (determined in the field surveys) and the EGNOS velocity model, the RIMS method was validated [15]. A key issue in the validation was the accurate determination of the antenna phase center offsets of the RIMS antennas. A main result of the validation is summarized in Table 3, which provides the overall statistics of the difference between RIMS-determined and predicted coordinates for a large number of daily coordinate samples from several time windows in 2005 and 2006. For none of the components, significant systematic deviations were found for either RIMS A or B, although at some sites a few individual days showed larger differences, which normally were associated with degraded data quality during these days.

Based on the validation of the RIMS method, a geodetic analysis of the RIMS observations can be used to monitor the reference frame and to determine update values whenever needed. Such an operational monitoring also allow to detect minor offsets due to, for example, earthquakes or technical changes at the stations.

Updated coordinates were determined in 2006 with the RIMS-method, using again three independent groups with specific software packages and analysis strategies. No significant deviations were found between RIMS-determined and predicted coordinates, underlining the quality of the velocity model as well as the stability of the EGNOS stations.

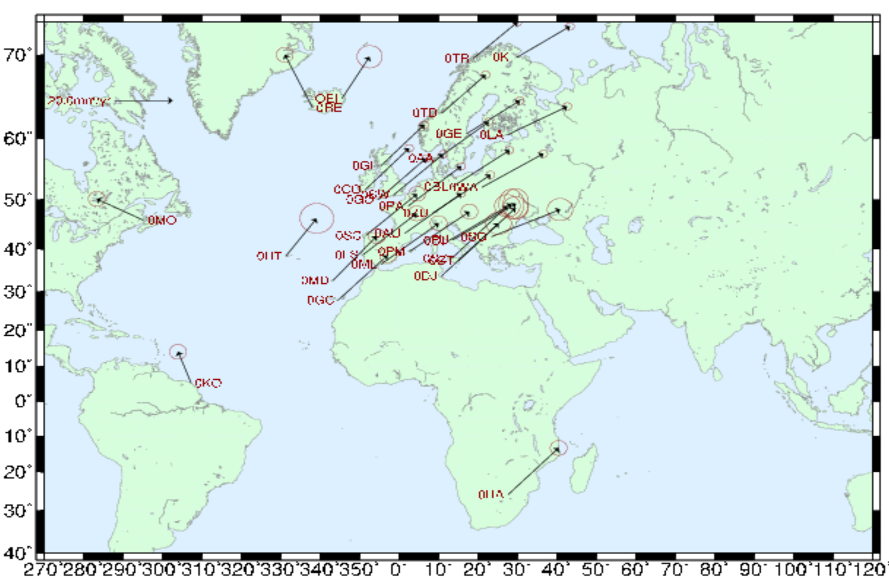

Figure 3: *Horizontal velocity model for the EGNOS sites.*

Table 3: *Main statistics of the daily differences between RIMS-determined and predicted coordinates.* All values are in mm. Modified from [15].

Component	***RIMS A (247 samples)***		***RIMS B (514 samples)***	
	Median	Mean	Median	Mean
East	0.5< 1.1< 1.7	2.3±10.5	-0.5< 0.1< 0.6	0.6±16.5
North	-0.5<-0.2< 0.0	-0.6± 8.4	-6.7<-6.2<-5.3	-5.2±11.0
Up	2.0< 3.4< 4.5	9.0±21.2	11.7<13.0<15.5	17.8±25.6

7 TOWARDS CERTIFIABILITY OF EGNOS

The initial coordinates of the EGNOS reference station were not only expected to be reliable but also certifiable as part of the EGNOS system. Similarly, any updated coordinates have to be produced in a way that does not compromise the certifiability of EGNOS. The request to provide certifiable coordinates translates into the requirement that the coordinates would be endorsed by *Regulation Authorities in Geodesy* (RAG) without significant extra work. This requirement poses two questions: (1) Who are the RAGs that can be consulted for certification in the case of EGNOS? (2) What are the general requirements by national RAGs for the acceptance of coordinates?

In answering (2), a detailed study showed that a main requirement was the traceability of the process used to determine the coordinates (including preparation and actual field work, data processing, and production of the final coordinates and their error estimates, see also Requirement EGNOS-COR-RNC-006 in Box 2). In order to ensure reliability, error sources were eliminated as far as possible and the methodology, techniques, equipments, and processing software were validated. The demand for certifiability was met through detailed documentation of the work carried out in the determination of the initial coordinates as well as the velocity model. Reliability was ensured by automating the data processing as far as possible. Furthermore, the chosen methodology was redundant and based on fully validated approaches and software.

For updated coordinates determined with the RIMS-method, this also applies to the data processing and coordinate determination. The analysis methodology used for the RIMS-method is similar to the one used for the initial coordinates, which ensures that also the updated coordinates are certifiable.

Question (1) is more difficult to answer: RAGs exist mainly on national level. In Europe, there is currently no regional or pan-European RAG, nor is there any international RAG. A certification procedure involving the acceptance of the coordinates by national RAGs can turn out to be extremely tedious in Europe and even more so internationally. There is an obvious need for a regional European or even an international RAG, particularly in the context of safety-of-life applications of GNSS, including Galileo. The increasing official acceptance of ITRS and ITRF requires a detailed consideration of the complex issue. Today, ITRS and ITRF are maintained under the auspice of the *International Association of Geodesy* (IAG), while the *Subcommission for the European Reference Frame* (EUREF) is maintaining a reference frame for the stable part of the Eurasian plate (EUREF89). However, it appears unlikely that IAG or EUREF as scientific organizations based on the best effort of their members can take the role of an international or European RAG. An international body might be established under the umbrella of an appropriate agency of the United Nations.

8 CONCLUSIONS

Initial geodetic coordinates of the EGNOS RIMS and NLES were determined through dedicated field surveys in ITRF2000 with an accuracy better than 5 cm. The determination of the coordinates was based on a methodology and data processing designed to ensure the reliability of the coordinates and their error estimates as well as their certifiability.

The surface kinematics induced by plate tectonics, post-glacial rebound, and regional and local tectonics lead to a relatively rapid degradation of the coordinates. In order to maintain an accuracy of 5 cm for the EGNOS reference coordinates, a frequent update on a time interval of six to twelve months is necessary. A model for the secular station velocities was determined utilizing available information from geophysical models and nearby reference stations. This model allows the prediction of new coordinates when needed. However, the model uncertainties limit the prediction interval to time periods of up to two or three years, depending on the station. Some EGNOS stations are in tectonically active areas where non-linear motion and even rapid displacements due to earthquakes can not be excluded. While the

EGNOS operational routines will safeguard the system against any significant changes of the coordinates and will be able to exclude reference stations if such changes occur, the EGNOS system itself will not be able to provide new reference coordinates with the prescribed accuracy when needed. Frequent geodetic analyses of the RIMS observations offer all necessary features to monitor the reference coordinates and to maintain their accuracy with respect to a global reference frame throughout the lifetime of EGNOS. A main advantage of an operational implementation of the RIMS method is a continuous monitoring of the station coordinates, which will support detection of minor changes in the coordinates or other geodetically defined quality parameters.

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