# Commission 1 - Reference Frames

http://iag.ensg.ign.fr

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## Introduction

Commission 1 activities and objectives are to deal with theoretical aspects of reference systems and the practical applications for their realizations as well as applied researches. The main objectives of Commission 1 are:

- Definition, establishment, maintenance and improvement of the geodetic reference frames.
- Advanced terrestrial and space observation technique development for the above purposes.
- International collaboration for the definition and deployment of networks of terrestrially-based space geodetic observatories.
- Theory and coordination of astrometric observation for reference frame purposes.
- Collaboration with space geodesy/reference frame related international services, agencies and organizations.
- Promote the definition and establishment of vertical reference systems at global level, considering the advances in the regional sub-commissions.

## Overview of the main activities of Commission 1

The main activities of Commission 1 during the period 2007-2011 are the following:

- A dedicated web site was established immediately after the IUGG General Assembly in Perugia 2007, where the new Commission members were approved by the IAG Executive Committee. The Web site (http://iag.ensg.ign.fr) contains all the information related to the activities and objectives of the commission, its sub-commissions, projects and Working Groups. The Web site is regularly updated directly by the presidents of sub-commissions and sub-components to reflect changes and continuous activities of all commission entities.
- Steering Committee meetings were held
  - in Vienna, April 16, 2008 were 7 participants from the commission sub-components attended. The meeting was devoted to discussion on the main structure and activities of the commission. A few reports and presentations were provided, e.g. SC 1.3 (Regional Reference Frames), SIRGAS with a complete informative presentation, and IC-P1.2. The main highlights of the meeting were twofold: the IAG should give more emphasis to the activities of SC-1.3 and from the research side, the participants indicated the need for some theoretical work on Nutation under the lead of SC-1.4 in cooperation with Commission 3.
  - in Buenos Aires during the IAG General Assembly 2009 where most of Commission 1 members were attended. Reports from all the sub-commissions and most of the working groups were presented
  - in conjunction with Commission 1 Symposium – REFAG (see below) held in Marne la Vallée 4-8 October. This SC meeting was devoted to review the main sub-component activities, but also the review process of the REFAG papers and the preparation of the Proceedings.

  An additional SC meeting is foreseen during the IUGG2011 General Assembly in July in Melbourne, Australia.
- Participation in COSPAR GA held in Montreal, July 2008 and in Hotine Marussi symposium in Rome, July 2009.
- Commission 1 Symposium: Reference Frames for Applications in Geosciences (REFAG), held in Marne la Vallée, October 4-8. A dedicated website is set up, containing all the symposium related information: http://iag.ign.fr/index.php?id=140.

  Six sessions were organized as follows:

  1. Theory and realization of global terrestrial reference systems. Conveners Claude Boucher & David Coulot
  2. Strenghts, weaknesses, modelling standards and processing strategies of space geodetic techniques. Conveners: Markus Rothacher & Peter Steinberger
  3. Definition, establishment, maintenance and integration of regional reference Frames. Conveners: Joao Torres & Mike Craymer
  4. Interaction between the celestial and the terrestrial reference frame. Conveners: Harald Schuh, Chopo Ma
  5. Definition and establishment of vertical reference systems. Conveners: Michael Sideris and Johannes Ihde

6. Usage and applications of reference frames in Geosciences. Conveners: Richard Gross and Frank Lemoine

All the session summaries are available at the Symposium WEB site, together with all oral and some poster presentations.

About 150 participants were attended the symposium which was sponsored by IGN, CNES, NASA and Leica.

The REFAG Proceedings will be published in the symposia IAG series by Springer where about 40 papers will be published.

– As a joint effort between the ICCT Study Group IC-SG1 and Commission 1 a first IAG School on Reference Frames was held on June 7-12 2010. The School was hosted by the Department of Geography of the Aegean University in Mytilene, Lesvos Island, Greece. The School was attended by 58 students from 19 countries. More details about the school are available in the ICCT Report of this Volume.
– The main activities of Commission 1 were obviously undertaken by the commission sub-components as presented in the rest of this final report and highlighted hereafter.

**Main highlights of the activities of Commission 1' sub-components**

*Sub-commission 1.1: Coordination of Space Techniques.*

The main activities of SC-1.1 are the development of GGOS-D project and the experimental combination of the observation data from CHAMP and the GRACE satellites.

*Sub-commission 1.2: Global Reference Frames*

The main activities of SC-1.2 are: summary report on terminology related to reference systems and frames, contribution to the updates of IERS Conventions and in particular, Chapter 4 dealing with the terrestrial reference system and the establishment of working group on an ITRS standardization for the benefit of GGOS.

*Sub-commission 1.3: Regional Reference Frames*

The activities of each of the regional Sub-Commissions and the WG Regional Dense Velocity Fields show that all the components of the structure are developing according to the main objectives of the SC 1.3.

It must also be emphasized that during the 4-year period covered by this report there was a strong increase of activity in the less developed regions, as it is demonstrated by the results achieved. Some general aspects deserve to be referred:

– The activities are contributing to the scientific and technical development in several topics such as GNSS analysis and processing, precise reference frame establishment, among others.
– The organizational aspects play a more and more important role and are crucial for the efficient achievement of results.
– There is a great effort to bring together different types of institutions (R&D structures, National Mapping Agencies, political and economic agencies, etc.) to support the realiza-

tion of international campaigns (GNSS and other space techniques) and the installation of continuously observing GNSS sites.

- The products delivered are used not only by the scientific community but are also being used to define world-wide national reference frames related to the ITRF.
- There is a concern to develop education and training events, especially in less developed regions and countries. This effort must be continued and supported by the IAG.
- It is recognized the role of the WG Regional Dense Velocity Fields to detect some problems that were not evident in each of the regional Sub-commissions, due to the fact that the data are processed in limited areas.

Last but not least, the reports of all the components of SC 1.3 show the importance to keep and develop this kind of organization within the IAG, since each region of the world has its own way to proceed, considering all the variables involved in this kind of work.

*Sub-commission 1.4: Interaction of Celestial and Terrestrial Reference Frames*

Main objective of IAG Sub-Commission 1.4 is the study of the interaction of the celestial and the terrestrial reference frames. In particular, SC 1.4 is focusing on the consistency between the frames. Sub-Commission 1.4 has established three Working Groups.

*IC Project 1.2: Vertical Reference Frames*

The main IC-P1.2 is the realization of a global vertical reference system (GVRS) based on the classical and modern observations and a consistent modeling of both, geometric and gravimetric parameters. At present, there are some hundred physical height systems realized worldwide.
The realization of a unified global reference surface for physical height systems, the relation of individual tide gauge records with respect to this reference surface, the separation of sea level changes and vertical crustal movements at tide gauges, and the connection with the terrestrial reference system are to at large unsolved problems. To proceed towards a unified physical height system we need at the centimetre accuracy level:

- a unified global height datum,
- consistent parameters, models and processing procedures for the Terrestrial Reference Frame (TRF) and gravity field,
- a closed theory for the combination of parameters (space techniques, gravity),
- consideration of time dependency, and
- a rigorous concept for the realization.

The definition and realization of a World Height System (WHS) is a fundamental requirement of GGOS (Global Geodetic Observing System). In the same way as the ITRS/ITRF provides a high precision geometrical reference frame, the WHS shall provide the corresponding high precision physical reference frame for studying the system Earth.

ICP 1.2 is a common project of IAG Commission 1 and 2. From beginning of 2010 the activities of ICP1.2 were integrated in GGOS as Theme 1.

*IC Working Gr. 1.1: Environment Loading: Modelling for Reference Frame and Positioning*

The principal objective of the scientific work of Working Group 1.1 is to investigate optimal methods to mitigate loading effects in ITRF frame parameters and site coordinates. The main activities of the members of this working group are represented in papers published or in preparation, as well as oral and poster presentations at the Fall Meetings of the American Geophysical Union (San Francisco, CA, USA), General Assemblies of the European Geo-sciences Union (Vienna, Austria), and occasional other special and topical meetings. Based on the WG research findings, the WG recommendation is that displacements due to non-tidal geophysical loadings not be included in the a priori modeled station positions for reasons detailed in the WG full report.

*IC Working Gr. 1.2: Precise Orbit Determination and Reference Frame Definition*

The members of the working group have agreed to focus on the effects of non-conservative force model error in precision orbit determination and how it aliases into POD solutions. Progresses have also been made to mitigate the radiation pressure modelling on DORIS TRF geocenter estimates.

*IC Working Gr. 1.3: Concepts and Terminology Related to Geodetic Reference Systems*

The WG has established a detailed report on recommended nomenclature related to Geodetic Reference Systems.

*IC Working Gr. 1.4: Site Survey and Co-locations*

The WG held meetings in conjunction with EGU and AGU. A particular emphasis was placed on attempting to establish a new challenging methodology for monitoring collocation vectors in near real time.

# Sub-Commission 1.1: Coordination of Space Techniques

*President: Markus Rothacher (Switzerland)*

## Objectives

Sub-Commission 1.1 coordinates efforts that are common to more than one space geodetic technique. It studies combination methods and approaches concerning the links between techniques co-located onboard satellites, common modeling and parameterization standards, and performs analyses from the combination of a single parameter type up to a rigorous combination on the normal equation (or variance-covariance matrices) or even the observation level. The list of parameters includes site coordinates (e.g. time series of positions), Earth orientation parameters, satellite orbits, atmospheric refraction (troposphere and ionosphere), gravity field coefficients (primarily the low-degree harmonic coefficients), geocenter coordinates, etc.

The work of Sub-Commission 1.1 is done in close cooperation with the IAG Services, namely the International Earth Rotation and Reference Systems Service (IERS), its Working Groups on Combination and on Site Co-locations, the International GNSS Service (IGS), the International Laser Ranging Service (ILRS), the International VLBI Service for Geodesy and Astrometry, the International DORIS Service (IDS), the IAG project "Global Geodetic Observing System" (GGOS), and with COSPAR.

For more details see the Sub-Commission description at http://www.iag-aig.org.

## General Remarks

Within Sub-Commission 1.1 three working groups have been established and continued their work also in this second phase, i.e., after the IUGG General Assembly in Perugia 2007, in order to make progress towards the goals described above:

- SC1.1-WG1 on "Comparison and combination of precise orbits derived from different space geodetic techniques"
- SC1.1-WG2 on "Interactions and consistency between Terrestrial Reference Frame, Earth rotation, and gravity field"
- SC1.1-WG3 on "Comparison and combination of atmospheric information derived from different space geodetic techniques"

The three working groups are very important as steps towards GGOS, the Global Geodetic Observing System of the IAG. They have the task to (1) compare and combine precise orbits, to (2) study the interactions between the three pillars of geodesy, namely the Earth's geometry, Earth rotation and the Earth's gravity field as well as the temporal variations of these three parts, and to (3) compare and combine the atmospheric information derived from different space geodetic techniques.

Considerable progress has been made in some of the field addressed by IAG Sub-Commission 1.1. Let us just name a few:

- As part of the GGOS-D project consistent long-term series of SINEX solutions have been generated for GPS, VLBI and SLR including not only station coordinates and Earth Rotation Parameters (ERPs) but also troposphere zenith delays and gradients, quasar coordinates and low-degree coefficients of the Earth's gravity field. Not all the common parameters have yet been combined in one large multi-year solution, but many studies have already been performed with these very valuable SINEX data sets.

- Quite some experience has been gained with the combination of the observation data from CHAMP and the GRACE satellites with the observations (GPS and SLR) of the ground networks, an important step to combine geometry and gravity more extensively. Also, co-location of GPS and SLR onboard LEOs has been investigated and has led to the insight that the correction for the antenna phase center variations of the GPS antenna on the LEOs are crucial for gravity field determination.
- JPL is studying a satellite project specifically dedicated to the co-location of the space geodetic techniques onboard a new satellite, called GRASP. An initial study, but with a different concept, i.e. a low-cost nano-satellite with co-location, is also running at present with GFZ, ETH Zurich, TU Berlin and space industry. Both these missions, if realized, will be complementary to the co-location efforts on the ground.
- An new IERS Working Group has been formed (Chair: Richard Biancale) to make progress in the combination of the space geodetic techniques on the observation level.

The activities of the three working groups of Sub-Commission 1.1 during the last few years are summarized below.

**Report on Working Group 1 (SC1.1-WG1):**

*Chair: Henno Boomkamp (Germany)*

*Long-term strategy*

The Working Group is involved in an ambitious scheme of three related projects that were conceived and planned several years ago and are now gradually being implemented. The projects are called DIGGER, DANCER and DART and will be briefly revisited here (various other publications are available for further details).

The DIGGER project is the most relevant in terms of the WG charter, and the overall objectives of the IAG Reference Frame commission. It aims at coherent reprocessing of all different space geodetic datasets in the form of a cloud computing scheme on the internet. Current reprocessing activities of the IAG services are very useful, but not well coordinated between the techniques. Simultaneous estimation processes that include e.g. GPS, VLBI and SLR simultaneously can ensure much better consistency of common model parameters, but no individual Analysis Centre is currently performing such analyses. The key problems are typically a lack of processing capacity, and a lack of adequate knowledge of multiple tracking techniques at a single centre. The cloud computing approach on internet will eliminate the processing capacity problems, while process description databases can be derived from reprocessing activities of the separate services, even by non-experts. A functional prototype of DIGGER was developed by late 2006 around the grid computing software from Berkeley University. This showed that the concept was feasible, but no estimation software that could be freely distributed was available at that time. This is why the DANCER project will have to be completed first.

The DANCER project aims at computing GPS reference frame time series for an unlimited number of receivers. This solves the problem that at present only a very small percentage of permanent GPS sites have formal ITRF coordinates, and that many receivers cannot release their observation data for ITRF analysis by third parties. DANCER splits a typical GPS orbit estimation process into as many identical sub-tasks as there are receivers, and implements this task in the form of a scalable peer-to-peer process on the internet so that one task can run on one computer. Most naturally, this computer would be collocated with the GPS site, and can in the future even be fully embedded on the receiver itself (a so called "smart receiver" that immediately generates precise estimation products). This allows solutions for a virtually unlimited number of reference frame receivers at zero operational cost. The DANCER project is in an advanced state of implementation and will therefore be discussed in more detail in the next section.

The DART project (DAncer Real-Time-kinematic) aims to implement a web interface to the DANCER reference frame realization software in such a way that RTK users can establish accurate position coordinates in the DANCER ITRF realization. To this purpose, a DART user downloads the most recent global solution (and prediction) for GPS orbits, clocks and polar motion from any DANCER computer in the area, and interacts with other near-by DART users for ambiguity resolution in a short-baseline network. Today, the DART project only exists as a concept: not even a prototype has been constructed. The DANCER project has implemented a complete orbit estimation process that currently only processes GPS data. Some other geodetic datasets – notably VLBI, for observing absolute UT1 – might be added in the future. The intention is to use the same estimation module in DIGGER, and to construct DART by reusing existing RTK software. The main effort in terms of implementation of the three projects is therefore to produce the DANCER system.

*Status of the DANCER project*

Because the current WG activities focus on the DANCER project, its status will be discussed in some more detail. DANCER is implemented as a JAVA application around the JXTA peer-to-peer protocol, and uses the JXSE implementation of JXTA that is freely available from SUN Microsystems. This means that the entire peer-to-peer layer, including facilities for e.g. firewall transversal or network discovery, are readily available, and do not need to be implemented by the project. The application layer is nonetheless fairly complicated, in particular because it needs a high "network volatility robustness", i.e. high tolerance against processes that may go off-line at arbitrary moments.

The software implementation stage covered a series of around 16 milestones, each representing relatively independent tasks so that relatively small sub-tasks could be handled by different volunteers. Implementation started in the summer of 2009, and the last milestone was achieved in October 2010. For a project that has a budget of zero, this is a major achievement.

The present stage is one of the most complicated of the project, and is therefore progressing slowly (…but steadily). This is the first of four system test phases, in which the two main components of DANCER - the network communication module, and the parameter estimation module - are tested and stabilized separately. The first two stages perform all system testing off-line, i.e. not on the public internet. Once that off-line processing is entirely stable, both system test stages will be repeated on the real internet, using real GPS receivers. If this also works to satisfaction, the system can be declared operational. On-line testing of the communication layer can be done in parallel to the off-line testing of the estimation module (see Figure 1). At present, the off-line testing of the network is almost completed, so that the project is close to going on-line for the first time. This involves the installation of a first JXTA "relay-peer" with a public IP address.

It is remarkable that a complex system like DANCER can apparently be implemented in the form of a voluntary project at a budget of zero. The advantage is that there are no political dependencies on agencies or other entities, so that free distribution of the software can be ensured. The disadvantage is of course that progress is difficult to predict, as it depends entirely on availability of some very specific people.

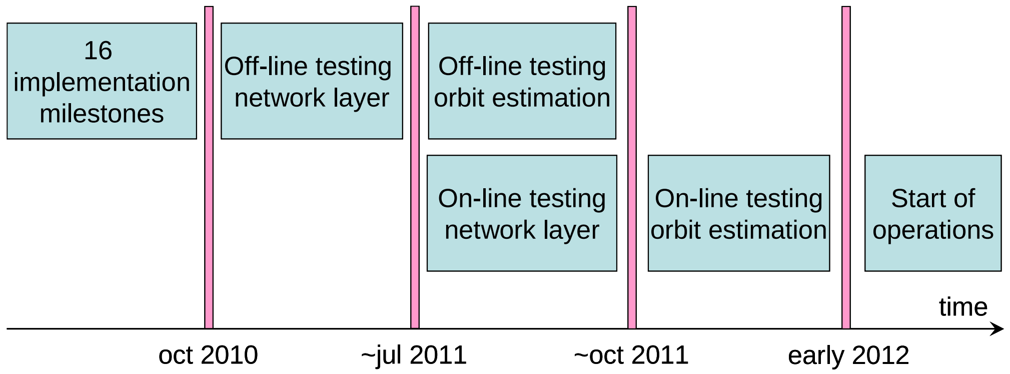


*Figure 1: Implementation schedule of the DANCER project*

Nonetheless, it seems reasonable to aim for the following remaining target dates in this project

- Start of on-line testing of network module: before IUGG 2011 Melbourne
- Start of on-line testing of estimation run: before AGU Fall meeting 2011
- Start of operations: before IGS Workshop 2012

During the IGS Workshop in Newcastle, a splinter meeting was dedicated to the DANCER project. Posters and papers on the Dancer project have been presented in e.g. Advances in Space Research and the REFAG2010 Symposium in Paris. Further details can be found on the project website www.GPSdancer.com.

*Working Group issues*

Membership of the Working Group is not very well-defined, partially because the WG was initially a merger between two earlier Working Groups, and partially because the actual project implementation requires significant assistance from people of very different fields, notably experienced JXSE users from other JXTA-based projects. However, it never seems very meaningful to remove people from a list of Working Group members, nor does it really happen that new members are formally added. Strict membership could create an illusion of exclusiveness that is only counterproductive, and the current situation does not really cause problems. However, in a future revision of IAG structures or WG structures it may be realistic to think of a different term than "Working Groups". In practice, most IAG Working Groups seem to consist of one or two active members who can fall back on a large network of experts – not just formal WG members - for occasional assistance. This concept works quite well in practice, but is probably not what most people would call a Working Group.

*Mid and long term perspective*

From the above it should be clear that the WG has a coherent strategy to reach its objectives, and that the planned projects are progressing in a satisfactory way. If the DANCER system succeeds in starting on-line operations around early 2012, this represents a major accomplishment of an IAG Working Group, and shows that much can be done even without any real resources. The implementation of the DIGGER and DART systems will still require a substantial additional effort, but good progress in the DANCER project gives reason to be optimistic. Together, these three systems will ultimately offer the following improvements

1. DANCER: coherent reference frame time series for *all* GPS reference receivers
2. DIGGER: consistency of reference frame of other techniques with GPS DANCER
3. DART: real-time access to this reference frame for all geodetic GPS users

## Report on Working Group 2 (SC1.1-WG2):

*Chair: Detlef Angermann (Germany)*

*Objectives*

This working group is a joint WG together with Commission 2, Commission 3, and GGOS. The long-term objective of WG2 is to investigate the interaction between the terrestrial reference frame, Earth rotation and the gravity field and to develop methods for a consistent determination of the relevant parameters of these three fields by combining all contributing space geodetic observation techniques.

The main research topics are:

- Study the theoretical and practical interactions/relationships between parameters and models describing the terrestrial reference frame (station positions and their variations), Earth rotation (pole coordinates, UT1, nutation, …) and the gravity field (e.g., low-degree spherical harmonic coefficients).
- Analyses of the sensitivity of the different space geodetic observations for the determination of the relevant parameters and the correlations between them, and assess systematic biases between different space techniques.
- Assess and study the consistency of the products of these three fields.
- Develop improved methods to integrate and combine these three fields by using different space geodetic techniques (VLBI, SLR, GNSS, DORIS) and by including Low Earth Orbiting (LEO) satellites.

*Working Group activities*

Within this working group various activities related to the integration of geometry, Earth rotation and gravity, and the interactions between these three fields were carried out during the period of this report. A major focus was on the assessment and study of systematic biases between different space techniques, improvements regarding the unification of standards for the modeling and parameterization of the different observations, as well as the development of improved methods for a consistent estimation of products of the three fields geometry, Earth rotation and gravity. A significant progress has been achieved in these fields during the last four years. In the following, two projects that address various issues of WG2, are exemplarily mentioned:

- The project "Integration of Earth rotation, gravity field and geometry using space geodetic observations" within the DFG Research Unit „Earth Rotation and Global Dynamic Processes“ is closely related to the objectives of WG2. The project has been started in 2006 and is now in the second funding period (2009 - 2012). Refined combination procedures have been developed to estimate consistently station positions, Earth Orientation Parameters (EOP), satellite orbit parameters together with the spherical harmonics of low degree and order of the Earth gravity field. SLR is the primary space technique to estimate all these parameters in a common adjustment. However, there are high correlations between several parameters (e.g., LOD, $C_{20}$ and the empirical accelerations estimated once per revolution for the satellite orbits). Methods for a decorrelation of these parameters by using multi-satellite constellations were studied. Another issue was to investigate the benefits of a combination of SLR with GPS and VLBI. Since the SLR observation stations are not homogeneously distributed over the Earth, in particular the stable GPS network contributes significantly to stabilize the SLR network. In this context, the integration of the technique-specific networks via co-location sites is a key issue. An example for the results of the present activities is given below.
- The second project that shall be explicitly mentioned in context with the working group activities is the GGOS-D project. The project has been carried out from 2005 to 2008 with the major goal to investigate optimal possibilities for the integration of the various space-geodetic observations, thus fitting perfectly into the framework of GGOS (Rothacher et al., 2011). The members of the group belonged to Helmholtz-Zentrum Potsdam, Deutsches GeoForschungsZentrum (GFZ), Deutsches Geodätisches Forschungsinstitut (DGFI), Institut für Geodäsie und Geoinformation, Universität Bonn (IGG) und Bundesamt für Kartographie und Geodäsie, Frankfurt am Main (BKG). With the project GGOS-D an important contribution could be made to GGOS in that it performed the first steps of an integration of the geometric and gravimetric space geodetic techniques. The major activities may be summarized as follows: (1) Definition and implementation of standards, models and parameterizations for a consistent processing of VLBI, GPS, and radar altimetry observations and for the representation of the products (Steigenberger et al., 2010); (2) Generation of a consistent reference frame for the computation and provision of all parameters of the global observing system (Angermann et al., 2010); (3) Development of methods for the computation of consistent time series of the most important parameters such as station coordinates, EOP, quasar coordinates, low-degree coefficients of the Earth gravity field, troposphere parameters (Nothnagel et al., 2010; Tesmer et al., 2009); (4) Investigation of relationships and correlations between time series of parameters and the comparison and validation of the geodetic results with external geophysical data.

As an example for the working group activities some results are given, that were obtained from the project "Integration of Earth rotation, gravity field and geometry using space geodetic observations" within the DFG Research Unit „Earth Rotation and Global Dynamic Processes“. Figure 2 shows the time series of the low-degree spherical harmonic coefficients ($C_{21}$, $S_{21}$ and $C_{20}$) that were computed at DGFI from SLR data to Lageos 1 and 2 (Bloßfeld et al., 2011). The results were obtained from a consistent estimation of station positions, EOP and orbit parameters of the satellites together with the spherical harmonic coefficients of the Earth gravity field. The results with an arc length of 7-days were compared with those of 28 days. An external comparison with the monthly solutions of the Center of Space Research (CSR), USA shows a very good agreement.

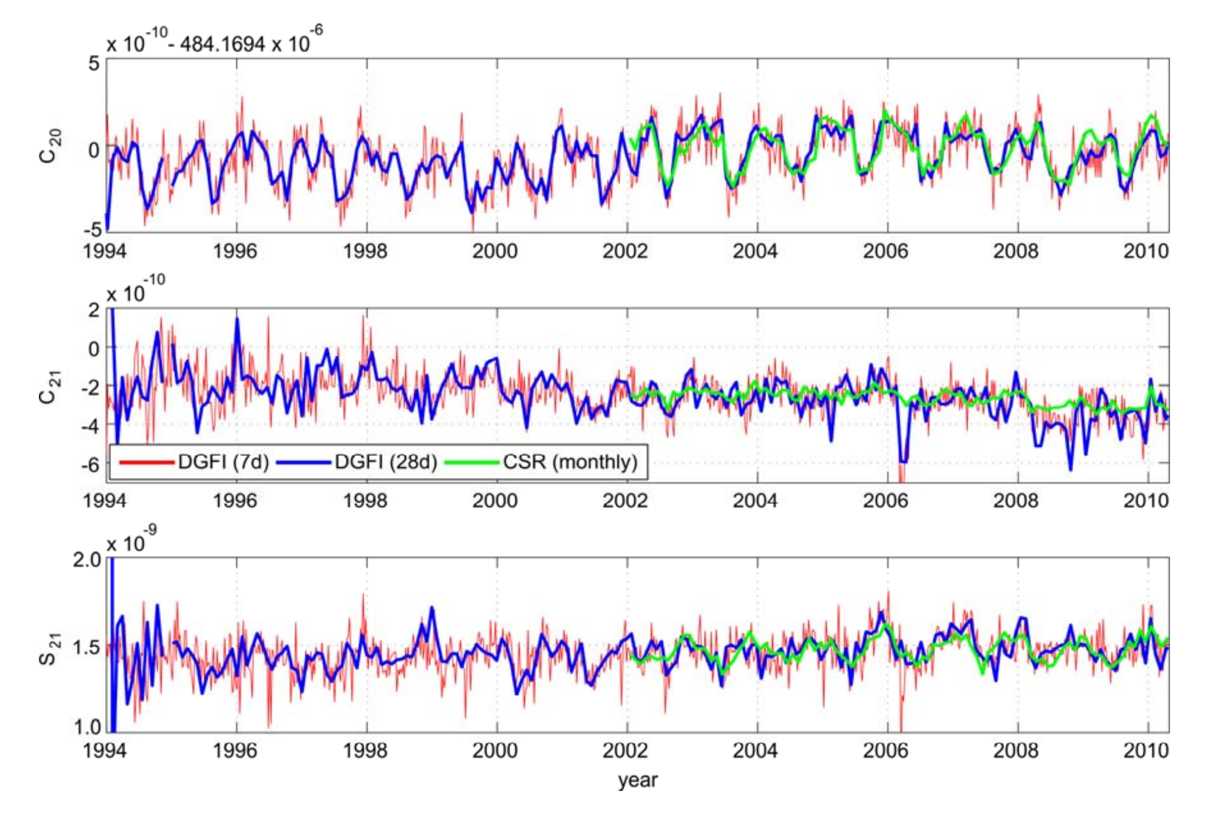


*Figure 2: Estimated normalized low-degree harmonic coefficients C21, S21 and C20 of the Earth gravity field. The DGFI solutions (arc lengths of 7 days and 28 days) contain only data from Lageos 1 and 2, whereas the CSR solution includes in addition data from Stella, Starlette and Ajisai.*

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## Report of Working Group 3 (SC1.1-WG3):

*Chair: Johannes Böhm (Austria)*

The main task of Working Group 3 is the comparison and combination of atmospheric information derived from different space geodetic techniques, such as GPS, VLBI, DORIS, or altimetry. Major research topics are the investigation of differences between the troposphere delay parameters and the Total Electron Content (TEC) values with the assessment of systematic biases between the techniques in particular. The Global Geodetic Observing System (GGOS) with the goal to integrate all observations of geometry, rotation and gravity field of the Earth, is requiring the accurate, consistent, and bias-free modelling of delays in the neutral atmosphere ('troposphere') as well as in the ionosphere over all techniques.

Prerequisite for the comparison and combination of troposphere parameters is the application of consistent models and parameters, i.e., hydrostatic, wet, and gradient mapping functions, as well as a priori zenith delays and a priori gradients. (Read below for more details on this issue.) Also critical in the analysis of space geodetic observations and consequently for the comparison of TEC values (and also troposphere parameters) is the use of higher-order ionospheric terms, as e.g. discussed by Petrie et al. (2010) for GPS.

As replacement or extension to present-day troposphere delay modelling, direct ray-tracing through numerical weather models for the individual observations will become more and more important in the analysis of space geodetic observations. As a consequence, a *Workshop on Ray-Tracing for Space Geodetic Techniques* was held in Vienna in April 2010 within SC1.1-WG3 which was devoted to technical and physical details of ray-tracing, to the development of models from the ray-traced delays, and to their application in the analysis of space geodetic techniques. As an outcome of the workshop, a comparison campaign of various software packages for ray-tracing was initiated, and the results were described by Nafisi et al. (2011). High-resolution data from the operational analysis of the European Centre for Medium-Range Weather Forecasts (ECMWF) were provided to the five participating institutions for the stations Tsukuba (Japan) and Wettzell (Germany). In general, Nafisi et al. (2011) found good agreement among the submissions with standard deviations and biases at the 1 cm level (or significantly better for some combinations) between the ray-traced slant factors (azimuth-dependent mapping functions multiplied with a nominal zenith delay) from the different solutions at 5 degrees elevation if determined from the same pressure level data of the ECMWF (see Figure 3).

Many investigations have been carried out to compare the troposphere parameters derived from GPS, VLBI, and DORIS with observations from water vapour radiometers (WVR) and values from numerical weather models, e.g. Krügel et al. (2007) for the 15-days continuous VLBI campaign CONT02 or recently Teke et al. (2011) for CONT08. Furthermore, Steigenberger et al. (2007) and Heinkelmann et al. (2007) compared long time series from VLBI and GPS. From 2005 to 2008, a common research project by several German institutions dealt with the *Integration of Space Geodetic Techniques as the Basis for a Global Geodetic-Geophysical Observing System* (GGOS-D, Rothacher et al., 2010). More information about this project is available at the webpage *http://www.ggos-d.de*.

Some Ph.d. theses (partly in German) were finished in the last four years which also deal with the comparison and combination of atmosphere delay parameters derived from space geodetic techniques, e.g. Thaller (2008), Heinkelmann (2008), and Schmid (2009) for the troposphere or Todorova (2009) for the ionosphere. Those theses contain detailed and very important information for this working group.

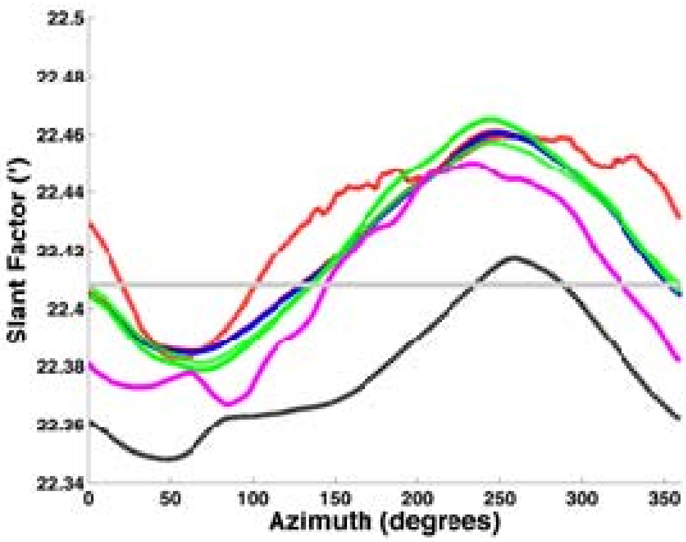


*Figure 3: (from Nafisi et al., 2011). Ray-traced slant factors in m at 5 degrees elevation at Wettzell (Germany) on 1 January 2008 at 0 UT as determined with different programs and/or approaches from data of the ECMWF. Mind that two group used model level instead of pressure level data (magenta and black lines). More discussion of the results can be found in (Nafisi et al., 2011).*

*Troposphere delay comparisons*

Teke et al. (2011) compared troposphere parameters for CONT08, a 15-days campaign of continuous VLBI observations in the second half of August 2008. In their study, VLBI estimates of troposphere zenith total delays and gradients were compared with those derived from observations with the GPS, DORIS, and water vapour radiometers (WVR) co-located with the VLBI radio telescopes. Similar geophysical models were used for the analysis of the space geodetic data, whereas the parameterization for the least-squares adjustment was optimized for each technique. In addition to space geodetic techniques and WVR, zenith delays and gradients from various global and regional numerical weather models were used for comparison. The best inter space geodetic agreement of zenith delays during CONT08 is found between the combined IVS and the IGS solutions with a mean standard deviation of about 6 mm over all CONT08 sites, whereas the agreement with numerical weather models is between 6 and 20 mm. The standard deviations are generally larger at low latitude sites because of higher humidity, and the latter is also the reason why the standard deviations are larger at northern hemisphere sites during CONT08 in comparison to CONT02 which was observed in October 2002 (Snajdrova et al., 2005). This finding also confirms Thaller et al. (2008) who found that the standard deviations between zenith delays from GPS and VLBI are correlated with the size of the zenith wet delays. Figure 4 is from Teke et al. (2011), and it shows the various zenith delays at Wettzell (Germany) during CONT08 which were used in the comparison.

Furthermore, it is described by Schmid et al. (2005) and Schmid (2009) that the biases between the techniques decrease when using absolute phase center patterns for GPS. However, there remains a significant influence on the zenith delays at those GPS antennas covered by a radome.

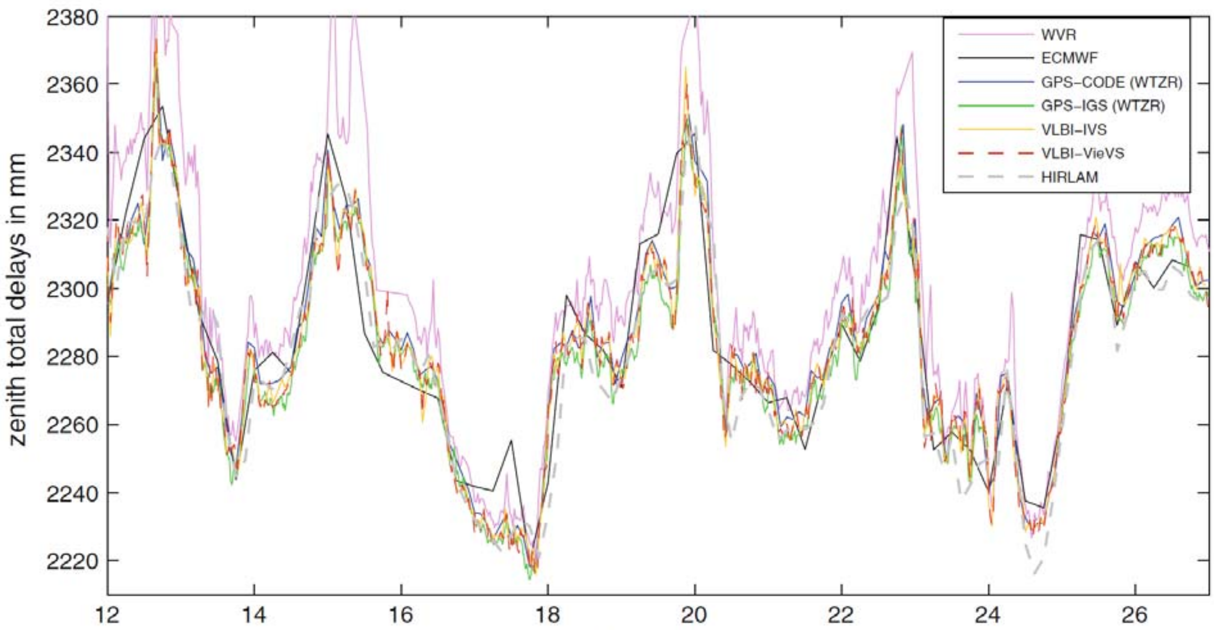


*Figure 4: (from Teke et al., 2011). Zenith total delays at site Wettzell (Germany) vs. day in August 2008 from space geodetic techniques (VLBI, GPS), numerical weather models (ECMWF, HIRLAM) and WVR.*

The assessment of troposphere gradients from the different techniques is not as clear because of different time intervals, different estimation properties, or different observables (Teke et al., 2011). However, the best inter-technique agreement for CONT08 is found between the IVS combined gradients and the GPS solutions with standard deviations between 0.2 and 0.7 mm. Nothnagel et al. (2009) compared mean gradients as derived from GPS and VLBI analysis, and they found that GPS gradients are generally larger (in absolute sense) than those determined with VLBI. Moreover, Böhm et al. (2011) described recently that mean GPS gradients are larger than those derived from numerical weather models. However, more investigations need to be carried out to explain these differences.

Important for the comparison and in particular for the combination is the use of identical geophysical models for the determination of the a priori troposphere delays. The a priori hydrostatic zenith delays are usually determined from pressure values at the site, which can be measured locally, extracted from a numerical weather model or - with minor precision - determined from empirical equations like the GPT model (Böhm et al., 2007). The same holds for the selection of the hydrostatic mapping function: mapping functions based on data from numerical weather models like the VMF1 (Böhm et al., 2006a) are more accurate, but empirical mapping functions like GMF (Böhm et al., 2006b) are easier to be implemented and yield also consistent values across the techniques. However, geodetic analysis should certainly go for the most accurate models as e.g. shown by Steigenberger et al. (2009), requiring that special care is taken to derive consistent values for the different techniques.

*Combination of troposphere delays*

It is essential to apply very accurate measures for the local ties between the various antennas at a site, because the differences in the station coordinates also correspond to differences in the hydrostatic and wet zenith delays. This is important for the combination of space geodetic observations: Any technique observing at microwave frequencies at a site is sensitive to the same troposphere delays; thus, if the local ties and the troposphere ties (!) are accounted for properly, the geodetic results (e.g. station coordinates but also troposphere parameters) benefit from the combination because more observations are contributing to the estimation of the same parameters. So far, routine combinations at the normal equation level do not include troposphere parameters, but future combinations should definitely take them into account. As another step towards its realization, there are also plans within the *IERS Working Group on the Combination at the Observation Level* to combine troposphere parameters.

Thaller (2008) concludes in her Ph.D. thesis that the inclusion of the troposphere parameters into the combination yields time series of zenith delay and horizontal gradients for the GPS and VLBI sites that are fully consistent with the common reference frame. The consistency is especially important as the time series based on the independent single-technique solutions' reference frames differ from those time series based on a common reference frame by up to 2 mm at mean. Thaller (2008) states that a combination of the zenith delays can stabilize the determination of the height coordinate, although this stabilization has not been seen for all co-locations. But she has demonstrated that a stabilization of the height component by combining the zenith delay is achieved if the local tie for the corresponding co-location is missing. The combination of the zenith delay acts only indirectly on the stability of the station height, thus, the combination of the zenith delay cannot fully replace the information that is given by introducing the local tie directly. However, as the problems concerning local tie values are manifold, the combination of the troposphere parameters might be an alternative to the application of local tie values that are questionable.

Thaller (2008) also summarizes that a stabilization of the solution similar to the effect seen for the combination of the troposphere zenith delay could not be shown for the combination of the troposphere gradients, neither with horizontal local ties additionally introduced nor without applying the local ties. However, it could be demonstrated that the common treatment of troposphere gradients together with the TRF can give valuable information about the discrepancy between the local tie and the coordinate differences derived from the space-geodetic techniques.

*Comparison and combination of ionosphere delays*

The ionosphere (from approximately 50 km to 1000 km) is dispersive for microwaves, and therefore the ionospheric delays (or phase advances, respectively) can be mostly eliminated by observing at two frequencies. However, the ionospheric delays, which are different for all techniques, are caused by similar Total Electron Content (TEC) values. Thus, all dual-frequency techniques should determine similar TEC values at the same line of sight or Vertical (VTEC) values above a point on the Earth surface.

IGS Ionosphere Working Group comparisons of TEC values were carried out between those values determined from IGS TEC maps and TEC values from altimeter observations (e.g. JASON, TOPEX, ENVISAT) (Hernández-Pajares et. al, 2009). These comparisons, which are only possible over the oceans and thus provide a lower boundary for the GPS TEC performance, yielded a mean bias of about zero and a mean standard deviation over all latitudes of about 5 TECU, but comparisons near the coast (with close GPS stations) implied that standard deviations can be as low as 2 TECU.

Within the IGS Analysis Centers (AC) the classical input data for the development of Global Ionosphere Maps (GIM) of VTEC are obtained from dual-frequency observations carried out at GNSS ground stations. However, GNSS stations are inhomogeneously distributed around the world, with large gaps particularly over the oceans; this fact reduces the precision of the GIM over these areas. On the other hand, dual-frequency satellite altimetry missions such as

TOPEX/Poseidon (T/P) and Jason-1 provide information about the ionosphere precisely above the oceans; and furthermore Low Earth Orbiting (LEO) satellites, such as Formosat-3/COSMIC (F-3/C) provide well-distributed information of the ionosphere globally. The combined GIMs connect the advantages of the different techniques and, thus, provide more homogeneous global coverage and higher reliability. Todorova et al. (2007) performed the combination of GNSS observations and satellite altimetry measurements for global modeling of the VTEC. Their studies showed that the combined GIMs from GNSS and satellite altimetry increased the precision of GIMs over the oceans. In the recent studies carried out by Alizadeh et al. (2011) VTEC values calculated from transformed F-3/C radio occultation measurements were also included in the combination procedure. Within their study it was shown that the combined VTEC maps of GNSS, Jason-1, and F-3/C have a higher accuracy and reliability compared to the GNSS-only maps (see Figure 5). They found a mean VTEC bias (combined minus GNSS) of -0.7 TECU through a whole day and a mean RMS difference (combined minus GNSS) of -0.2 TECU, which verified an improvement of 0.2 TECU in the accuracy of VTEC maps after combination. Dettmering et al. (2010) performed the combination of several space geodetic techniques for a regional modeling of VTEC. Their approach used the International Reference Ionosphere (IRI) as a background model. The GPS observations were included in the model in combination with radio occultation data from LEOs, dual-frequency radar altimetry measurements, and data obtained from VLBI. It was shown in their study that a combination of different observation techniques for ionospheric modeling could provide reliable VTEC maps with high resolution and accuracies better than 2 TECU.

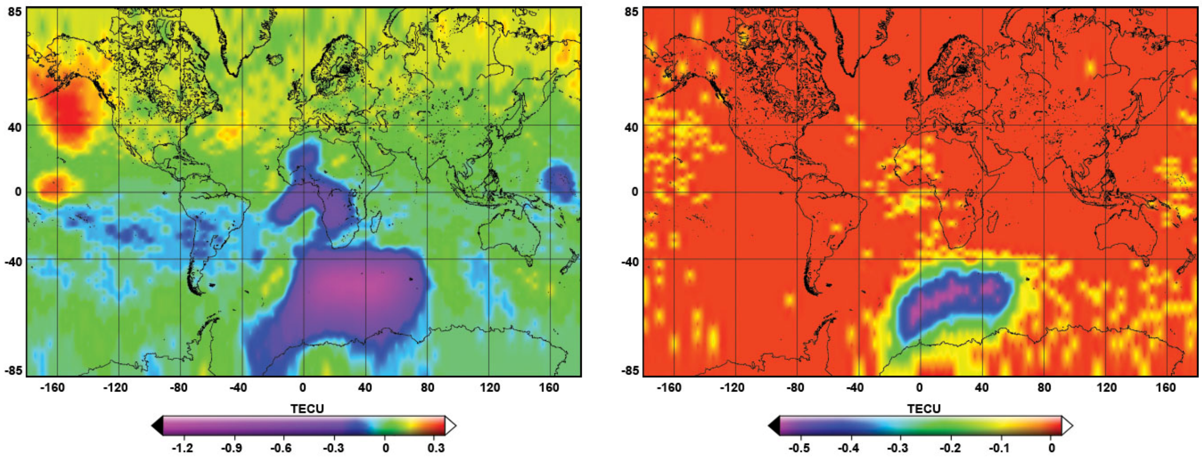


*Figure 5: (from Alizadeh et al., 2011) (a) VTEC map of GNSS, satellite altimetry and COSMIC combined <minus> GNSS, satellite altimetry combined solution (global RMS 0.37 TECU), and (b) RMS map of GNSS, satellite altimetry and COSMIC combined <minus> GNSS, satellite altimetry combined solution (global RMS 0.89 TECU), day 202, 2007 – 9:00UT.*

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## Outlook

Considerable progress has been made in some of the combination issues that are addressed by IAG Sub-Commission 1.1. However, in order to reach a rigorous combination of all common parameters present in the solutions of the individual space geodetic technique much has still to be achieved. The next steps should be:

- The terrestrial reference frame, the Earth Orientation Parameters (EOPs) and the celestial reference frame should be linked in a consistent way. Therefore, the quasar coordinate estimates (derived from VLBI data) should be included in the normal equations systems or variance-covariance matrices to be combined. The VLBI community is working in this direction.
- Daily solutions should be generated from GPS, DORIS and VLBI that contain not only station coordinates and Earth Rotation Parameters (ERPs) but also troposphere zenith delays and gradients. The combination of troposphere zenith delays and gradients is important to improve the consistency of the solutions and to detect technique-specific biases.
- Low-degree coefficients of the Earth's gravity field and range biases should be included in the SLR weekly solutions and should become part of the combined intra-technique solutions produced by the ILRS combination centers.
- Low Earth Orbiters with more than one observation technique onboard should be analyzed to benefit from the co-location of instruments in space. The inclusion of LEOs like CHAMP, GRACE, and GOCE into the global solutions based on the ground networks (GPS and SLR) would also help to link geometry and the gravity field.

We see from the few items above, that large deficits still exist and a lot of work is still ahead of IAG Sub-Commission 1.1. The long-term goal of Sub-Commission 1.1 is still the development of a much better understanding of the interactions between the parameters describing geometry, Earth rotation, and the gravity field, as well as the study of methods to validate the combination results, e.g., by comparing them with independent geophysical information.

## Sub-Commission 1.2: Global Reference Frames

*President: Claude Boucher (France)*

The IAG Sub-Commission 1.2 was created in 2003 as a part of the new structure of the International Association of Geodesy (IAG). The present missions were fixed by the charter for the period 2007-2010. This report provides only summaries of activities. More details or references can be found in the web pages hosted by the IAG Commission 1 website.

*Structure*

The sub-commission has an open membership. Several Study Groups and Working Groups are linked to SC1.2 :

- IC-SG1: Theory, implementation and quality assessment of geodetic reference frames (jointly with ICCT)
- IC-WG1-3: Concepts and terminology related to Geodetic Reference Systems
- IC-WG1-4: Site Survey and Co-location (jointly with IERS)

Please refer to their own activity reports.

In order to stimulate some specific research topics, two task forces were established within the Sub-commission:

- External Evaluation of Terrestrial Reference Frames Chairman : Xavier Collilieux (France)
- Global Geodetic Observatories Chairman: Perguido Sarti (Italy)

*Terminology*

The IC-WG1-3 was specifically devoted to this subject. Please refer to its report

*Site survey and co-locations*

The IC-WG1-4 has reactivated its involvement into research topics, and therefore its close link with the SC activities, thanks to Perguido Sarti who is now chairing this group. See its report.

*International Terrestrial Reference System (ITRS)*

At the IUGG/IAG General Assembly of Perugia, an IUGG resolution was approved about ITRS, related to its definition and adoption by the geoscience community. The definition is consistent with the recent IAU resolutions. More details can be found in the new version of the IERS Conventions.

It is worthwhile to mention numerous efforts to promote the adoption of ITRS and its realizations as unique preferred system among the various communities. Several actions have started within GGOS, specifically:

- Establishment of a working group on an ITRS standard
- Leading a sub-task in the frame of GEO on these issues

Within the GNSS community, a Task force on Geodetic references has been recently (dec 2008) established by the International Committee for GNSS (ICG)

Within the metrological community, the Consultative Committee on Time and Frequencies (CCTF) took a resolution to adopt ITRS, submitted to the International Conference for Weights and Measurements (CGPM), the relevant inter-governmental organization.

Concerning ITRS itself, some discussions were raised about the possible refinement of its present definition, in particular about its origin and scale. The present situation did not show a clear need to modify the current definition.

*International Terrestrial Reference Frame (ITRF)*

Numerous research activities are developed related to ITRF, either as the methodological level or on quality assessment. More details can be found in the various reports by IERS, in particular related to ITRF2005 and the new solution, ITRF2008, released end of May 2010.

We can mention the relevant chapters of the new GGOS 2020 document , and the organization by Sakis Dermanis of a session during the Hotine-Marussi symposium in July 2009.

*External Evaluation of Terrestrial Reference Frames*

Considering the importance of the external evaluation of ITRF, a task force has been recently created by the SC. Its main objectives are:

- To investigate various activities in which the adopted Terrestrial Reference Frame (TRF) has a quantitative influence on the results of this activity, such as
  - Precise Orbit Determination (POD)
  - Data reduction of satellite radar altimetry
  - Correction of vertical motions at tide gauges
  - Antenna Phase Center Offsets/Variations calibration for GNSS (on board and ground)
  - Geophysical models (plate motions, post-glacial rebound…)
  - Geophysical Fluid Mass inversions
  - ….
- To discuss for each identified activity whether there is a preferred numerical effect in view of a priori expectations
- To inverse the relation to evaluate TRF datum and derive possible external constraints on TRF datum fixation, related to its origin, scale or orientation and their time evolutions

Although TRF in general are under consideration, a major impact of these activities is clearly for ITRF.

*Global Geodetic Observatories*

In order to satisfy the need to activate work on Global Geodetic Observatories (GGO) which is in the SC charter , a task force was recently established, which is just starting. Items to be considered:

- GGO as fundamental station for geodetic networks of various types (space techniques, gravimetric, clocks, tide gauges…)
- Metrological aspects
- Co-locations of instruments : tie issues, colocated sensors, other geophysical sensors (seismometers, magnetometers, atmospheric sensors…)
- Operational and logistic issues
- Network design and coordination of network deployments

# Sub-Commission 1.3: Regional Reference Frames

*President: João Torres (Portugal)*

## Introduction

Sub-Commission 1.3 deals with the definitions and realizations of regional reference frames and their connection to the global International Terrestrial Reference Frame (ITRF). It offers a home for service-like activities addressing theoretical and technical key common issues of interest to regional organizations.

In addition to specific objectives of each regional sub-commission, the main objectives of SC1.3 as a whole are:

- Develop specifications for the definition and realization of regional reference frames, including the vertical component with special consideration of gravity data and other data.
- Coordinate activities of the regional sub-commissions focusing on exchange and share of competences and results.
- Develop and promote operation of GNSS permanent stations, in connection with IGS whenever appropriate, to be the basis for the long-term maintenance of regional reference frames.
- Promote the actions for the densification of regional velocity fields.
- Encourage and stimulate the development of the AFREF project in close cooperation with IGS and other interested organizations.
- Encourage and assist, within each regional sub-commission, countries to re-define and modernize their national geodetic systems, compatible with the ITRF.

Six regional Sub-Commissions compose the Sub-Commission 1.3:

- Sub-Commission 1.3 a: Europe
- Sub-Commission 1.3 b: South and Central America
- Sub-Commission 1.3 c: North America
- Sub-Commission 1.3 d: Africa
- Sub-Commission 1.3 e: Asia-Pacific
- Sub-Commission 1.3 f: Antarctica

Furthermore, the Working Group on Regional Dense Velocity Fields was created within SC 1.3. This WG aims at joining the efforts of the regional sub-commissions together with the groups processing local/regional CORS or repeated GNSS campaigns in order to compute a dense velocity field referenced in a unique global frame.

### *Overview*

The activities of each of the regional Sub-Commissions and the WG Regional Dense Velocity Fields are reported hereafter.

A summary of those activities and the main results achieved, are summarized as follows.

*Sub-Commission 1.3 a: Europe*

- The number of permanent GNSS tracking sites in Europe has grown considerably; more than 244 EPN stations are operated the end of 2010 by national European institutions. The number of sites which record GLONASS data simultaneously to GPS data and which stream real time data is steadily increasing (59 % and 49 % resp.). Also a new Local Analysis Centre joined the group of EPN analysis centres, increasing the total number to 17.
- The majority of the EPN Local Analysis Centres (LAC) participate in the EUREF Special Project “EPN Reprocessing”. The complete EPN is re-analysed using the data from 1996 until 2006. The first results of EPN REPRO1 campaign are expected soon. Another re-analysis of the entire EPN is foreseen using the ITRF08.
- The number of regional broadcasters for real-time GNSS data increased to 3. One of them started to broadcast satellite orbits in the ETRS89 (realization ETRF2000). Using these orbits, users can directly derive in real-time coordinates in the ETRS89.
- The continuation of the promotion of the ETRS89 (European Terrestrial Reference System) and the EVRS (European Vertical Reference System), following the adoption by INSPIRE of these systems as the basis for georeferencing in Europe.
- The computation of transformation parameters between national height systems and EVRS (EVRF2007) and its delivery in April 2010. Additionally the online-transformation for heights of single points was implemented.
- The continuation of the ECGN (European Combined Geodetic Network). The ECGN is considered as a European contribution to the IAG Project Global Geodetic Observation System (GGOS).
- The realization of symposia in 2008 (Brussels), in 2009 (Florence), 2010 (Gävle) and 2011 (Chisinau) (in preparation).

*Sub-Commission 1.3 b: South and Central America*

- The implementation of the SIRGAS-CON network, which replaces the former realizations and allows a permanent monitoring of the reference frame. The SIRGAS-CON network was extended to 270 continuously operating GNSS stations. 48 stations are integrated in the IGS global network, and 72 receivers are able to track GLONASS. The data are weekly processed by 9 analysis centres.
- The new strategy used to realize the SIRGAS datum, in order to reduce network deformations due to the effect of seasonal variations in the datum realization, with the alignment of the weekly solutions of the SIRGAS-CON frame to the ITRF using the IGS weekly coordinates.
- The reprocessing of the entire SIRGAS-CON network applying the reprocessed IGS products (IG1), allowing the improvement of the reliability and accuracy of station positions and velocities computed within multi-year solutions.
- The availability of a Velocity Model for SIRGAS (VEMOS), consisting on horizontal velocities in those regions which are not covered by SIRGAS-CON.
- The systematic adoption of official geodetic reference system at national level based on SIRGAS in 16 of the 18 SIRGAS member countries.

- The development of actions for capacity building and the promotion of SIRGAS in the member countries, in particular the support to the establishment of new experimental associated analysis centres and the organization of the SIRGAS School on Reference System, under the sponsorship of the IAG and PAIGH.
- The Executive Committee met in Bogotá (2007), in Montevideo (2008), in Buenos Aires (2009) and Lima (2010).

*Sub-Commission 1.3 c: North America*

- The realization of densifications of the ITRF and IGS global networks by weekly combinations of seven different regional weekly solutions using different GPS processing software, including for the first time a solution from Mexico.
- The generation of the last cumulative solutions (coordinates and velocities) based on the weekly NAREF combinations to produce new solutions on an annual basis.
- The reprocessing of regional solutions prior to GPS Week 1400 using the new IGS procedures and absolute antenna phase center variation models is underway. A solution has been realized at one processing center for 2,264 CORS stations based on weekly reprocessed solutions from 1994 to 2010.5 with absolute antenna calibrations and global sites for alignment to IGS08.
- The progress towards a new realization of NAD (North America Datum). This new realization will be truly geocentric, fixed to North America and fully consistent with the ITRS.
- The continuation of the activities related to the definition and maintenance of the relationships between international and North American reference frames/datums. The transformation between NAD83 and ITRF2008 was determined for use in Canada and the US, and other activities have focused on education and outreach efforts.
- The re-activation of the working group related to the maintenance of the vertical datum for the management of the Great Lakes water system, taking also into consideration the need to update the International Great Lakes Datum by 2015.

*Sub-Commission 1.3 d: Africa*

- The Steering Committee met several times. The most significant was a series of joint meetings held in June 2008 in Johannesburg, June 2010 in Washington and November 2010 in Johannesburg which brought together representatives from the fields of seismology, meteorology, space weather, geophysics and geodesy.
- Progress has been made with the installation of permanent GNSS reference stations in Africa. These have been installed by National Mapping Agencies, Universities and research groups.
- An Operational Data Centre (ODC) for AFREF with an open data policy, became operational in June 2010 and is currently archiving data from approximately 45 permanent continuous GNSS base stations.
- Four annual training courses were held between 2007 and 2010 at the Regional Centre for Mapping of Resources for Development (RCMRD), covering the concepts of AFREF, permanent GNSS reference stations, reference frames and the processing of GNSS data. The first two courses were more theoretical in nature while the latter two placed greater emphasis on the practical aspects of the project.

- A Call for Participation in the processing of GNSS data in support of the AFREF project has been prepared and will be distributed shortly.

*Sub-Commission 1.3 e: Asia-Pacific*

- The resolution of the 18th United Nations Regional Cartographic Conference (UNRCC) for Asia and the Pacific to mandate APREF, also endorsed by the International Global Navigation Satellite System Service (IGS), the United Nations Office for Outer Space Affairs (UNOOSA) and the Federation of International Surveyors (FIG).
- The APREF initiative to realize a high-standard regional reference frame by processing the GNSS data of the network in different Analysis Centres (ACs).
- The availability since 2010 of a weekly solution containing weekly estimates of the coordinates of the participating Asia-Pacific GNSS tracking stations and their covariance information. This product gives a reliable time-series of a regional reference frame in the ITRF and a quality assessment of the performance of the GNSS CORS stations included in the network. The APREF combined solution will be also a contribution to the IAG Regional Dense Velocity Field Working Group.
- The realization of an annual geodetic observation campaign in order to densify the ITRF in the Asia-Pacific Region and to provide an opportunity to connect to national geodetic networks and to determine site velocities. These campaigns have focused on GPS observations but incorporated also other geodetic techniques, SLR and VLBI.
- The large activity in the Asia-Pacific area in order to upgrade and extend the geodetic infrastructure, by the installation of GNSS and VLBI stations, and the launch of projects for crustal monitoring.
- The contribution to enhance the regional geodetic infrastructure, to encourage the transfer of GPS technology and sharing of analysis techniques to nations in need.
- The meetings held in Seoul (2007), Kuala Lumpur (2008), Bangkok (2009), Singapore (2010). The next meeting is planned for Ulaanbaatar in July 2011.

*Sub-Commission 1.3 f: Antarctica*

- The realization of SCAR GPS Campaigns in 2008 and 2009. The data of 34 Antarctic sites are collected in the SCAR GPS database beginning with the year 1995.
- The continuation of data analyses and presentation of the results at the XXX SCAR Meeting (2008) and at the EGU Meeting (2009).
- The meeting that took place during the XXX SCAR Meeting, resulting in the working plan of the SCAR Group of Experts on Geodetic Infrastructure in Antarctica (GIANT) for the years 2008-2010.
- The active participation in the project POLENET (Polar Earth Observing Network), in the frame of the International Polar Year 2007/2008.

*Working Group on Regional Dense Velocity Field*

- The WG appointed for each region a region coordinator to gather velocity solutions for their region (in accordance with the WG requirements) to produce one regional combined velocity solution. The cumulative velocity solutions submitted in 2009 showed that they could not be rigorously combined.

- The investigations are being carried out in order to verify the agreement between regional and global GNSS solutions and on the best possible procedures to reduce network effects.
- The latest tests are being carried out with one new global solution and 4 new regional solutions, all of them based on a reprocessing and using absolute antenna models, in about 400 densification sites to the ITRF2008.
- The WG is concentrated on identifying the sources of disagreements between the solutions submitted to the WG and the ITRF2008 before using any site as a frame-attachment site.
- The WG met in Miami Beach (2008), San Francisco (2008), Vienna (2009), Buenos Aires (2009) and Paris (2010). A website has been set up providing a gateway to the WG activities.

### *Conclusion*

The activities of each of the regional Sub-Commissions and the WG Regional Dense Velocity Fields show that all the components of the structure are developing according to the main objectives of the SC 1.3.

It must also be emphasized that during the 4-year period covered by this report there was a strong increase of activity in the less developed regions, as it is demonstrated by the results achieved.

Some general aspects deserve to be referred:

- The activities are contributing to the scientific and technical development in several topics such as GNSS analysis and processing, precise reference frame establishment, among others.
- The organizational aspects play a more and more important role and are crucial for the efficient achievement of results.
- There is a great effort to bring together different types of institutions (R&D structures, National Mapping Agencies, political and economic agencies, etc.) to support the realization of international campaigns (GNSS and other space techniques) and the installation of continuously observing GNSS sites.
- The products delivered are used not only by the scientific community but are also being used to define world-wide national reference frames related to the ITRF.
- There is a concern to develop education and training events, especially in less developed regions and countries. This effort must be continued and supported by the IAG.
- It is recognized the role of the WG Regional Dense Velocity Fields to detect some problems that were not evident in each of the regional Sub-commissions, due to the fact that the data are processed in limited areas.

Last but not least, the reports of all the components of SC 1.3 show the importance to keep and develop this kind of organization within the IAG, since each region of the world has its own way to proceed, considering all the variables involved in this kind of work.

# Sub-Commission 1.3a: Regional Reference Frame for Europe (EUREF)

*Chair: Johannes Ihde (Germany)*

## Introduction

The long-term objective of EUREF, as defined in its Terms of Reference "is the definition, realization and maintenance of the European Reference Systems, in close cooperation with the pertinent IAG components (Services, Commissions, and Inter-Commission projects) as well as EuroGeographics". For more information see http://www.euref.eu.

The results and recommendations proceeding from EUREF support the use of the European Reference Systems in all scientific and practical activities related to precise geo-referencing and navigation, Earth sciences research and multidisciplinary applications. EUREF makes use of the most accurate and reliable terrestrial and space-borne techniques available, and develops the necessary scientific background and methodology. Its activities are focused on a continuous innovation and on the changing user needs, as well as on the maintenance of an active network of people and organizations, and may be summarized as follows:

- to maintain the ETRS89 (European Terrestrial Reference System) and the EVRS (European Vertical Reference System) and upgrade the respective realizations;
- to refine the EUREF Permanent Network (EPN) in close cooperation with the IGS;
- to improve the European Vertical Reference System (EVRS);
- to contribute to the IAG Project GGOS (Global Geodetic Observing System) using the installed infrastructures managed by the EUREF members.

These activities are reported and discussed at the Technical Working Group (TWG) Meetings and annual EUREF Symposia, an event that occurs every year since 1990, with an attendance of about 100-150 participants coming from more than 30 countries in Europe and other continents, representing universities, research centers and the NMCA (National Mapping and Cadastre Agencies). It's an open forum, and may be attended by any person interested in the work of the Sub-Commission. The organization of the EUREF Symposia has been and will be supported by EuroGeographics, the consortium of the European National Mapping and Cadastral Agencies, reflecting the importance of the EUREF work for practical purposes. This involvement is consolidated since 2007 by a formal liaison between EUREF and EuroGeographics. The latest EUREF symposia took place in Brussels, Belgium (2008), in Florence, Italy (2009), in Gävle, Sweden (2010), the 2011 symposium will be held in Chisinau, Moldova.

To achieve these activities, EUREF works closely together with EuroGeographics. A Memorandum of Understanding between EUREF and EuroGeographics guarantees on one hand that the developments made by EUREF are absorbed and implemented by the NMCA; and on the other hand, to involve EUREF in the NMCA concerns and problems on geodetic issues that must be solved in a European and global perspective

EUREF is an associated member of the International Committee on Global Navigation Satellite Systems (ICG) since 2009. Goals of the annual meetings are to review and to discuss developments in GNSS and to allow ICG members, associate members and observers to consider matters of interest. ICG also addressed GNSS technology in the era of multi-systems receivers and the impact of GNSS interoperability on timing and other user applications.

## Conventional frame ETRF2000

The ETRS89 is linked to the International Terrestrial Reference System (ITRS) and up to the release of the ITRF2005, each new realization of the ITRS (i.e. ITRFyy) was followed by a new realization of the ETRS89 (i.e. ETRFyy). However, from ITRF2005 on, the TWG decided to continue using the ETRF2000 as the ETRS89 realization and it adopted the ETRF2000 as the conventional realization of the ETRS89. The ETRF2000 will thus also be the ETRS89 frame adopted in conjunction with the latest release of the ITRS, ITRF2008 (release May 2010, for more information see http://itrf.ign.fr/ITRF_solutions/2008/).

The mathematical transformation from ITRFyy to ETRF2000 can be done in a two-step approach using two successive Helmert transformations (ITRFyy → ITRF2000 followed by ITRF2000 → ETRF2000), or can be done by one single 14-parameter transformation (directly from ITRFyy → ETRF2000), (Altamimi, 2009). The parameters of all these transformations are available from the Memo by Boucher and Altamimi (2008) which was updated on Nov. 24, 2008 and which will soon be updated again to include the transformation formula to and from the ITRF2008. To help users to perform the necessary transformations, an on-line transformation tool, which allows transforming between any ITRS/ITRS, ITRS/ETRS89 and ETRS89/ETRS89 realization has been put on-line at http://epncb.oma.be/_dataproducts/coord_trans/.

## EUREF Permanent GNSS Network (EPN)

The EPN is a permanent GNSS network created by the IAG Sub-Commission for Europe (EUREF). Its primary objective is to maintain and provide access to the ETRS89. The EUREF Technical Working Group (TWG) is responsible for the general management of the EPN. The EPN Coordination Group and the EPN Central Bureau implement the operational policies of the EUREF TWG.

The EPN is based on a well-determined structure including GNSS tracking stations, operational centers, local and regional data centers, local analysis centers, a combination centre and a central bureau. The EPN is the European densification of the network operated by the International GPS Service (IGS). Therefore, the EPN uses the same standards and exchange formats as the IGS. In 2010, a new Local Analysis Centre (Military University of Technology (MUT, Poland)) joined the group of EPN analysis centres, increasing the total number to 17.

Two workshops of the Local Analysis Centres (LAC) were held in Frankfurt, Germany (2008) and Warsaw, Poland (2010). The scope of such workshops is to verify the current and future direction of the EPN analysis activities and to continue in improving the processing strategy and options. The initiation of the EPN re-processing activities and encouragement of the Analysis Centres to step towards GNSS (GPS, GLONASS, Galileo) was one of the outcomes of the mentioned workshops.

Special Projects are set up by the EPN Coordination Group in order to introduce new applications into the EPN or study special aspects of the permanent network. The different EPN components (such as the tracking stations, data centers and analysis centers) follow specific guidelines. Candidate EPN stations can also find the necessary instructions for becoming an EPN station in http://www.epncb.oma.be. The number of permanent GNSS tracking sites in Europe has grown considerably; more than 244 EPN stations are operated the end of 2010 by national European institutions. The number of sites which record GLONASS data simultaneously to GPS data and which stream real time data is steadily increasing (59 % and 49 % resp.).

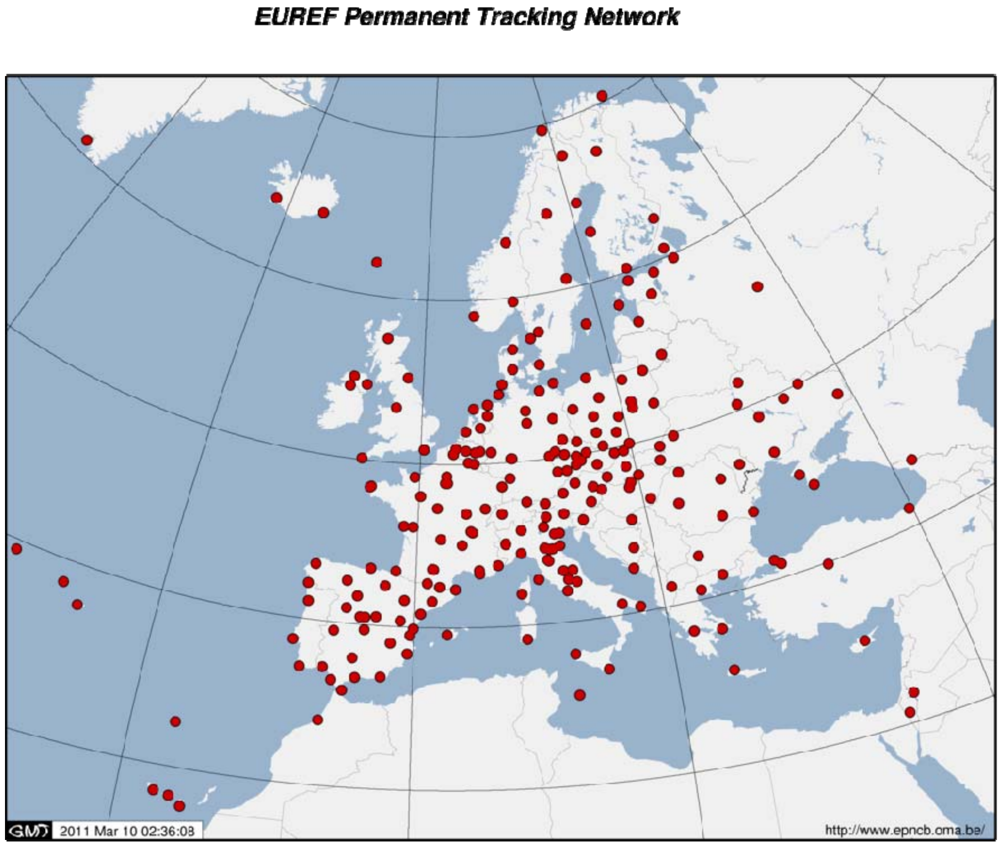


Figure 1: EUREF Permanent GNSS Network EPN

**EUREF Densification of the ITRF**

Even while the number of permanent GNSS tracking sites in Europe has grown considerably, only a selection of these sites (mostly those belonging to the IGS) are included in recent ITRS realizations.

The latest realization of the ITRS, the ITRF2005, is based on observations from space geodetic techniques (GNSS, DORIS, VLBI, and SLR) up to December 2005 and does not take into account any of the IGS/EPN data gathered after Jan 1st, 2006. Consequently it cannot reflect the most recent status of the EPN (e.g. antenna changes). The limited number of stations and the lack of frequent updates limit therefore the use of the ITRF for EUREF densifications.

To take full advantage of the EPN and its most recent GNSS observation data, the EUREF TWG decided at its meeting of Nov. 3-4, 2008 in Munich, to release regularly recomputed cumulative official updates of the ITRS/ETRS89 coordinates/velocities of the EPN stations. Using the 15-weekly updates of the EPN site coordinates, the EPN sites are classified in two classes:

- Class A stations with positions at 1 cm accuracy at all epochs of the time span of the used observations
- Class B stations with positions at 1 cm accuracy at the epoch of minimal variance of each station

Following the EUREF "Guidelines for EUREF Densifications", only Class A EPN stations can be used for densifications of the ETRS89.

**EPN re-processing activities**

During the past years it has been realized that the analysis of the global as well as the regional GNSS networks are affected by different factors causing systematic biases like the reference system realization, correction models, analysis strategies and software packages. Inconsistencies in the coordinates and long time series are therefore very frequent. The TWG has therefore decided to define a new EPN project "EPN Reprocessing". The aim of the EPN reprocessing project is to obtain improved and consistent coordinates, position time series and troposphere parameters for each of the EPN sites. Most of the EPN Local Analysis Centres (LAC) participate in this project. Different software packages like BERNESE, GIPSY/OASIS and GAMIT are used for the analysis of the data. Within the so called *Pilot Phase* the data of 2006 have been re-analysed with different models and strategies in order to select the best common strategy for the complete re-analysis of the EPN data. The first results of the reprocessing have been presented and discussed at the EPN Local Analysis Centres workshop hosted in Warsaw from Nov. 18-19, 2010. At present, the LACs have analysed a benchmark campaign in order to compare the results of the individual LACs and to tune the setup. Currently the complete EPN is re-analysed using the data from 1996 until 2006 using the reprocessed orbits and ERPs of the IGS reprocessing campaign. Data from 2007 until present are already computed in the most recent realization of the ITRS (currently ITRF2005) and will be used together with the reprocessed solutions to derive consistent coordinates and velocities for the EPN that will support the realization of the ETRS and shall be made available to the community.

The first results of EPN REPRO1 campaign are expected before the summer of 2011. It is quite clear that the new realization of the ITRS, the ITRF08, will cause another re-analysis of the entire EPN applying again the most recent models, strategies and standards, as long as new reprocessed products based on the ITRF08 for a global network will be made available by the IGS community. More information the EPN reprocessing is available from http://epn-repro.bek.badw.de/.

**EPN Real-time Analysis Project**

The EPN Project on "Real-time Analysis" focuses on the processing of the EPN real-time data to derive and disseminate real-time GNSS products. The EPN regional broadcaster at BKG (http://www.euref-ip.net) is broadcasting satellite orbits in the ETRS89 (realization ETRF2000). Using these orbits, users can directly derive in real-time coordinates in the ETRS89.

One aim of the project is to increase the reliability of the EPN real-time data flow and to minimize the possibility of regional broadcaster's outage. For this purpose, two additional regional broadcasters have been put in operation, one at ASI (Italian Space Agency, http://euref-ip.asi.it/ and one at ROB (Royal Observatory of Belgium, http://www.euref-ip.be/). based on the existence of three regional broadcasters, several stations started uploading their data in parallel to all of the broadcasters. By this strategy dependency on one broadcaster will be avoided and the real-time data flow become more consistent. More information of the EPN "Real-time Analysis" Special Project is available from http://www.epncb.oma.be/_organisation/projects/RT_analysis.

The new broadcaster which has been set up at BKG (http://products.igs-ip.net) allows access to several real-time product (orbit and clock correction) streams. These streams are uploaded by various institutions participating to the IGS Real-time pilot project.

**Promotion of Adoption of the ETRS89**

Since 1989, many European countries have defined their national reference frames in (or closely aligned to) ETRS89 by calculating national ETRS89 coordinates following the EUREF guidelines. The national ETRS89 coordinates, adopted by the different countries, can differ from each other due to differences in datum definition: they are often based on different ETRFyy frames and each of them refers to different observation periods.

The difference between the ETRS89 adopted in each of the different countries with respect to the most recent estimates of the ETRS89 coordinates of the EPN stations is now monitored on a regular basis by EUREF. The results of the comparison show an agreement of a few cm (see Figure 2).

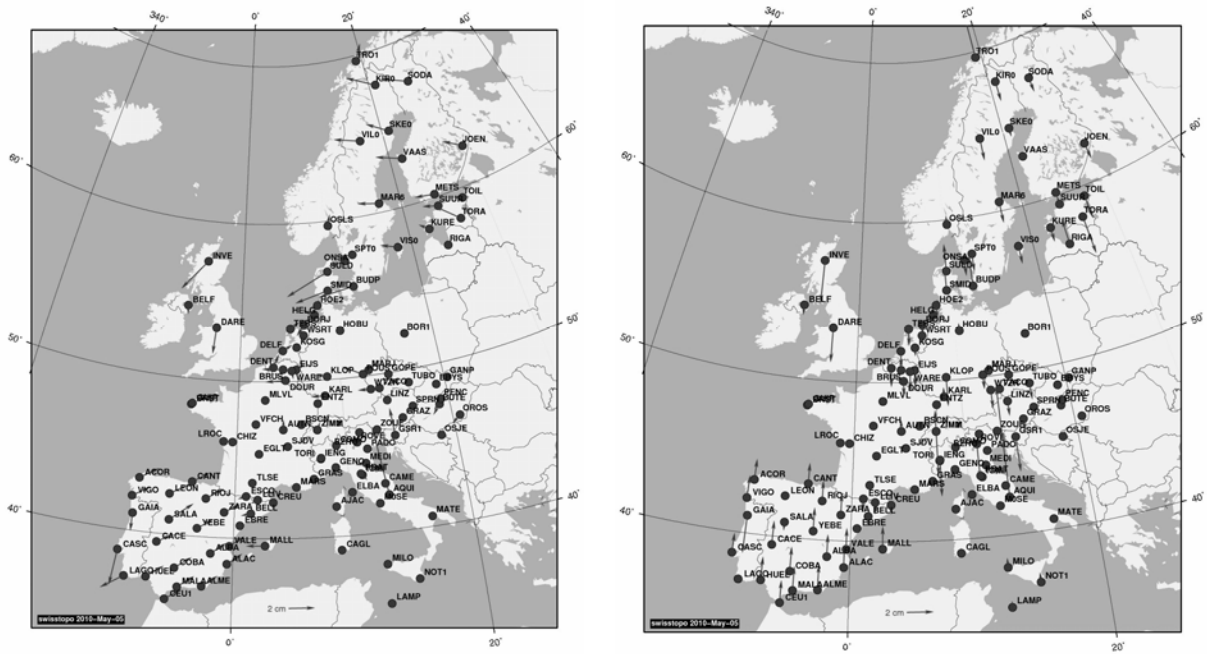


Figure 2: Difference between ETRS89 coordinates adopted in the different countries and the latest EPN cumulative coordinate solution.

In addition, the EUREF TWG also decided to update its information concerning the usage of ETRS89 in the different countries. The goal of this activity is to issue a new questionnaire to be distributed among the National Mapping and Cartographic Agencies. This questionnaire will be the follow up of the questionnaire distributed in 2005.

**European Vertical Reference System (EVRS)**

Since 1994 the IAG Sub-commission for Europe (EUREF) have enhanced the Unified European Leveling Network (UELN) and defined a European Vertical Reference System (EVRS). About 50 % of the participating countries provided new national leveling data to the UELN data centre after the release of the last solution EVRF2000. Therefore a new realization of the EVRS was computed and published under the name EVRF2007.

The datum of EVRF2007 is realized by 13 datum points distributed over the stable part of Europe. The measurements have been reduced to the common epoch 2000 using the land uplift model of the Nordic Geodetic Commission (NKG).

The results of the adjustment are given in geopotential numbers and normal heights, which are reduced to the zero tidal system. At the EUREF symposium June 2008 in Brussels, Resolution No. 3 was adopted proposing to the European Commission to adopt the EVRF2007 as the mandatory vertical reference for pan-European geo-information.

The availability of EVRF2007 necessitated an update of the Geodetic Information and Service System CRS. Transformation parameters between national height systems and EVRF2007 were calculated and provided on http://www.crs-geo.eu/ in April 2010. Furthermore the transformation parameters to EVRF2000 are available. Additionally the online-transformation for heights of single points was implemented.

After providing the EVRF2007 results the development of the UELN will be continued.

In 2009 the measurements of the 1. Order Leveling Network of the European part of Russia were handed over to the UELN data center. These additional data finally allow to close the loop around the Baltic Sea. Moreover, Belarus and Ukraine have decided to participate in the UELN project. As both countries report, the preparation of their leveling data is in progress.

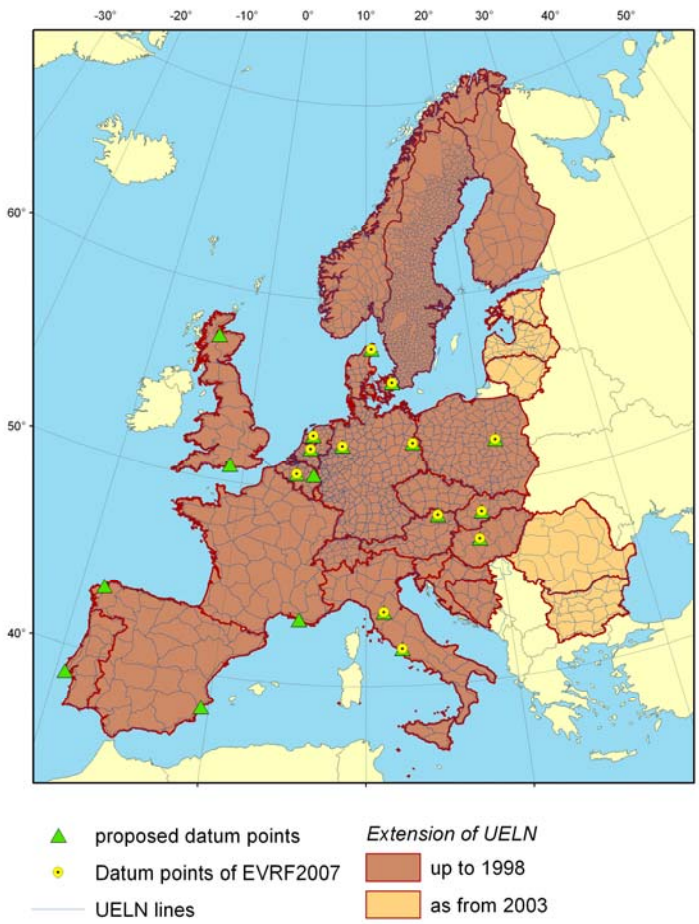


Figure 3: EVRF2007

The delivery of the new leveling network of Spain has been announced for about 2009. Besides that, a partial re-measurement of the French leveling network (NIREF) has been performed.

**ECGN continuation**

The ECGN combines the integration of time series of spatial/geometric observations by GNSS technique, and physical quantities by gravity field related observations and parameters including precise levelling, tide gauge records, gravity observations, as well as earth and ocean tides. The objective of ECGN as an integrated European Reference System for Spatial Reference and Gravity is the maintenance of the terrestrial reference system with long-term stability for Europe.

The objectives of ECGN can be summarized as follows:

- Monitoring the long term stability of the terrestrial "3D+1" reference system for Europe with an accuracy of $10^{-9}$, including 3D geometric parameters together with the gravity related height component
- In-situ combination of geometric positioning (C-GNSS time series) with physical height (UELN) and repeated gravity measurements on 1 cm accuracy level or better
- To contribute to the maintenance and improvement of precise geoid models
- To provide connection to the sea level and sea level changes via tide gauges in the area concerned
- To maintain databases (via existing components, such as EPN) and a metadata base for access to the data and products of the ECGN

ECGN, 2011. http://www.bkg.bund.de/nn_165056/geodIS/ECGN/EN/Home/homepage__node.html__nnn=true (30.1.2011)

## 1.3b: Regional Sub-Commission for South and Central America (SIRGAS)



| | |
|---|---|
| *Chair:* | *Claudio Brunini (Argentina)* |
| *Vice-chair:* | *Laura Sánchez (Germany)* |
| *SC1.3b-WG1 (Reference Frame) chair:* | *current: Virginia Mackern (Argentina)* |
| | *former: Sonia Costa (Brazil)* |
| *SC1.3b-WG2 (Geocentric Datum) chair:* | *current: William Martínez (Colombia)* |
| | *former: Tomas Marino (Costa Rica)* |
| *SC1.3b-WG3 (Vertical Datum) chair:* | *current: Roberto Luz (Brazil);* |
| | *former: William Martínez (Colombia)* |



Sub-commission 1.3b (Latin America and Caribbean) encompasses the activities developed by the "Geocentric Reference System for the Americas" (SIRGAS) initiative, whose main objective is the definition and realization of a unified and globally consistent geometrical reference frame for the region (SC1.3.b – WG1). Besides, SIRGAS promotes the establishment of national densifications of the continental frame (SC1.3b – WG2), and the definition and realization of a unified and globally consistent vertical reference system for the region supporting physical and geometrical heights (SC1.3b – WG3).

The SC1.3b Executive Committee met in four opportunities for evaluating the ongoing and planning the forthcoming activities. The meetings were:

- in Bogotá (Colombia), on June 7 – 8, 2007 (reported in SIRGAS Newsletter No 12);
- in Montevideo (Uruguay), on May 28 – 30, 2008 (reported in SIRGAS Newsletter 13);
- in Buenos Aires (Argentina), in the frame of the Scientific Assembly "Geodesy for Planet Earth" of the International Association of Geodesy (IAG), August 31 – September 4, 2009, (reported in SIRGAS Newsletter 14); and
- in Lima (Peru), on November 11 – 12, 2010, (reported in SIRGAS Newsletter 15) .

The main achievements of SIRGAS in this period can be summarized as follows:

- Continuous monitoring of the Reference Frame: the first SIRGAS realizations were established by means of two GPS campaigns: the first one in May 1995 including 58 stations, and the second one in 2000 with 184 stations. At present, SIRGAS is realized by a network of continuously operating stations. This so-called SIRGAS-CON network replaces the former realizations and allows a permanent monitoring of the reference frame.
- Geographical densification of the reference stations: the SIRGAS-CON network was extended from 163 continuously operating GNSS stations in June 2007, to 270 in February 2011. Forty eight stations are integrated in the IGS global network, and 72 receivers are able to track GLONASS.
- Redundancy in the analysis of the reference frame: in June 2007, the SIRGAS-CON network was processed by one processing centre in a common block adjustment. Today, the analysis strategy is based on the combination of individual solutions of different clusters of stations, guaranteeing that each station is included in three individual solutions. These clusters are weekly processed by 9 analysis centres, namely: CEPGE (Ecuador), CIMA (Argentina), CPAGS-LUZ (Venezuela), IBGE (Brazil), IGAC (Colombia), IGN (Argentina), INEGI (Mexico), SGM (Uruguay), and DGFI (Germany). The last one continues acting as the IGS RNAAC for SIRGAS. The combination of the different solutions is performed by DGFI and IBGE.

- GLONASS processing: Until now, the SIRGAS Analysis Centres process GPS data only. Since the number of GLONASS stations is increasing in the SIRGAS region, the SC1.3b - WGI initiates the routine processing of GLONASS observations on a weekly basis. All GLONASS stations will be analysed as an individual network, loosely constrained solutions of which will be combined with the similar solutions generated for the other SIRGAS-CON sub-networks.
- Datum definition strategy and availability of weekly reference coordinates: after a carefully study devoted to reduce network deformations due to the effect of seasonal variations in the datum realization, SIRGAS changed the strategy used to realize its datum. Currently, the weekly solutions of the SIRGAS-CON frame are aligned to the ITRF using the IGS weekly coordinates (igsyyPwwww.snx), instead of applying epoch positions and constant velocities. The geodetic datum is defined by constraining the coordinates of the IGS reference stations. The applied constrains guarantee that the positions of the IGS reference stations do not change more than 1,5 mm within the SIRGAS-CON adjustment.
- Reprocessing of the entire SIRGAS-CON network applying the reprocessed IGS products (IG1): weekly solutions from January 2000 (GPS week 1043) to November 2006 (GPS week 1399), formerly computed with relative antenna phase centre corrections and referring to previous ITRF solutions, have been reprocessed based on absolute phase centre corrections provided by the IGS and the IGS05 as reference frame. This reprocessing allows improving the reliability and accuracy of station positions and velocities computed within multi-year solutions.
- Kinematics of the SIRGAS reference frame: every year, a cumulative solution containing all available weekly normal equations delivered by the SIRGAS analysis centres is computed. The latest one is called SIR10P01 and covers the period between January 2, 2000 (GPS week 1043) and June 5, 2010 (GPS week 1586). It refers to the ITRF2008 at epoch 2005,0 and provides positions and velocities for 183 SIRGAS-CON stations. Its precision was estimated to be ~±0,5 mm (horizontal) and ~±0,9 mm (vertical) for the station positions at the reference epoch, and ~±0,2 mm/a (horizontal) and ~±0,4 mm/a (vertical) for the constant velocities. A loosely constrained version of this solution was delivered to the IAG SC1.3 Working Group on Regional Dense Velocity Fields as the SIRGAS contribution.
- Velocity Model for SIRGAS (VEMOS): the availability of horizontal velocities in those regions which are not covered by SIRGAS-CON stations is strongly improved through the new Velocity Model for SIRGAS (VEMOS 2009), which represents the continuous present-day deformation of the Earth crust in the SIRGAS region. It is based on nearly 500 velocity stations observed in 13 GPS projects. The overall precision of the point velocities is better than ±1 mm/a in South-North and ±1,5 mm/a in West-East direction.
- Long-term stability of the SIRGAS reference frame: the former SIRGAS realizations of 1995 and 2000 and the computed multi-year solutions were compared with the new ITRF2008 frame. Results show a very good consistency between the different SIRGAS solutions. The largest discrepancies (~2 cm) were detected for the SIRGAS realizations referring to ITRF94 and ITRF97. Realizations referring to ITRF2000 and IGS05 have an agreement better than ±5 mm. This reflects the expected improvement of the reference frame as consequence of longer time series of station positions and the better new models, standards, and analysis strategies applied today. However, special care shall be given to the deformations caused by seismic events.
- Reference frame deformations caused by seismic events: the western part of the SIRGAS region is an extremely active seismic area because it is located in the plate boundary zone of six tectonic plates. The frequent occurrence of earthquakes causes episodic station

movements, which affect the long-term stability of the SIRGAS reference frame. For instance, in the last three years, three big earthquakes caused displacements of about 2,5 cm in Costa Rica, between 2 cm and 3 m in Chile and Argentina, and 26 cm in Baja California, Mexico. To mitigate the impact of these events on the reference frame, SIRGAS is developing a strategy oriented to measure and model the generated deformations as soon as possible after any strong seism.

- Applicability of SIRGAS as reference frame: 16 of the 18 SIRGAS member countries adopted SIRGAS as official reference frame, i.e. the SIRGAS continental network is extended through national densification networks. Today, users of precise GNSS positioning refer to SIRGAS (or their densifications) by: i) introducing weekly station positions of the SIRGAS-CON stations as reference coordinates to process GNSS surveying; and ii) applying the velocities provided by the multi-year solutions to reduce new station positions to the conventional reference epoch defining the official reference frame.
- Extension of the SIRGAS reference frame at national level: the national reference frames of El Salvador and Bolivia were integrated into SIRGAS. The frame of El Salvador (SIRGAS-ES2007.8) is composed by 35 stations observed in a GPS-campaign in 2007. Adjusted station positions refer to the IGS05, epoch 2007.8. The reference frame of Bolivia (Referencia Geodésico Nacional, MARGEN) comprises 17 GPS stations, 8 of them are those continuously observing stations. The final coordinates are given in IGS05, epoch 2010.2.
- Capacity building within SIRGAS: In order to divulge and promote the adequate use of SIRGAS as reference frame in the different countries of the region, the SC1.3b-WG2 (in charge of the SIRGAS activities at national level) coordinates a capacity building activity oriented to strengthen the fundamental concepts associated with the Geodesy of Reference. This activity is sponsored by the International Association of Geodesy (IAG) and the Pan American Institute of Geography and History (PAIGH), and therefore, it is called IAG-PAIGH-SIRGAS School on Reference Systems. The first School was held in Bogotá (Colombia), between 13 and 17 July 2009. It was hosted by the Instituto Geográfico Agustín Codazzi and attended by 120 participants from 12 Latin American and Caribbean countries. The second IAG-PAIGH-SIRGAS School was carried out in Lima (Peru), between 8 and 10 November 2010. It was hosted by the Instituto Geográfico Nacional of Peru and was attended by 112 participants from 13 countries.
- IAG Inter Commission Project 1.2: SC1.3b-WG3 activities are integrated in the IAG Inter Commission Project 1.2, "Vertical Reference Frames", and were focused on two major issues: i) determination of a reliable geopotential value $W_0$ within a global realization; and ii) evaluation of levelling data combined with gravimetric measurements, including the direct connection of the first levelling networks between neighboring countries and to SIRGAS2000 realization. These activities are complemented by the formulation of a combined system of observation equations based on spirit levelling, GNSS positioning, and geoid determination. It includes the common analysis of tide gauge registrations, satellite altimetry observations, and GNSS positioning at those tide gauges which serve as vertical datum in the classical height systems. This analysis is carried out in the frame of the IGS TIGA project.
- SIRGAS in Real Time: the SIRGAS Real Time (SIRGAS-RT) project was established in the SIRGAS 2008 General Meeting (May 2008). Its main objective is to evaluate the possibility of providing near real time corrections for GNSS positioning based on the SIRGAS-CON stations. After two years, Argentina, Brazil, Uruguay, and Venezuela, who are applying the NTRIP tool, show significant advances in the implementation and use of this technique. The SC1.3b-WG2 will continue promoting the development of similar

studies in other SIRGAS countries. The planned activities include a capacitation course of two weeks to provide expertise in the implementation and adequate use of the NTRIP protocol in the SIRGAS countries. This course will be partially supported by the Agencia Española de Cooperación Internacional together with the Instituto Geográfico Nacional de España.

– Ionospheric analysis within SIRGAS: the routine production of vTEC maps for South America by the Universidad Nacional de la Plata (Argentina) as SIRGAS Ionosphere Analysis Centre provides control and improvement for different kind of projects such as the International Reference Ionosphere (IRI) over South America, positioning with single-frequency GPS receivers, and the feasibility of computing ionosphere corrections for a satellite based augmentation system (SBAS) for the region.

During the four years, the SC1.3b was represented in the following meetings:

– III Seminario de Geomática, Sociedad Colombiana de Ingenieros. Bogota, Colombia. October 27 - 29, 2010.
– IAG Commission 1 Symposium 2010, Reference Frames for Applications in Geosciences (REFAG2010). Marne-la-Vallée, France. October 4 - 8, 2010.
– 20th UN/IAF Workshop on GNSS Applications for Human Benefit and Development. Prague, Czech Republic. September 24 - 25, 2010.
– XI Congreso internacional de Geomática: Geodesia, Topografía y Catastro en tiempo real. San José, Costa Rica. September 16 - 18, 2010.
– AGU 2010, The Meeting of the Americas. Foz do Iguaçu, Brazil. August 8–12, 2010.
– European Geosciences Union, General Assembly 2010 (EGU 2010). Vienna, Austria. May 02 – 07, 2010.
– II Convención de las Ingenierías de las Geociencias y la Química - V Congreso de agrimensura. La Habana, Cuba. March 2 - 5, 2010.
– 20th Technical Consultative Meeting on Cartography, Pan American Institute for Geography and History (PAIGH). Quito, Ecuador. November 26-27, 2009.
– United Nations/Azerbaijan/European Space Agency/United States of America Workshop on the Applications of Global Navigation Satellite Systems. Baku, Azerbaijan. May 11-15, 2009.
– European Geosciences Union, General Assembly 2009 (EGU 2009). Vienna, Austria. April 19 - 24, 2009.
– Reunión Científica 24 de la Asociación Argentina de Geodesia y Geofísica (AAGG). Mendoza, Argentina. April 14 - 17, 2009.
– Semana Geomática Internacional. Barcelona, Spain. March 3 - 5, 2009.
– Third Meeting of the International Committee on Global Navigation Satellite Systems (ICG). Pasadena, California, USA. December 8 - 12, 2008.
– International Symposium on Global Navigation Satellite Systems, Space-based and Ground-based Augmentation Systems and Applications. Berlin, Germany. November 11 - 14, 2008.
– IAG International Symposium on Gravity, Geoid and Earth Observation. Chania, Crete, Greece. June 23 - 27, 2008.

- United Nations/Colombia/United States of America Workshop on the Applications of Global Navigation Satellite Systems. Medellin, Colombia. June 23 - 27, 2008.
- AGU 2008 Joint Assembly. Fort Lauderdale, Florida, USA. May 27 - 30, 2008.
- AGU Fall Meeting. San Francisco, USA. December 10 - 14, 2007.
- 6th FIG Regional Conference. San Jose, Costa Rica. November 12 - 15, 2007.
- SDI Americas Symposium: Concepts, Practices, and Projects. IGAC-IPGH-GSDI. Bogota, Colombia. November 7 - 8, 2007.

The most relevant information regarding SC1.3b, related newsletter, presentations and papers, as well access to its main products can be found in the web at www.sirgas.org.

# Sub-Commission 1.3c: Regional Reference Frame for North America (NAREF)

*Co-Chairs: Michael Craymer (Canada), Richard Snay/Jake Griffiths (USA)*

## Introduction

The objective of the NAREF Sub-Commission is to provide international focus and cooperation for issues involving the horizontal, vertical, and three-dimensional geodetic control networks of North America, including Central America, the Caribbean and Greenland (Denmark). Some of these issues include:

- Densification of the ITRF reference frame network in North America and promotion of its use.
- Maintenance and future evolution of vertical datums (ellipsoidal and orthometric), including NAVD88 and the International Great Lakes Datum.
- Collocation of different measurement techniques such as VLBI, SLR, DORIS, GPS, etc.
- Effects of crustal motion, including tectonic motions along, e.g., the western coast of N.A. and in the Caribbean, and post-glacial rebound.
- Standards for the accuracy of geodetic positions.
- Outreach to the general public through focused symposia, articles, workshops and lectures and technology transfer to other groups, particularly in N.A.

The Sub-Commission is currently composed of four working groups:

- SC1.3c-WG1: North American Reference Frame (NAREF)
- SC1.3c-WG2: Stable North American Reference Frame (SNARF)
- SC1.3c-WG3: Reference Frame Transformations
- SC1.3c-WG4: International Great Lakes Datum (IGLD)

The following summarizes the activities of each WG. For more information see www.naref.org. Note the U.S. co-chair, Dr. Richard Snay, retired from the U.S. National Geodetic Survey in 2010 and was succeeded by Dr. Jake Griffiths from the same agency.

## SC1.3c-WG1: North American Reference Frame (NAREF)

Most of the effort of the Sub-Commission is focused on this WG with the aim of densifying the ITRF and IGS global networks in the North American region. Until GPS week 1399, the densification consisted of weekly combinations of six different weekly regional solutions spanning the continent and using four different GPS processing software packages. These NAREF contributors and some details of their solutions are given in the table and figures below.

A number of sites have been omitted from the combination of submitted contributions due mainly to problems with antenna heights. Investigations are being conducted to resolve these issues during the reprocessing phase described below. Many other stations have been removed from the MIT and Scripps solutions because of current software limitations and the very high density of sites in southern California and some local areas of the PBO network. Presently, only those stations in the U.S. common with the NGS CORS solution are being included in the current weekly combinations.

Table 1.3c-1: NAREF weekly regional coordinate solution contributions up to GPS Week 1399.

| Contributor | Software | Region | No. Stations (total/used) |
|---|---|---|---|
| NGS | PAGES | US & territories (CORS network) | 820/762 |
| Scripps | GAMIT | North America | 700/140 |
| MIT | GIPSY & Bernese Combo | Western North America | 670/183 |
| NRCan/GSD | Bernese | Canada & border areas of US & Greenland | 112/112 |
| NRCan/GSD | GIPSY | Canada | 43/43 |
| NRCan/PGC | Bernese | Western Canada Deformation Array (WCDA) | 55/55 |

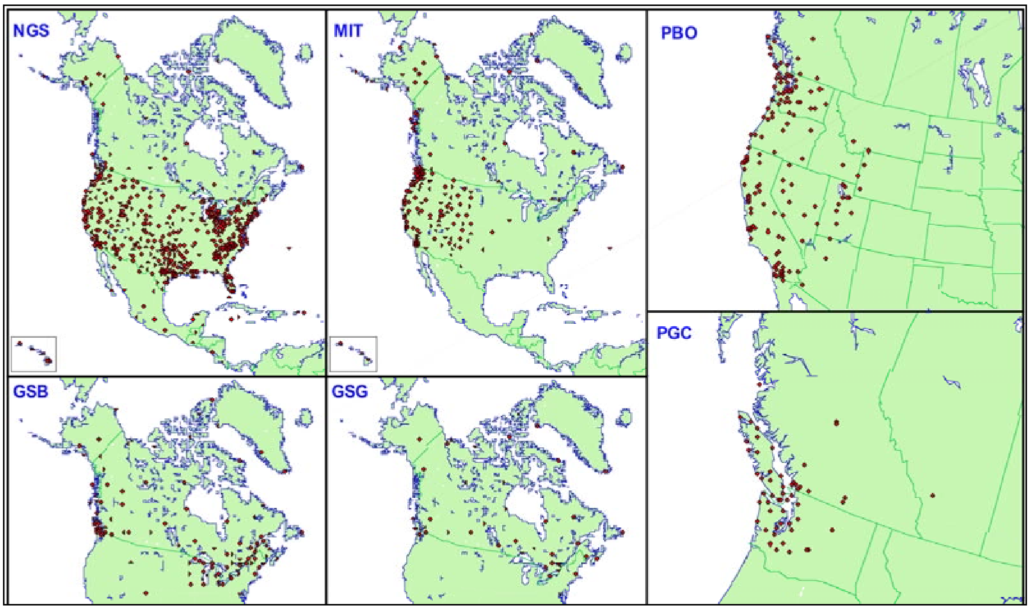


Figure 1.3c-1: NAREF regional contributions for GPS week 1399.

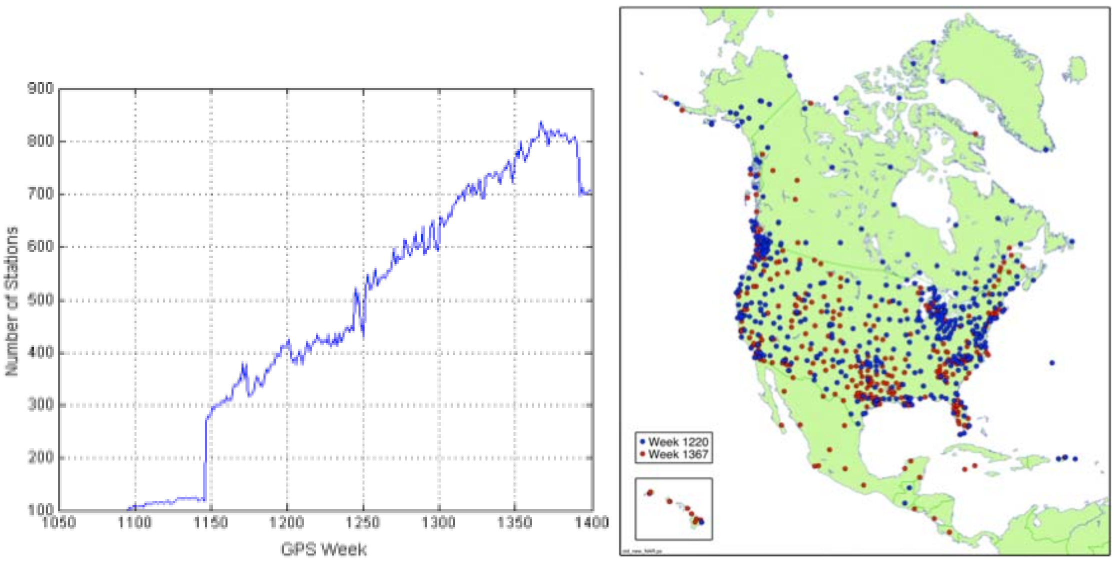


Figure 1.3c-2: NAREF network growth until GPS week 1399.

Since GPS week 1400, a number of changes have been made to the regional solutions. First and foremost was the implementation of the new IGS procedures and absolute antenna calibrations. In addition, many more stations were included not only in the regional solution being submitted but also in the number of stations used in the weekly combinations. These additional stations increased the number of sites in more than one solution, thereby improving redundancy. The table below summarizes the number of sites used in each of the regional submissions since GPS week 1400 and the figure show the increase in total number of stations since week 1399. New regional submissions were also obtained from the Mexican National Institute of Statistics and Geography (INEG) beginning with week 1563.

All of the solutions also included a subset of IGS global reference frames sites to better align the NAREF combinations to ITRF. The exception was that from NRCan/PGC (it being a local solution by design). The following figure illustrates the distribution of sites for a recent week.

Table 1.3c-2: NAREF weekly regional coordinate solution contributions since GPS week 1400.

| Contributor | Software | Region | No. Stations (approx.) |
|---|---|---|---|
| NGS | PAGES | US & territories & Mexico (CORS network) | 1200+ |
| Scripps | GAMIT | North America | 1100+ (~625 used) |
| MIT | GIPSY & Bernese Combo | Western North America | 1100+ (~520+ used) |
| NRCan/GSD | Bernese | Canada & border areas of US & Greenland | 200 |
| NRCan/GSD | GIPSY | Canada | 45 |
| NRCan/PGC | Bernese | Western Canada Deformation Array (WCDA) | 75 |
| INEGI | GAMIT | Mexico | 30 (since 1563) |

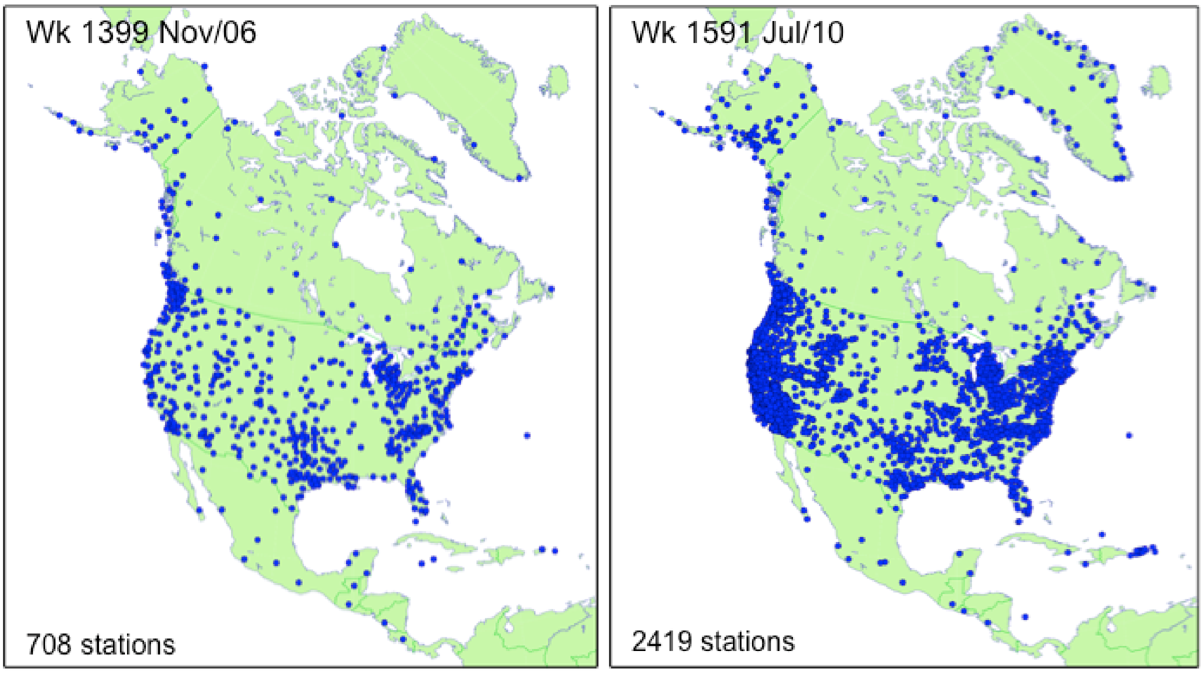


Figure 1.3c-3: Increase in number of NAREF stations since GPS Week 1399.

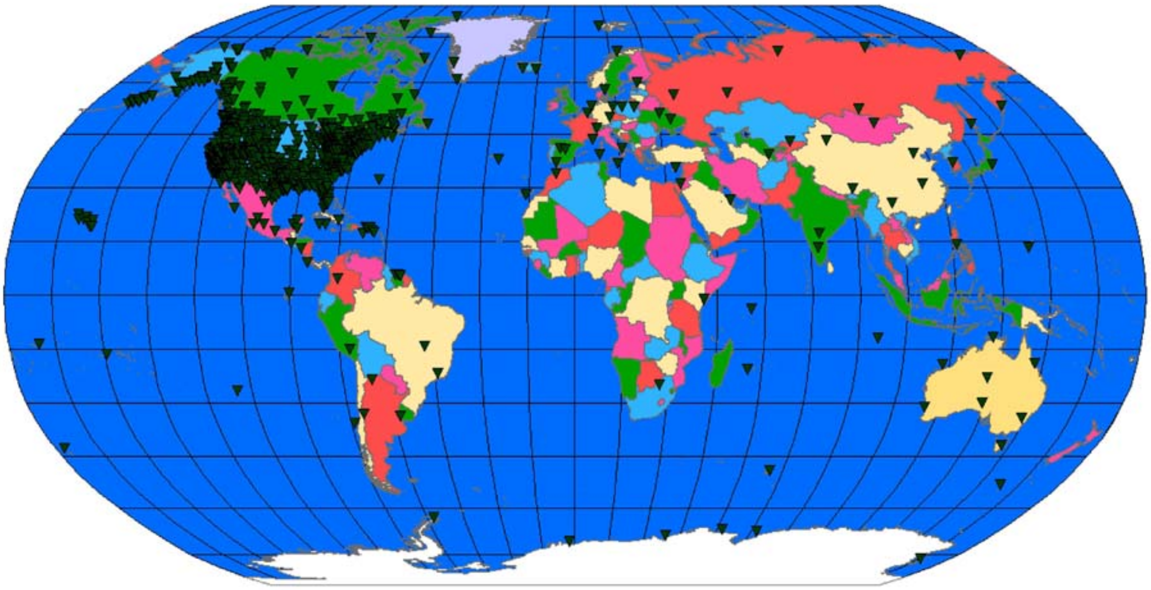

Figure 1.3c-4: NAREF network since GPS Week 1400 with global sites used to align with ITRF.

The submitted weekly regional solutions, NAREF weekly combinations and the current cumulative solution are available from the NAREF FTP archive (see www.naref.org). The NAREF weekly combinations are also submitted to the IGS data archive at CDDIS.

Unfortunately, no combinations have been possible after GPS week 1513 due to the total number of stations in the combination (2000+) exceeding the capabilities of the SINEX combination software. NRCan/GSD is presently enhancing the SINEX combination software to handle many more sites and to increase its processing speed. In the interim, NGS is implementing a weekly combination procedure based on the CATREF software.

A major reprocessing effort of regional solutions prior to GPS Week 1400 has been completed by NGS, NRCan/GSD and Scripps using the new IGS procedures and absolute antenna calibrations. For Scripps and NGS, the regional solutions have essentially been a densification of their global reprocessing efforts for the IGS. On the other hand, NRCan/GSD uses fixed IGS orbits in their solutions and had to wait for the completion of the IGS repro1 project to obtain the new orbits before they could begin their reprocessing. They are just now completing that effort after which all reprocessed solutions will be combined into new NAREF weekly combinations that will be compatible with current solutions.

Absent from this reprocessing effort were MIT and NRCan/PGC, who also use fixed IGS orbits in their processing. They are instead planning to reprocess with the new IGS08.atx antenna calibrations later in 2011. Also absent from the reprocessing effort was the NRCan/GSD GIPSY solution. NRCan/GSD plans to eventually replace this with one based on their Precise Point Positioning (PPP) software. INEGI does not have plans to reprocess.

Although the intention is to eventually produce updated NAREF cumulative solutions along with the weekly NAREF combinations each week, this has not yet been possible. A NAREF cumulative solution (coordinates and velocities) has been generated based only on the weekly NAREF combinations up to week 1399. The following figures show the horizontal and vertical velocity fields from this solution. Weekly solutions after this were not included because of the change from relative to absolute antenna calibrations, which would have produced a discontinuity in the positional time series for all sites. Once solutions before week 1400 are reprocessed with the new absolute antenna calibrations and IGS repro1 orbits, a new cumulative solution will be generated with all weeks to date. This solution will then be updated weekly with each new NAREF weekly solution.

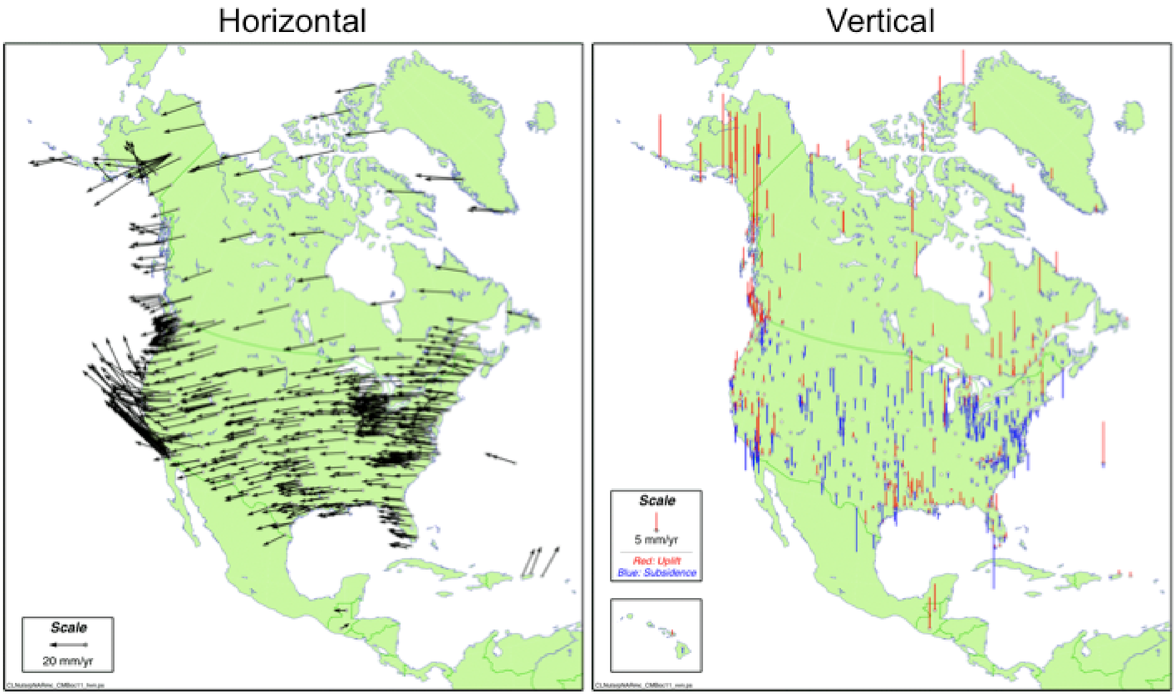


Figure 1.3c-5: NAREF velocity field aligned to ITRF2005 using weekly solutions up to GPS week 1399.

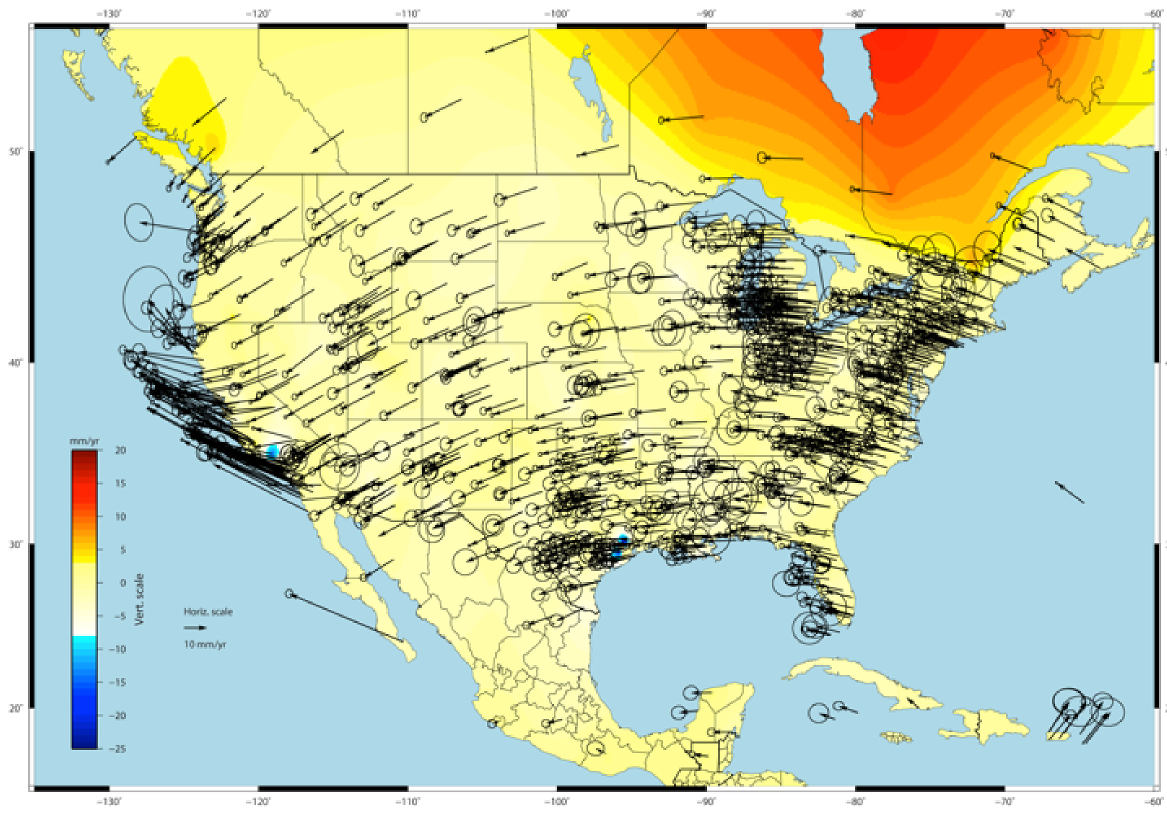


Figure 1.3c-6: CORS velocity field aligned to IGS08 using weekly solutions from 1994 to 2010.

Although no recent NAREF cumulative solution is available using reprocessed results, NGS has generated a solution using the CATREF software for 2,264 CORS stations based on their own weekly reprocessed solutions from 1994 to 2010.5 with absolute antenna calibrations and global sites for alignment to IGS08. The above figure displays the horizontal velocity field for this solution.

**SC1.3c-WG2: Stable North American Reference Frame (SNARF)**

This WG is joint with UNAVCO, Inc. in support of the EarthScope project. The goal of the WG is to define a plate-fixed regional reference frame for North America, stable at the sub-mm level, in order to provide a standardized and consistent reference frame in support of geo-dynamics studies throughout the continent. Nine workshops to define the reference frame have been held since 2004, including two during this reporting period. All of the workshops were funded by UNAVCO.

The SNARF frame is being defined via a no-net-rotation condition for a set of stable frame sites with respect to the ITRF. A novel technique has been used to assimilate GPS velocity solutions together with a geophysical model of glacial isostatic adjustment to model both horizontal and vertical intra-plate motions. The first version of the reference frame was released at the UNAVCO Annual Meeting in June 2005.

An updated version of the frame was begun in 2007 using several improved velocity solutions from the members of the WG, including the last NAREF cumulative solution up to GPS week 1399. Unfortunately, the SNARF workshop funding contract with UNAVCO expired before the new SNARF frame could be completed and the working group has since become inactive.

It is now expected that this WG will evolve into one on defining a replacement for NAD83 that is truly geocentric, fixed to North America and fully consistent with the ITRS (i.e., SNARF-like). Progress towards such a new realization of NAD began with the first "Federal Geospatial Summit on Replacing NAD83 and NAVD88" held in Washington on May 11-12, 2010.

**SC1.3c-WG3: Reference Frame Transformations**

This sub-commission is concerned with the definition and maintenance of the relationships between international and North American reference frames/datums. This primarily involves maintaining the officially adopted relationship between ITRF and NAD83 in Canada and the U.S. The NAD83 frame is now defined in terms of a time-dependent 7 parameter Helmert transformation from ITRF96 (Craymer et al., 2000). Transformations from/to other subsequent versions of ITRF are obtained by updating the NAD83-ITRF transformation with the official incremental fourteen parameter transformations between ITRF versions as published by the IERS. In 2006, the transformation was updated with the introduction of ITRF2005.

In late 2010, ITRF2008, a new realization of the International Terrestrial Reference System was publically released and the transformation between NAD83 and ITRF2008 was determined for use in Canada and the US. The new transformation was derived from the NAD83-ITRF2005 transformation by incrementally adding the ITRF2005-ITRF2008 transformation published by the IERS.

## SC1.3c-WG4: International Great Lakes Datum

The purpose of this working group is to consider problems related to the maintenance of the vertical datum for the management of the Great Lakes water system, including post-glacial rebound, the use of GPS/geoid techniques, lake level transfers through hydrodynamic models, comparisons with NAVD88 and the implementation of a revised height system by 2015.

Until 2010, this sub-commission has been inactive since the inception of the NAREF sub-commission. However, with recent plans for height modernization in both Canada and the U.S., and the need to update the International Great Lakes Datum by 2015 due mainly to the effects of glacial isostatic adjustment, the WG has been re-activated in collaboration with the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data. It is expected that a new IGLD datum will be defined by a geoid-based datum similar to height modernization plans in the Canada and the U.S.

## NAREF-Related Publications & Presentations

The following are a list of papers and presentations related to NAREF activities since 2007.

Craymer, M.R., M. Piraszewski, J.A. Henton. The North American Reference Frame (NAREF) project to densify the ITRF in North America. Proceedings of ION GNSS 2007, Fort Worth, Texas, September 25-28, 2007.

Craymer, M., G. Sella. Making Sense of Evolving Reference Frames for North America. Eos Transactions, AGU, 88(23), Joint Assembly Supplement, Abstract G32A-01 Invited, 2007.

Craymer, M., R. Snay. Regional Reference Frames for North America: Status and Future Plans of Sub-commission 1.3c. IUGG XXIV General Assembly, Perugia, Italy, July 2-13, 2007.

Craymer, M.R., J.A. Henton, M. Piraszewski. Predicting Present-Day Rates of Glacial Isostatic Adjustment Using a Smoothed GPS-Based Velocity Field for the Reconciliation of NAD83 Reference Frames in Canada. Eos Transactions, AGU, 89(53), Fall Meeting Supplement, Abstract G31A-0638, 2008.

Craymer, M.R., J.A. Henton, M. Piraszewski. Transforming PPP results to different realizations of the NAD83 reference frame in Canada. Eos Transactions, AGU, 90(52), Fall Meeting Supplement, Abstract G11C-0659, 2009.

Craymer, M., R. Ferland, J. Henton, E. Lapelle, M. Piraszewski. IGS, NAREF & CBN Velocity Fields for Monitoring GIA in Canada. COST ES0701 Working Group Meeting: Inter-comparison of GIA Estimates from GPS, Dresden, March 29-30, 2010.

Craymer, M.R., J. Henton, E. Lapelle, M. Piraszewski. Preliminary results of an updated North American GPS velocity field. Eos Transactions, AGU, 91(51), Fall Meeting Supplement, Abstract G23B-0825, 2010.

Craymer, M., R. Snay. Regional Reference Frames for North America: Current Status & Future Plans of Regional Sub-commission SC1.3c. IAG Commission 1 Symposium 2010, Reference Frames for Applications in Geosciences (REFAG2010), Marne-La-Vallée, France, October 4-8, 2010.

Griffiths, J., J.R. Rohde, J. Ray, M. Cline, W.H. Dillinger, R.L. Dulaney, S. Hilla, W.G. Kass, J. Ray. Reanalysis of CORS and Global GPS Data at the National Geodetic Survey. Eos Transactions, AGU, 89(53), Fall Meeting Supplement, Abstract G33B-0686, 2008.

Griffiths, J., J. Ray, J.R. Rohde, W.G. Kass, R.L. Dulaney, M. Cline, S. Hilla, R.A. Snay, An assessment of the NGS's contribution to the reprocessed IGS products. Eos Transactions, AGU, 90(52), Fall Meeting Supplement, Abstract G11B-0631, 2009.

Griffiths, J., J.R. Rohde, M. Cline, R.L. Dulaney, S. Hilla, W.G. Kass, J. Ray, G. Sella, R. Snay and T. Soler. Reanalyis of GPS data for a large and dense regional network tied to a global frame. IAG Commission 1 Symposium 2010, Reference Frames for Applications in Geosciences (REFAG2010), Marne-La-Vallée, France, October 4-8, 2010.

Herring, T., M. Craymer, G. Sella, R. Snay, G. Blewitt, D. Argus, Y. Bock, E. Calais, J. Davis, M. Tamisiea. SNARF 2.0: A Regional Reference Frame for North America. Eos Transactions, AGU, 89(23), Joint Assembly Supplement, Abstract G31B-01, 2008.

Henton, J., M. Craymer, E. Lapelle, M. Piraszewski. Contributions of the North American Reference Frame Working Group to the next realization of the Stable North American Reference Frame (SNARF). Eos Transactions, AGU, 88(52), Fall Meeting Supplement, Abstract G21B-0498, 2007.

Kass, W.G., R.L. Dulaney, J. Griffiths, S. Hilla, J. Ray, J. Rohde. Global GPS data analysis at the National Geodetic Survey. J. Geod., Vol. 83, pp. 289-295, doi: 10.1007/s00190-008-0255-4.

Mtamakaya, J., M.C. Santos, M. Craymer. Harmonic analysis of IGS stations time series. Eos Transactions, AGU, 90(52), Fall Meeting Supplement, Abstract G11B-0634, 2009.

Mtamakaya, J.D., M.C. Santos, M.R. Craymer. In search of periodic signatures in IGS REPRO1 solution. Eos Transactions, AGU, 91(51), Fall Meeting Supplement, Abstract G51B-0665, 2010.

Rohde, J.R., J. Griffiths, M. Cline, R.L. Dulaney, S. Hilla, W.G. Kass, J. Ray, G. Sella, R.A. Snay. NGS2008-beta: A preliminary estimate of an update to the North America CORS velocity field. Eos Transactions, AGU, 90(52), Fall Meeting Supplement, Abstract G11C-0660, 2009.

Sella, G.F., S. Stein, T.H. Dixon, M. Craymer, T.S. James, S. Mazzotti, and R.K. Dokka, Observation of glacial isostatic adjustment in "stable" North America with GPS, Geophys. Res. Lett., Vol. 34, L02306, doi:10.1029/2006GL027081, 2007.

Sella, G., S. Stein, T. Dixon, M. Craymer, T. James, S. Mazzotti, R.K. Dokka. Constraints on Glacial Isostatic Adjustment (GIA) Motion in North American Using GPS. IUGG XXIV General Assembly, Perugia, Italy, July 2-13, 2007.

Zilkoski, D.B., J.D. D'Onofrio, S.J. Frakes. Guidelines for Establishing GPS-derived Orthometric Heights (Standards: 2 cm and 5 cm). NOAA TM NOS NGS-59 (http://www.ngs.noaa.gov/PUBS_LIB/NGS592008069FINAL2.pdf), March 26, 2008.

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Craymer, M.R., R. Ferland and R. Snay. Realization and Unification of NAD83 in Canada and the US via the ITRF. In R. Rummel, H. Drewes, W. Bosch, H. Hornik (eds.), "Towards an Integrated Global Geodetic Observing System (IGGOS)", IAG Section II Symposium, Munich, October 5-9, 1998, International Association of Geodesy Symposia Volume 120, Springer-Verlag, Berlin, 2000.

# Sub-Commission 1.3d: Regional Reference Frame for Africa (AFREF)

*Chair: Richard Wonnacott (South Africa)*

## Introduction

IAG Sub-Commission 1.3d (Africa) of Commission 1 Reference Networks was established with the objective:

- To establish a continental reference system for Africa consistent and homogeneous with the global reference frame of the ITRF as a basis for national 3-d reference networks;
- To realize a unified vertical datum and to support efforts to establish a precise African geoid;
- To establish continuous, permanent GPS base stations at a spacing such that users will be within 1000km of a base station and that data is freely available to all nations;
- To provide a sustainable development environment for technology transfer so that these activities will enhance the national networks and other applications;
- To understand the necessary geodetic requirements of participating national and international agencies; To determine the relationship between the existing national reference frames and the ITRF to preserve legacy information based on existing frames; andTo assist in establishing in-country expertise for implementation, operation, processing and analysis of modern geodetic techniques, primarily GNSS.

While AFREF is an African project which is to be designed, managed and executed by African countries, these objectives are to be carried out with the technical assistance and in collaboration with the IAG community and its service organization, the IGS, together with the National and Regional Mapping Organizations of Africa. Although many of these objectives have not been met during the review period, progress has been made with the installation of permanent GNSS reference stations and a number of the other objectives such as the transfer of technology through training programmes and to broaden the understand the geodetic and GNSS requirements of a number agencies and projects engaged in disciplines other than geodesy.

## Installation of Permanent GNSS Stations

Since July 2007, the number of permanent GNSS reference station installations has increased throughout Africa. These have been installed by National Mapping Agencies, Universities and research groups. In spite of the number of installations increasing, there remains a difficulty in knowing where stations have been installed, who has installed them, what standards have been used and where data is being archived. Networks of permanent GNSS base stations in a few countries in Africa but because of data policies of some of these countries, free and open access to the data has been denied for all but a few of these stations.

At a recent AFREF Steering Committee meeting in Addis Ababa in April 2009, the Chief Directorate: National Geospatial Information in South Africa offered to establish an Operational Data Centre (ODC) for AFREF. This ODC became operational in June 2010 and has created a single data base for permanent GNSS stations in Africa and the AFREF project which has an open data policy. Data will be mirrored to the Regional Data Centre at the Hartebeesthoek Radio Astronomy Observatory. Data for approximately 45 permanent stations is currently being archived on ODC.

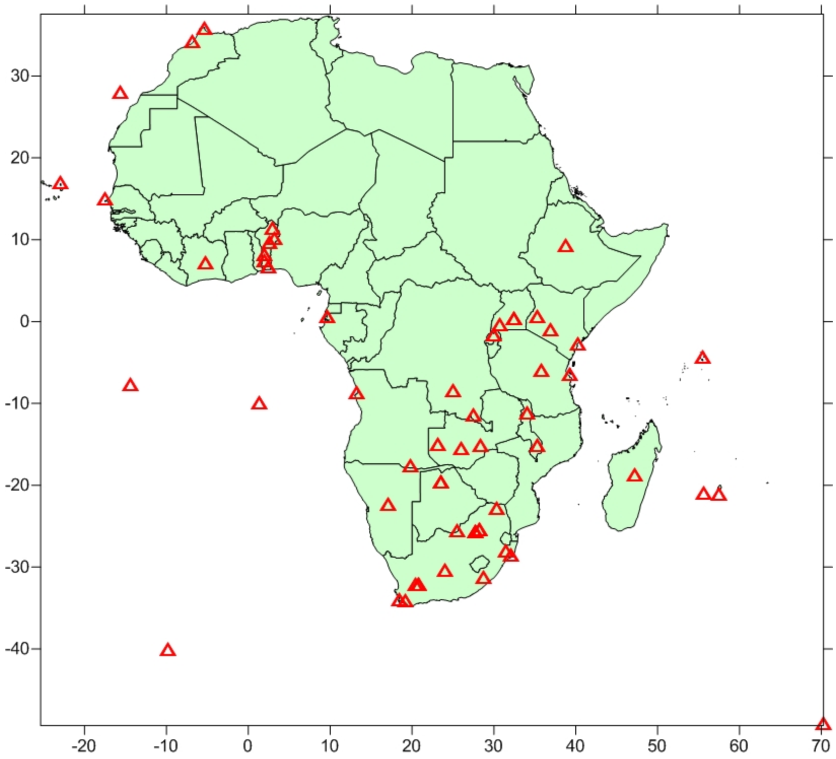


Figure 2 Permanent GNSS base stations for which continuous data is being archived at the AFREF Operational Data Centre as at February 2011. Although some campaign style data is also available, this has not been shown here.

## Meetings and Training Courses

A number of Steering Committee meetings were held during the reporting period but perhaps the most significant has been a series of joint meetings held in June 2008 in Johannesburg, June 2010 in Washington and Johannesburg in November 2010. These meetings brought together representatives from the fields of seismology, meteorology, space weather, geophysics and geodesy. The groups that met were

- AFREF (geodesy)
- Africa Array (seismology and geophysics)
- AMMA-GPS (meteorology)
- SCINDA/ IHY (space weather)
- Universities (geophysics)

All these groups have a common interest in and requirement for GNSS data and it is felt that with a common understanding and by working in a collegial environment, the groups should be able to share resources and expertise.

Four training courses were held between 2007 and 2011. The courses were held in August each year between 2007 and 2010 at the Regional Centre for Mapping of Resources for Development (RCMRD). The courses covered the concepts of AFREF permanent GNSS reference stations, reference frames and the processing of GNSS data. The courses were run by RCMRD in conjunction with Hartebeesthoek Radio Astronomy Observatory and the University of Beira in Portugal.

## Processing of GNSS Data for AFREF

A Call for Participation in the processing of GNSS data from the permanent stations has been prepared and will be distributed before the IUGG General Assembly in July 2011. The call has both practical processing and capacity building aspects to it.

## Funding for AFREF

Finding remains one of the main stumbling blocks to significant progress being made with AFREF. An application for funding was submitted to the African Union Commission (AUC) and European Union (EU) for inclusion within the EU/ AU Lighthouse Projects. The application was not successful. Apart from this application, there are a few other direct or indirect sources of support for the project such as the Millennium Challenge Corporation funding granted to selected low or low middle income countries for various development projects or the donation of equipment and software from receiver manufacturers.

# Sub-Commission 1.3e: Regional Reference Frame for South-East Asia and Pacific (APREF)

*Co-Chairs: Shigeru Matsuzaka (Japan), John Dawson (Australia)*

## Overview and Organization

The Sub-Commission 1.3e continues to maintain a close working relationship with the Regional Geodesy Working Group of the Permanent Committee for GIS Infrastructure in the Asia and the Pacific region (PCGIAP) and the Asia Pacific Space Geodynamics project (APSG). The activities of this Sub-Commission are principally carried out by the members of national surveying and mapping organisations, in the region, through the PCGIAP, which operates under the purview of the United Nations Regional Cartographic Conference for Asia and the Pacific (UNRCC-AP), and through the scientific members of the APSG.

The efforts of the Sub-Commission have provided a regional focus for cooperation in the definition, realisation and densification of the International Terrestrial Reference Frame (ITRF). More specifically, the Sub-Commission has sought to:

– Enhance the regional geodetic infrastructure by contributing to monitoring, warning and post-event reconstructions through the cooperative observation of crustal deformation and plate motion, and information exchange, including tide gauge networks and placement of new GPS key sites;
– Encourage the transfer of GNSS technology to nations in need through annual campaign observations, and the development and sharing of analysis techniques;
– Promote the application of new geodetic adjustment techniques and datum transformation parameters for regional spatial data integration and for geo-referencing cadastral information;
– Interact with IAG commissions 1 and 2 on the status of the regional geodetic reference frames and geoid determination using absolute gravity, satellite, airborne and terrestrial gravity; and
– Support the densification of continuous GNSS installations in areas of earthquake and tsunami hazard and strongly encourage nations to make their geodetic data readily available.

## Outputs

### *Asia Pacific Reference Frame (APREF)*

The Asia-Pacific Reference Frame (APREF) project is an initiative that recognizes the importance of improving the regional geodetic framework in the Asia-Pacific region. A substantial number of state-of-the-art GNSS networks, operated by national mapping agencies and private sector organizations, are available in the region.

In the APREF initiative these networks are combined to realize a high-standard regional reference frame. The GNSS data of the network is processed by different Analysis Centres (ACs). The contributions of the different ACs are combined into a weekly solution by the APREF Central Bureau. This weekly solution is the core product of the APREF; it contains weekly estimates of the coordinates of the participating Asia-Pacific GNSS tracking stations and their covariance information.

The APREF product, which is available since the first quarter of 2010, gives a reliable time-series of a regional reference frame in the International Terrestrial Reference Frame and a quality assessment of the performance of the GNSS CORS stations included in the network.

APREF is mandated by Resolution 1 (Regional Geodesy) of the 18th United Nations Regional Cartographic Conference (UNRCC) for Asia and the Pacific, 26 – 29 October 2009, Bangkok, Thailand. Demonstrating a broad community desire to improve the reference frame it is also endorsed by the International Global Navigation Satellite System Service (IGS), the United Nations Office for Outer Space Affairs (UNOOSA) and the Federation of International Surveyors (FIG).

APREF is a voluntary, collegial, non-commercial endeavor, and has to date encouraged wide participation from government agencies, research institutes and the private sector. There is no central funding source and each participating organization is contributing their resources. APREF is encouraging the sharing of GNSS data from Continuously Operated Reference Stations (CORS) in the region while also developing an authoritative source of coordinates, and their respective velocities, for geodetic stations in the Asia-Pacific region. The APREF combined solution will be contributed to the IAG Regional Dense Velocity Field Working Group.

In response to the March 2010 Call for Participation (CfP) a large number of agencies have agreed to participate in APREF, Table 1 summarizes their commitments. APREF products presently consist of a weekly combined regional solution, in SINEX format and a cumulative solution which includes velocity estimates. In addition to those stations contributed by participating agencies, the APREF analysis also incorporates data from the International GNSS Tracking Network including stations in the Russian Federation (16), China (10), India (3), French Polynesia (2), Kazakhstan (1), Thailand (1), South Korea (3), Uzbekistan (1), New Caledonia (1), Marshall Islands (1), Philippines (1), Fiji (1), and Mongolia (1).

| Country/Locality | Responding Agency | Proposed Contribution | | |
|---|---|---|---|---|
| | | Analysis | Archive | Stations |
| Afghanistan | National Geodetic Survey (USA) | | | 2 |
| Alaska, USA | National Geodetic Survey (USA) | | | 90 |
| American Samoa | National Geodetic Survey (USA) | | | 1 |
| Australia | Geoscience Australia | ✓ | ✓ | 50 |
| Australia | Curtin University of Technology | ✓ | | 1 |
| Australia | University of New South Wales | ✓ | | |
| Australia | Department of Environment and Resource Management, Queensland | | | 8 |
| Australia | Department of Sustainability and Environment, Victoria | ✓ | | 55 |
| Australia | Department of Lands and Planning, Northern Territory | | | 5 |
| Australia | Department of Primary Industries, Parks, Water & Environment, Tasmania | | | 2 |
| Australia | Land and Property Management Authority, New South Wales | | | 52 |
| Cook Islands | Geoscience Australia | | | 1 |
| Cook Islands | Geospatial Information Authority of Japan | | | 1 |
| Federated States of Micronesia | Geoscience Australia | | | 1 |
| Fiji | Geoscience Australia | | | 1 |
| French Polynesia | Geospatial Information Authority of Japan | | | 1 |
| Guam, USA | National Geodetic Survey (USA) | | | 1 |
| Hawaii, USA | National Geodetic Survey | | | 19 |
| Hong Kong, China | Survey and Mapping Office | | | 6 |
| Indonesia | Bakosurtanal | | | 4 |
| Iran | National Cartographic Center, Iran | | | 5 |
| Iraq | National Geodetic Survey (USA) | | | 6 |
| Japan | Geospatial Information Authority of Japan | ✓ | ✓ | 10 |
| Kazakhstan | Kazakhstan Gharysh Sapary | | | 2 |
| Kiribati | Geoscience Australia | | | 1 |
| Kiribati | Geospatial Information Authority of Japan | | | 2 |
| Macau, China | Macao Cartography and Cadastre Bureau | | | 3 |
| Marshall Islands | Geoscience Australia | | | 1 |
| Micronesia | Geoscience Australia | | | 1 |
| Nauru | Geoscience Australia | | | 1 |
| New Zealand | Land Information New Zealand | ✓ | ✓ | 38 |
| Northern Mariana Islands | National Geodetic Survey (USA) | | | 1 |
| Papua New Guinea | Geoscience Australia | | | 1 |
| Philippines | Department of Environment and Natural Resources, National Mapping and Resource Information Authority | ✓ | ✓ | 4 |
| Samoa | Geoscience Australia | | | 1 |
| Solomon Islands | Geoscience Australia | | | 1 |
| Tonga | Geoscience Australia | | | 1 |
| Tuvalu | Geoscience Australia | | | 1 |
| Vanuatu | Geoscience Australia | | | 1 |

Table 1: Responses to the APREF CfP. Responding agencies have indicated whether they would undertake analysis, provide archive and product distribution or supply data from GNSS stations. Geoscience Australia has agreed to act as the Central Bureau coordinating the overall activities of APREF.

*Asia Pacific Regional Geodetic Project (APRGP)*

In order to densify the ITRF in the Asia-Pacific Region an annual geodetic observation campaign has been held to provide an opportunity to connect to national geodetic networks and to determine site velocities. While these campaigns have focused on GPS observations, coordinated through the PCGIAP, they also incorporated other geodetic techniques, including: Satellite Laser Ranging (SLR), coordinated through cooperation with International Laser Ranging Service (ILRS) and Western Pacific Laser Tracking Network (WPLTN); and Very Long baseline Interferometry (VLBI), coordinated through the APSG and International VLBI Service (IVS).

APRGP campaigns were coordinated by Geoscience Australia (GA) and the campaign data (1997 – 2010) were collated by Geoscience Australia, and subsequently made available, on request, to participating countries for analysis. The data from these GPS surveys are available, from Geoscience Australia, for both scientific research and local applications.

**Other Activity**

Other activities associated with the regional reference frame development include:

- The 13th PCGIAP meeting was held in Seoul, Korea in June 2007.
- The 14th PCGIAP meeting was held in Kuala Lumpur, Malaysia in August 2008.
- The 15th PCGIAP meeting was be held in Bangkok, Thailand in October, 2009.
- The 16th PCGIAP meeting was be held in Singapore in October, 2010.
- The 17th PCGIAP meeting will be held in Ulaanbaatar, Mongolia in July 2011.
- China, Japan, Korea and Australia are densifying their GNSS networks;
- Indonesia and the Philippines are planning to build and/or densify their continuous GPS networks;
- Australia, under the AuScope Initiative, has completed the construction of 3 new VLBI stations and new IGS standard GNSS stations;
- New Zealand has constructed a new geodetic VLBI station;
- Korea has engaged in a construction of a new geodetic VLBI observatory, 2008-2011;
- GSI, Japan, has launched a new project: Asia-pacific Crustal Monitoring Project;
- South Pacific Sea Level Monitoring Project (SPSLMP) installation phase complete, 12 CGPS stations have been collocated with tide gauges. GPS data is publicly available from Geoscience Australia; and
- Japan has upgraded its South Pacific (Plume) sites.

# Sub-Commission 1.3f: Regional Reference Frame for Antarctica (SCAR)

*Chair: Reinhard Dietrich (Germany)*

## Observation Campaigns

The SCAR GPS Campaigns 2008, 2009, 2010 and 2011 were carried out in the austral summers 2008 to 2011. All together, the data of 34 Antarctic sites are now collected in the SCAR GPS database beginning with the year 1995.

## Data Analysis

The data analyses continued. All data analyses were carried out with the Bernese GPS Software, version 5.0. The results were presented at the XXX SCAR Meeting in St. Petersburg/Russia in July 2008 and at the EGU Meeting 2009 in Vienna. New results will be presented at the IUGG Meeting 2011.

## Meetings

During the XXX SCAR Meeting in St. Petersburg the members of SC1.3f met and the working plan of the SCAR Group of Experts on Geodetic Infrastructure in Antarctica (GIANT) was discussed and fixed for the years 2008-2010. R. Dietrich (Germany) was confirmed as the coordinator of the SCAR GPS Campaigns. The members of GIANT represent the SC1.3f.

## The International Polar Year 2007/2008

The International Polar Year (IPY) 2007/2008 started at 1$^{st}$ of March 2007 and ended at 28$^{th}$ of February 2009. It was organized jointly by ICSU and WMO, and provided the frame for a broad range of coordinated, international projects. The SC1.3f actively participated in the frame of the IPY project POLENET (Polar Earth Observing Network). Results of POLENET were presented at the IPY Conference in Oslo in June 2010.

# Working Group: Regional Dense Velocity Fields

*Chair: Carnie Brunini*

## Activities

The long-term goal of the IAG Working Group "Regional Dense Velocity Fields" is to provide a globally referenced dense velocity field, based on GNSS observations, and to be used as a densification of the International Terrestrial Reference Frame. The Working Group (WG) closely links its activities with the regional reference frame sub-commissions, and regional coordinators have been appointed from the WG members. Their expertise, coordination role for their region, and their capability to generate a unique and unified cumulative GNSS-based position and velocity solution for their region, including velocity solutions from third parties (even campaigns), is a key element for the WG.

In reply to a first call for participation issued at the end of 2008, regional coordinators and analysts of global networks submitted in 2009, cumulative velocity solutions to the WG. Several of the regional solutions were a combination of cumulative velocity solutions based on the permanent GNSS network operated by the regional sub-commissions themselves and third party velocity solutions. A first test combination of the individual solutions (Bruyninx et al., in press) showed that the solutions could not be rigorously combined due to:

- inconsistent discontinuity epochs and solution numbers for the frame-attachment sites (mostly ITRF2005 sites) entailing large discrepancies at the common sites,
- inconsistent station naming and DOMES numbering,
- numerical instabilities caused by velocity constraints at sites with coordinate offsets.

In addition, using a European case study, Legrand et al. (2010, in press) showed that positions and velocities obtained from a regional GNSS network tied to the ITRF2005 using minimal constraints, can differ (up to 2 mm in the horizontal and 8 mm in the vertical for the positions and up to 0.5 mm/yr in the horizontal and 2 mm/yr in the vertical for the velocities) w.r.t. a global solution. When considering the residual velocity fields after removing the rigid block rotation, the velocity differences are considerably reduced but can still reach up to 0.8 mm/year in horizontal component. The disagreement between regional and global positions and velocities is caused by the so-called "network effect" and it is amplified when the reference stations used in the regional solution cover a smaller geographical area or the different solutions to be combined exhibit large discrepancies at common sites. This means that sites showing different discontinuities, time spans or large non-linear signals should be treated with extreme care. The network effect, of course, challenges the provision of a consistent dense velocity field partly based on regional position/velocity solutions.

Upon the release of the ITRF2008 (Altamimi et al., 2011), the investigation done in Legrand et al. (2010, in press), verifying the agreement between regional and global GNSS solutions, was repeated using the ITRF2008 reference frame. The tests showed that the disagreement between the global and regional position/velocity solutions is now reduced. It can nevertheless still reach 1 mm/yr in the vertical and 0.5 mm/yr in the horizontal. The investigation demonstrated that in order to reduce network effects, it is essential:

- to have the best possible agreement between the solutions we want to combine (by e.g. using similar data span, outlier rejection and discontinuity epochs for the common stations as well as a similar analysis strategy),

- to increase as much as possible the coverage of each of the solutions we want to combine (best is global),
- to increase to a maximum extend the redundancy between regional and global solutions in order to mitigate individual problems at the common stations.

With the goal to generate a high-quality solution for a core network, several newly reprocessed global and regional cumulative position and velocity solutions were submitted to the Working Group in the summer of 2010. In order to find a consensus on discontinuity epochs for stations common to several networks (an issue which was problematic in previous submissions) and reduce problems with the DOMES numbering and station naming, the new submissions were restricted to contain only the core networks over which the analyst has full control so that ITRF2008 discontinuities could be applied.

One new global solution was provided and 4 new regional solutions (Asia & Pacific, Africa, Europe, Latin America and Caribbean). All of these solutions are based on a reprocessing, using absolute antenna models (igs05.atx), and the stacking was done using the CATREF software (Altamimi et al., 2007) applying, as much as possible, the ITRF2008 discontinuity list. One exception is the African solution, where the site velocities have been computed using a linear regression through daily-estimated site positions expressed in the ITRF2008. For the North America region, no new solution has been made available.

In total, about 400 densification sites to the ITRF2008 were provided.

The 3D-RMS of the agreement of the new solutions with the ITRF2008 (after outlier rejection) varies between 0.6 and 1.1 mm/yr; it is extremely good for some solutions, while others still require more iteration to reach the required level of agreement. A part of these disagreements has been identified and often originates in the use of different data time spans within the ITRF2008 and submitted solution. Some cases were also identified where the residual position time series from the ITRF2008 significantly underperformed compared to the time series from a regional solution (see Bruyninx et al., submitted). This raises the need for more interaction between the regional reference frame sub-commissions and the IGS and/or the ITRF product center in order to prevent from facing a similar situation in the next release of the ITRF.

It was demonstrated that a careful inspection and comparison of both ITRF2008 and regional residual position time series is mandatory before using any site as a frame-attachment site. This adds as additional task for the WG which will need to verify and eventually discard some of the stations included in ITRF2008 before performing the combination. Therefore, at the moment, the WG concentrates on identifying the sources of disagreements between the solutions submitted to the WG and the ITRF2008 by comparing the residual position time series of all solutions. A dedicated software tools has been developed for this purpose. As soon as an agreement can be found on the discontinuities to be applied for the core solutions, and these core solutions can be successfully combined with the ITRF2008, then the WG will tackle the problem on how to integrate the third party (position and) velocity solutions.

In the upcoming year, several of the regional solutions will be reprocessed to embed the regional network in a global network and reduce the error induced by the network effect. For the regions of Asia & Pacific, Africa and North America such global solutions will become available in 2011. For South-America and Europe, however, the regional sub-commissions have no official plans to generate a global solution. Both regional groups offer as an alternative, as a first step, to combine their weekly regional solutions with the global weekly reprocessed solutions generated by the IGS or one of its Analysis Centers. In a second step, these weekly combined solutions will then be stacked and tied to the ITRF2008 taking advantage of the availability of a global set of reference stations.

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Legrand, J., N. Bergeot, C. Bruyninx, G. Wöppelmann, A. Santamaría-Gómez, M.-N. Bouin, Z. Altamimi (in press). Comparison of Regional and Global GNSS Positions, Velocities and Residual Time Series, *IAG Symposia Series "Geodesy for Planet Earth"*, Springer

## Working Group Meetings

- June 4, 2008, Miami Beach, US (IGS Analysis Centers Workshop)
- December 18, 2008, San Francisco, US (AGU 2008 Fall Meeting)
- April 20, 2009, Vienna, Austria (EGU 2009)
- September 3, 2009, Buenos Aires, Argentina (IAG 2009)
- October 5, 2010, Paris, France (REFAG 2010)

## Working Group Communications (in chronological order)

- Bruyninx C., Z. Altamimi, M. Becker, M. Craymer, L. Combrinck, A. Combrink, R. Fernandes, R. Govind, A. Kenyeres, B. King, C. Kreemer, D. Lavallée, J. Legrand, L. Sánchez, G. Sella, **IAG Working Group "Regional Dense Velocity Fields": Objectives and Future Plans**, IGS Analysis Centres Workshop, June 2-6, 2008, Miami, US, AFREF Workshop, June 17-18, 2008, Johannesburg, South Africa
- Bruyninx C., Z. Altamimi, M. Becker, M. Craymer, L. Combrinck, A. Combrink, R. Fernandes, R. Govind, A. Kenyeres, B. King, C. Kreemer, D. Lavallée, J. Legrand, L. Sánchez, G. Sella, **Objectives and Challenges of the IAG Working Group "Regional Dense Velocity Fields"**, EUREF 2008 Symposium, June 18-21, 2008, Brussels, Belgium
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- Legrand J., N. Bergeot, C. Bruyninx, G. Wöppelmann, M.-N. Bouin, Z. Altamimi, **Impact of the Reference Frame Definition on Geodynamic Interpretations**, WEGENER 2008 General Assembly, September 15-18, 2008, Darmstadt, Germany
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- Bruyninx C., Z. Altamimi, M. Becker, M. Craymer, L. Combrinck, A. Combrink, J. Dawson, R. Dietrich, R. Fernandes, R. Govind, T. Herring, A. Kenyeres, R. King, C. Kreemer, D. Lavallée, J. Legrand, L. Sánchez, G. Sella, Z. Shen, G. Wöppelmann, **Progress of the IAG SC1.3 Working Group in Providing a Dense Global Velocity Field Based on GNSS Observations**, EUREF 2009 Symposium, May 27-30, 2009, Florence, Italy
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- Legrand J., C. Bruyninx, N. Bergeot, A. Santamaría-Gómez, M.N. Bouin, G. Wöppelmann and Z. Altamimi, **Limitations of Regional GNSS Networks for Geophysical and Geodynamical Studies**, IAG Commission 1 Symposium REFAG, Oct. 4-8, 2010, Marne-La-Vallée, France
- Kenyeres A., K. Szafranek, **Regional Densification of the ITRF with Merging Global and Regional Solutions**, IAG Commission 1 Symposium REFAG, Oct. 4-8, 2010, Marne-La-Vallée, France

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- Legrand J., Bruyninx C., 2009, EPN Reference Frame Alignment: Consistency of the Station Positions, Bulletin of Geodesy and Geomatics, 2009(1), pp. 19-34
- Legrand J., N. Bergeot, C. Bruyninx, G. Wöppelmann, M.-N. Bouin, Z. Altamimi, 2010, Impact of the Reference Frame Definition on Geodynamic Interpretations, Journal of Geodynamics, Vol 49 (3-4), pp. 116-122, DOI: 10.1016/j.jog.2009.10.002
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## Sub-Commission 1.4: Interaction of Celestial and Terrestrial Reference Frames

*President: Harald Schuh (Austria)*

Main objective of IAG Sub-Commission 1.4 is the study of the interaction of the celestial and the terrestrial reference frames. In particular, SC 1.4 is focusing on the consistency between the frames. Sub-Commission 1.4 has established three Working Groups.

### WG 1.4.1 Theoretical Aspects of the Celestial Reference System and Systematic Effects in the CRF Determination (Chair: Zinovy Malkin)

WG members: Z. Malkin (Chair), N. Capitaine, A. Fey, A.-M. Gontier (deceased September 2010), S. Klioner, D. MacMillan, J. Sokolova, O. Titov, V. Zharov; ex officio: H. Schuh, President of IAG SC 1.4, C. Ma, Chair of WG 1.4.2, S. Lambert, Chair of WG 1.4.3

The main directions of the WG activity, according to its charter, are the following:

1. Analysis of ICRS definition in view of the latest development in astrometry and space geodesy.
2. Effect of 2000, 2003, 2006, and 2009 IAU resolutions related to Earth rotation on ICRS definition and realization.
3. Effect of the latest changes in the IERS Conventions on ICRS definition and realization.
4. Alignment of ICRF to ICRS.
5. Study of systematic errors in the current individual CRF and ICRF realizations.
6. Study of effects of geodetic datum definition on VLBI-determined CRF.

*1. Analysis of ICRS definition in view of the latest development in astrometry and space geodesy*

A detailed analysis of the ICRF definition in connection with other related issues, such as ICRF, time scales, CIO, etc., was given by the IAU Division I Working Group "Nomenclature for Fundamental Astronomy" (NFA) in its reports to the IAU 2006 and 2009 General Assemblies. No substantial progress was achieved since that report. However, the ICRF definition becomes not well understood and inconsistent when moving to the modern observations at a microarcsecond level of accuracy, e.g. VLBI2010 and GAIA. To solve arisen problems new considerations are needed. In particular, the hierarchy of relativistic reference systems should be extended beyond the galaxy to rigorously connect various kind of observations of near-Earth, galactic and extra-galactic objects at the microsecond level of accuracy.

*2. Effect of 2000, 2003, 2006, and 2009 IAU resolutions related to Earth rotation on ICRS definition and realization*

The IAU 2000 and 2006 resolutions on reference systems have modified the way how the Earth orientation (i.e. the transformation between the International Terrestrial Reference System (ITRS) and the Geocentric Celestial Reference System (GCRS)) is expressed. The IAU 2000, 2006, and 2009 resolutions have adopted high accuracy models for expressing the relevant quantities for the transformation from terrestrial to celestial systems. The concepts, nomenclature, models, and conventions in fundamental astronomy based on the IAU resolutions are suitable for modern and future realizations of the reference systems. This in particular allows the highest accurate realization of the celestial intermediate system linked to the CIP and the CIO that replaces the classical celestial system based on the true equator and equinox of date. The definition and the high accuracy realization of the celestial intermediate reference system based on the IAU 2000/2006 IAU Resolutions is consistent with microarcsecond accuracy of the celestial reference system and microarcsecond observational precision. The IAU 2009 resolution have significantly improved the realization of the ICRF, which allowed us the best realization of the ICRS

*3. Effect of the latest changes in the IERS Conventions on ICRS definition and realization*

No mentionable result is known. Improvement of the IERS Conventions is a continuous process, as well as analysis software development and collection of new observations. Thus a supplement detailed study aiming at separation of these factors is hardly feasible and difficult to be realized.

*4. Alignment of ICRF to ICRS*

A procedure for aligning of the ICRF2 to ICRF has been developed during preparation of the ICRF2. This procedure mainly follows the procedure used in the 1990ies for alignment of the ICRF with some updates related to the source classification, selection of the core (defining) sources, and inflation of formal errors. Special attention has been given to maintenance of stability of the ICRF2 axes, in particular through a choice of the optimal set of core sources. Development of a procedure for connection of the GAIA optical frame with radio ICRF is in progress.

*5. Study of systematic errors in the current individual CRF and ICRF realizations*

During the preparation and final phases of the ICRF2 construction, several IVS Analysis Centers (AUS, BKG, GSF, IAA, MAO, OPA, SHA, USN) produced a large series of the radio source position catalogs using various data sets, software and analysis options. Comparison of these catalogs allowed us to make some conclusions on a level of the CRF systematic differences depending on such factors as:

- Data set, e.g. using or omitting early observations, mobile occupations, and some other poor networks or VCS sessions (marginal effect),
- Software used (appreciable effect),
- Troposphere gradient modeling (largest effect),
- TRF vs. baseline solution (marginal/appreciable effect, needs further investigation),
- Atmosphere pressure loading (marginal effect)
- Axis offset estimation (marginal/appreciable effect, depends on software),
- NMF vs. VMF1 mapping functions (marginal effect).

In the list above, "marginal effect" means systematic differences at a level below 15-20 microarcseconds; "appreciable effect" means systematic differences at a level up to about 100 microarcseconds.

Besides, the following studies are being conducted:

- Investigation of systematic and individual (peculiar) source motion,

– Analysis of the consistency of CRF realizations at different bands,

– Methods of assessment of absolute accuracy and systematic errors of CRF catalogs.

New methods of the precision and accuracy assessment of the newest CRF realizations are under development.

*6. Study of effects of geodetic datum definition on VLBI-determined CRF*

A relevant study performed by the VLBI group of TU Wien has shown that the selection of celestial datum points has no significant systematic impact on source coordinates.

**WG 1.4.2 Realization of Celestial Reference Frames (CRF and Transformations) (Chair: Chopo Ma)**

WG members: C. Ma (Chair), O. Titov, R. Heinkelmann, G. Wang, F. Arias, P. Charlot, A.-M. Gontier (deceased September 2010), S. Lambert, J. Souchay, G. Engelhardt, A. Nothnagel, V. Tesmer, G. Bianco, S. Kurdubov, Z. Malkin, E. Skurikhina, J. Sokolova, V. Zharov, S. Bolotin, D. Boboltz, A. Fey, R. Gaume, C. Jacobs, L. Petrov, O. Sovers

*1. Goal*

Produce ICRF2 for IERS / IVS consideration and for submission the IAU

*Charter and purpose*

The purpose of Working Group 1.4.2 (which was identical with the corresponding IERS/IVS Working Groups) was to generate the second realization of the ICRF from VLBI observations of extragalactic radio sources, consistent with the current realization of the ITRF and EOP data products. The Working Group (WG) applied state-of-the-art astronomical and geophysical models in the analysis of the entire relevant S/X astrometric and geodetic VLBI data set. It carefully considered the selection of defining sources and the mitigation of source position variations to improve the stability of the ICRF. The goal was to present the second ICRF to relevant authoritative bodies, e.g. IERS and IVS, and submit the revised ICRF to the IAU Division I WG 'On the second realization of the ICRF' for adoption at the 2009 IAU General Assembly.

*2. Release and adoption of the ICRF2 in 2009*

The IERS/IVS Working Group released the ICRF2 mid-2009. It was adopted at the XVII IAU General Assembly, Rio de Janeiro, as the fundamental astrometric realization of the ICRS in replacement of the first ICRF in use since 1998 (IAU Resolution B3). The catalogue is made of 3.414 sources, which is five times more than the previous ICRF. The noise floor is 40 microarcseconds, i.e., five times better than for the ICRF. The axes are defined by 295 sources, selected on the basis of their time stability, low structure index, and repartition between North and South hemispheres. The axis stability is close to 10 microarcseconds, which is better than for the 212 ICRF defining sources by a factor of two (Fey et al. 2009).

## WG 1.4.3: Interaction Between Celestial and Terrestrial Reference Frames (Chair: Sébastien Lambert)

WG Members: S. Lambert (Chair), Ch. Bizouard, H. Boomkamp, R. Heinkelmann, F. Seitz, P. Steigenberger, D. Svehla; and C. Ma (Chair of WG 1.4.2), Z. Malkin (Chair of WG 1.4.1), H. Schuh (Ex officio, President of IAG SC 1.4).

### *1. Effects of CRF realization on EOP and TRF*

#### *1.1. ICRF2*

As described above the "Second Realization of the ICRF" was released mid-2009 and adopted at the XVII IAU General Assembly as the fundamental astrometric realization of the ICRS.

#### *1.2. On using ICRF2 in VLBI analysis*

Heinkelmann (2010) and Gordon et al. (2010) summarized the effects of using ICRF2 in VLBI analysis on EOP and TRF. When the observing configuration does not allow one to estimate source coordinates, fixing the CRF to ICRF2 is significantly better than fixing it to ICRF.

### *2. Effects of TRF realization on EOP and CRF*

#### *2.1. ITRF2008*

Mid-2010, the ITRF2008 was released by the IGN. It constitutes an improvement with respect to the previous version (ITRF2005). All IVS, ILRS, IGS, and IDS analysis centers participated in the production of the input data. As for ITRF2005, input data were time series of site positions and EOP of completely reprocessed solutions of the four space geodetic techniques. The accuracy of ITRF2008 origin and scale is 1 cm (Altamimi et al. 2011).

#### *2.2. Effect of ITRF2008 in other geodetic products*

Ma et al. (2010) compared VLBI analyses made by either fixing to ITRF2008 or estimating station coordinates and velocities. They identified a scale difference of -0.39 ppb between ITRF2008 and the VLBI TRF, and wrms differences less than 5 mm and 1 mm/yr for the 40 most participating sites. EOP obtained with both solutions agree well with the IGS solution.

### *3. Geophysical or technique modeling issues*

#### *3.1. Atmospheric pressure loading*

Recently, new atmospheric pressure loading (APL) data were released by the Institute of Geodesy and Geophysics at TU Vienna. This new product is derived from ECMWF data and is therefore fully consistent with the VMF1 data. Differences against Petrov and Boy (2004) loading data are less than 10% of the displacement (smaller than 3 mm). See Wijaya et al. (2010). The impact of different strategies for applying atmospheric pressure loading corrections on GNSS-derived parameters was studied by Dach et al. (2010).

### *3.2. Modeling of celestial pole offsets and effects on VLBI data analysis*

The UT1 intensive results depend on the celestial pole offset (CPO) model used during data processing. Since accurate CPO values are available with a delay of 2-4 weeks, CPO predictions are necessarily applied to the UT1 intensive data analysis, and errors in the predictions can influence the operational UT1 accuracy. Malkin (2010) showed that the impact of CPO prediction errors on UT1 is at a level of several microseconds, whereas the impact of the inaccuracy in the polar motion prediction may be about one order of magnitude larger for ultra-rapid UT1 results. He concluded that the situation could be amended if the IERS Rapid solution will be updated more frequently.

### *3.3. The IERS reference EOP series at the IERS EOP Center*

In order to be consistent with ITRF2008, the reference EOP series IERS 05C04 is being revised. The new solution 08C04 is the reference solution starting on 1 February 2011. Relative to 05C04, changes in the EOP series consist of (i) a negligible bias in x-pole and a bias of about 50 microarcseconds in y-pole, and (ii) changes in UT1-TAI and celestial pole offsets which are at the level of the WRMS between IVS individual solutions.

### *3.4. Space geodetic techniques and modeling of the glacial isostatic adjustment*

King et al. (2010) reviewed the ability of the four techniques to determine accurate and precise surface velocities. The study focused on the GPS network since it constitutes the corner stone for increasing the precision and accuracy to ~1mm/yr and constraining GIA models.

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# Inter-Commission Project 1.2: Vertical Reference Frames

*Chair: Johannes Ihde (Germany)*

## Introduction

At present, there are some hundred physical height systems realized worldwide. The realization of a unified global reference surface for physical height systems, the relation of individual tide gauge records with respect to this reference surface, the separation of sea level changes and vertical crustal movements at tide gauges, and the connection with the terrestrial reference system are to at large unsolved problems. To proceed towards a unified physical height system we need at the centimetre accuracy level:

- a unified global height datum,
- consistent parameters, models and processing procedures for the Terrestrial Reference Frame (TRF) and gravity field,
- a closed theory for the combination of parameters (space techniques, gravity),
- consideration of time dependency, and
- a rigorous concept for the realization.

The definition and realization of a World Height System (WHS) is a fundamental requirement of GGOS (Global Geodetic Observing System). In the same way as the ITRS/ITRF provides a high precision geometrical reference frame, the WHS shall provide the corresponding high precision physical reference frame for studying the system Earth.

ICP 1.2 is a common project of IAG Commission 1 and 2. From beginning of 2010 the activities of ICP1.2 were integrated in GGOS as Theme 1.

## 1. The ICP1.2 Vertical Reference Frames in the Period 2007 - 2011

The Inter-Commission Project 1.2 – World Height System-Pilot Project (ICP1.2 – WHS-PP) is an initiative of IAG ICP1.2.

The results of the work of the Inter-Commission Project 1.2 in the first term 2003 – 2007 are documented in **Conventions for the Definition and Realization of a Conventional Vertical Reference System (CVRS**), Ihde et al. 2007. In the CVRS conventions a general concept for the definition and realization of a unified, global vertical reference system is described. The CVRS conventions are aligned to the IERS 2003 Conventions. The conventions for a Global Vertical Reference System (GVRS) are a step forward to the realization of a WHS.

The main objective for the second term 2007 – 2011 is the initiation of a pilot project for a WHS realization (WHS-PP). The project continuation shall be realized in cooperation with other organizations.

This pilot project will provide an opportunity for the IAG Commission 1 (Reference Frames) and 2 (Gravity Field) to further expand and refine its existing reference frame infrastructure, to provide users with information about worldwide vertical reference frames, and to relate the regional height systems to a global datum.

The Deutsches Geodätisches Forschungsinstitut (DGFI) hosts the web site: http://whs.dgfi.badw.de. It will be used to convey further information about the project as required and as the project develops.

The main objectives in the period 2007 – 2011 are

- Considering the open topics of the period 2003 - 2007
- Further development of the CVRS conventions
- Preparation of decision about numerical standards as task in cooperation with International Astronomical Union (IAU) and international hydrological associations.
- Initiation of a pilot project for an WHS realization

## 2. The Realization Concept of a WHS

The realization of a WHS can be achieved mainly through the combination of different products of IAG services. The general case for realization of a WHS and unification of continental VRS is the combination of GNSS points and, if possible of GNSS/levelling points, with a global gravity model (GGM) which is named as the geodetic boundary value problem (GBVP) approach. This approach requires the following components:

– A global permanent GNSS network of stations connected with levelling networks, optionally supplemented by permanent (superconducting) and/or periodical (absolute) gravity observations at selected stations
– A global gravity model (GGM) with continental and regional densifications.

As result of this approach, we have available physical heights or geo-potential numbers related to a geoid/quasigeoid $T_{p\ RRT}$ which is related to a conventional zero level of the potential of the Earth gravity field $W_0$.

The WHS can be realized by two classes of points with two different procedures:

– GNSS points: $c_P = W_0 - W_P$ *and* $W_p = U_{p\ GPS} + T_{p\ RRT}$ , and
– points of levelling networks k: $c_P = c_{P\ k} + W_0 - W_{0k}$ . By this, $c_{P\ k}$ will be transformed from the regional level $W_{0k}$ to the conventional global level $W_0$. The difference $W_0 - W_{0k}$ can be determined by GNSS/levelling in selected co-location points by
  $W_0 - T_{p\ RRT} - U_{p\ GPS} - c_{P\ k}$.

An alternative approach which can be used for the unification of vertical reference frames is based on the combination of tide gauge observations with a global sea surface topography model. It is necessary that the tide gauge stations are linked to the regional levelling network and to the geometrical reference system ITRS/ITRF. (This approach will not further be considered).

In general, the realization of a WHS and the unification of the existing height systems into the global one require a combination of different elements based on a set of consistent conventional numerical standards. The accuracy of the WHS realization depends in the first order on the resolution of the gravity field model and the appropriate regional densification with gravity data. A service providing all relevant information would be useful.

## 3. WHS Pilot Project

In July 2010 the description of the of WHS Pilot Project with a call for information about planned contributions was send out. The deadline for final contributions Survey of WHS-PP results is May 2011 and the final report will be given at IAG General Assembly 2011.

The four WHS-PP Work Items are:

1. *Analysis centres for determining and monitoring the relationship between a conventional W0 and the potential of the Earth gravity field level surface closely coinciding with the mean sea surface*
2. *Regional processing centres and global combination centres for GNSS/levelling stations with coordinate time series in the current ITRF linked to TIGA stations and geo-potential numbers referred to the RHS at defined epochs*
3. *Investigations on the accuracy of computing point values Wp of the gravity potential by means of high resolution gravity field models and regional densifications of gravity data*
4. *Operative determination of physical WHS heights in regions with a weak geodetic infrastructure including and development of an information system (registry) providing relevant data*

It is assumed that the results of TIGA (i.e. land vertical velocities at tide gauges derived from GNSS positioning) are available.

Partners for the WHS-PP are inside the IAG: the IGFS (International Gravity Field Service) for GGM, absolute and super conducting gravity meter measurements, IGS (International GNSS Service) for TIGA, SC2.4 (Sub-Commission 2.4) for continental and regional densification of a GGM, PSMSL (Permanent Service for Mean Sea Level) for tide gauge measurements, and the IAS (International Altimetry Service) for a global sea surface topography model.

## 4. Proposed continuation

At the end of the second term of ICP1.2 and after the work of the various WIs is completed, the ICP will prepare a final report and recommendations on how to best realize the WHS (including all relevant issues such as the computation and adoption of a "best" $W_0$ value, an optimal global geoid surface, etc.) This report will be presented at the IAG General Assembly in Melbourne. Then the ICP will be dissolved.

In the future, the work of ICP should continue in the form of a GGOS Integrated Product (i.e., Theme 1) for the establishment and maintenance of a WHS. The International Gravity Field Service (IGFS) should take the leading role there and report directly to GGOS. GGOS has to clarify inconsistencies in the numerical parameters for integrated geodetic applications. Conventions for the definition and realization of the parameters of the MSSL have also to be agreed.

# Inter-Commission Working Group 1.1: Environment Loading: Modelling for Reference Frame and Positioning Applications

*Chair: Tonie van Dam (Luxembourg) , Jim Ray (USA*)

## Introduction

The accuracy and precision of current space geodetic techniques are such that displacements due to non-tidal surface mass loading are now measurable in many cases. Consequently, data analysts have an increasing interest in comparing geodetic and computed load displacements, or even in applying displacement corrections to geodetic results to remove the geophysical loading effects. Unfortunately, direct correction of geodetic estimates by computed load displacements can introduce undesirable errors into coordinate times series and thus into the ITRF itself if the corrections are not computed or applied with utmost care. Problems that are sometimes encountered include: a proliferation of different (and sometimes erroneous) loading models; lack of accurate load models for some effects; use of various different reference frames not always well suited to the geodetic reductions; applying corrections at the observation level versus longer-period a-posteriori average corrections; undesirable attributes of some geophysical loading models such as a lack of mass conservation or other errors. The main activity of this working group is to investigate procedures to ensure that suitable environmental corrections are available to users and that the optimal usage is made.

## Objectives

The principal objective of the scientific work of Working Group 1.1 is to investigate optimal methods to mitigate loading effects in ITRF frame parameters and site coordinates. Additional goals include basic research into the determination of accurate load displacements for the various component geophysical fluids, accuracy assessment for different loading models, assessment of the propagation of errors into the site coordinates and the ITRF, and specifications of which model displacements are best applied at the geodetic observation level and which are better applied in post-processing. Results of these investigations should be integrated into the recommendations of the IERS Conventions, where appropriate.

## Members

Tonie van Dam (Luxembourg, chair)
Jim Ray (USA, co-chair)
Zuheir Altamimi (France)
Xavier Collilieux (France)
Pascal Gegout (France)
David Lavallee (UK)
Ernst Schrama (Netherlands)
Xiaoping Wu (USA)

## General Activities and Recommendations

The main activities of the members of this working group are represented in papers published (see reference list) or in preparation, as well as oral and poster presentations at the Fall Meetings of the American Geophysical Union (San Francisco, CA, USA), General Assemblies of the European Geosciences Union (Vienna, Austria), and occasional other special and topical meetings.

### Modelling non-tidal loading a priori?

Based on our research findings, it is our specific recommendation that displacements due to non-tidal geophysical loadings not be included in the a priori modeled station positions. The most serious obstacles to including loading displacements as a priori corrections presently are:

- *reliability of the non-tidal effects in the sub-daily band* -- At best, non-tidal environmental models attempt to compensate mostly for seasonal variations, which are well outside the normal integration intervals for space geodetic data. None of the available global circulation models properly accounts for dynamic barometric pressure compensation by the oceans at periods less than about two weeks. Instead, both "inverted barometer" (IB) and non-IB implementations are produced as crude approximations of the actual Earth system behavior even though these are both recognized as unreliable in the high-frequency regime. While effective at longer periods (especially seasonal), the undesirable and unknown degradation that would affect sub-daily integrations (not only for geodetic parameters, but also for any other parameters estimated from the observations) is not an acceptable side-effect. This is particularly compelling when one considers that non-tidal loading effects can be readily considered in a posteriori studies with no loss whatsoever.
- *inaccuracies of the models* -- The basic types of studies and analyses that are normally considered a precondition to adoption of a conventional model are mostly lacking for non-tidal models. Documentation of error analyses is a basic requirement that must be fulfilled. In their statistical comparison of several publicly available atmospheric pressure loading services, van Dam and Mendes Cerveira (2007) have identified differences up to several mm (RMS) due to effects of varying model parameters and input data choices. This study does not account for possible common-mode error sources. As an illustration, van Dam et al. (2010) showed recently that high resolution topographic models were mandatory to compute atmospheric loading models. Before general users can be expected to routinely utilize non-tidal loading services sensibly, it is vital that the major sources of systematic differences identified in such studies be resolved. Studies of other loading effects (non-tidal ocean loading and continental water loading) are also mandatory. Continental water loading could also be evaluated using GRACE results (Schrama et al., 2007). Moreover, although inversion methods are sensitive to GPS systematic errors, we encourage comparison between available forward loading models and inverted loading models (Küche and Schrama, 2005; Wu et al., 2006) for evaluation purposes. However, it would be relevant to study how known GPS systematic errors (such as the harmonic of the draconitic frequency (Ray et al., 2008)) map into the inverted products. The approach considered by Koot et al. (2006) in their study of various models for atmospheric angular momentum (AAM) is a good example of how a combined series might be formed to reduce series-specific noise. This type of development should be considered in the provision of all forward non-tidal loading results, partly as a convenience to users as well as a potentially improved product.
- *must be free of tidal effects* -- Any non-tidal displacement corrections applied should be strictly free of residual tidal contaminations, otherwise the geodetic results will be adversely affected by aliasing and possible duplication of the directly modeled tidal signals. This is not always assured in operational atmospheric loading services that are currently available.– Conversely, atmospheric tides are recommended to be applied at the observation level. Indeed, applying atmospheric tide loading has been shown to reduce

spurious periodic signals in the station position time series (Tregoning and Watson, 2009).

- *long-term biases in the reference frame* -- Because environmental models do not yet conserve overall mass i.e. or properly account for the exchange of fluids between states or between reservoirs e.g. atmosphere and oceans, use of non-tidal models in solutions for the terrestrial reference frame will generally suffer from long-term drifts and biases that are entirely artificial. This is a completely unacceptable circumstance.
- *new datum requirements for the reference frame* – Introducing pressure-dependent non-tidal site displacement contributions into standard geodetic solutions would necessitate the adoption of a global reference atmospheric pressure field since the load density anomaly is computed with respect to a conventional reference. The ITRF reference coordinates (mainly height) for any given site would depend directly on the associated reference pressure for that site. In order to minimize deviations from the established frame, one would probably prefer that the reference pressures closely match long-term average pressure values (10 years) at every possible geodetic site. But the lack of long-term in situ met data from many locations could make such a goal unreachable. Furthermore, many ITRF users would probably not welcome nor understand the expansion of the ITRF datum to include such non-geodetic quantities as reference pressures. In certain other non-tidal loading cases, it might also be necessary to consider additional non-geodetic quantities as reference datum contributors (such as local mean temperatures). If non-tidal displacements are not allowed, then there is no ITRF requirement to adopt a conventional reference pressure field, though this might still be considered and might be useful for other reasons. Note that it is important to continue development of improved, unbiased methods to derive local a priori pressure values globally in order to properly model tropospheric delay effects optimally, which in turn is necessary for accurate station height estimates.
- *need to easily test alternative models* -- As noted above, it is vital to be able to compare different non-tidal models easily and efficiently, something that is not facilitated by direct inclusion of the models a priori into geodetic analyses. It is far simpler to make such comparisons and studies a posteriori as has been done for many years in research into the excitation of Earth orientation variations. However, in solutions where non-tidal displacements have nonetheless been applied, it is imperative that the full time-series of corrections used must be reported in new SINEX blocks that will need to be documented. Still, the availability of such information will permit only an approximate reconstruction of the non-tidal corrections, though, if the applied sampling is finer than the geodetic integration interval. Different interpolation schemes produce slightly different results.

We recommend that models of non-tidal station displacements be made available to the user community through the IERS Global Geophysical Fluid Center and its special bureaus, together with all necessary supporting information, implementation documentation, and software. Expansion of the IERS Conventions, Chapter 7, could include some essential aspects of this material to inform users. Continued research efforts are strongly encouraged, particularly to address the outstanding issues listed above. However, in the meantime non-tidal displacements must not be included in operational data reductions that are contributed to the IERS to support its products and services. It should be recognized that nowadays the non-linear deviations of geodetic time series are themselves a crucial product for many applications seeking to better understand the geodynamics of mass load variations. They are used to compare with and interpret GRACE inversions as well as for much higher spatially resolved investigations of more localized deformations and environmental changes. Removing such signals from geodetic results, especially using diverse and possibly inconsistent load models, would block the pursuit of such important studies.

**Modelling non-tidal loading a posteriori?**

Notwithstanding the preceding remarks concerning a priori load displacement corrections, we believe that further research is warranted into the possible utility of including non-tidal loading displacements in the formation of ITRF, a posteriori to the reduction of the space geodetic data. Tregoning and Watson (2009) showed that applying atmospheric loading model a priori is equivalent to a posteriori correcting the estimated coordinates for daily solutions. Dach et al. (2011) found a slightly better reduction of the WRMS using weekly samples probably due to missing data during the week and also a different handling of the sub-daily variations. However, they showed that a posteriori corrections are also effective. Indeed, Collilieux et al. (2011) showed that GPS height time series correlate well with full loading models in the height although the performance for the horizontal is not so good. They indicate that systematic errors still exists in space geodesy products, especially at the annual frequency. This is confirmed by comparisons made using GRACE solutions (Tregoning et al., 2009).

It is currently assumed implicitly in the ITRF procedures that varying site deformations, such as those due to loading, average out in the long-term stacking of time series of coordinate frames from each technique. If the loading models have a SNR greater than 1, at least at seasonal periods, then the averaging should be more effective if the load corrections are applied during the stacking. Furthermore, any effects of sparse networks and non-continuous observing ("network effects") are also reduced (Collilieux et al., 2010). This is likely to be more important for the weaker SLR and VLBI networks than for GPS and DORIS.

Such an approach could be implemented in the first step of the ITRF combination process, where the individual technique coordinate frame time series are stacked. Each of the load contributions would need to be integrated over the same time intervals as the frame increments (generally daily for VLBI and weekly for other techniques). The result would be a long-term frame for each technique consisting of the usual reference positions and velocities. The estimated positions and velocities would be especially different for stations with few observations and large loading effects. Time series of station residuals could be generated in two ways, with and without the a posteriori load corrections and the characteristics of each compared and assessed. It worth mentioning that station residual position time series should be carefully constructed especially when loading corrections are not introduced (Lavallée et al., 2006; Collilieux et al. 2011) since loading effects tends to leak into the Helmert parameters, especially the scale factor.

The time series of the Helmert parameters would be nominally free of loading effects. This is likely to be most significant for those parameters dominated by the SLR or VLBI contributions, such as the overall ITRF scale variations and geocenter motions (the Helmert translations from SLR). The EOP time series would also be free of loading contaminations and less affected by network effects, but this is unlikely to be significant for those components dominated by GPS observations. This was demonstrated by Collilieux et al. (2010) who showed that 50% of the annual signal in the SLR and VLBI scale has been reduced after loading corrections.

In the second step of ITRF formation, to combine the technique long-term frames, no further loading corrections are needed. Before such a procedure as this could be considered for operational use, careful studies would be required. Among other things, the issues raised above must be carefully evaluated, particularly the possibility of long-term biases in the loading models that could adversely affect the stability of ITRF. If this is a problem, the loading fields could be detrended for secular variations before being used in the ITRF stackings, for instance. Consideration would also be needed of the consequences for user applications, particularly for the EOPs. Collilieux et al. (2010) applied this method to the combination of VLBI, SLR and GPS terrestrial frames. Although this conclusion cannot be generalized to all sites, they found an improvement in the agreement of the long-term coordinates of the different techniques for some co-location sites.

Use of non-tidal loading models in this a posteriori way would affect only globally integrated estimates (Helmert parameters, EOPs, and ITRF itself). The potentially degrading effects discussed before of applying the models a priori at the observation level would be avoided. The inter-station vectors of individual technique coordinate frames, for example, would not be affected by high-frequency noise from the load models and simultaneously estimated non-geodetic parameters would be similarly unaffected.

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# Inter-Commission Working Group 1.2: Precise Orbit Determination and Reference Frame Definition

*Chair: Frank Lemoine (USA)*

The members of the working group have agreed to focus on the effects of non-conservative force model error in precision orbit determination and how it aliases into POD solutions. In addition, we discuss in this report the work accomplished by members of the DORIS community with respect to radiation pressure modelling, the development and testing of improved radiation pressure models for Jason-1 and ENVISAT. Finally we report how we have successfully mitigated the effects of atmospheric drag on DORIS POD and determination of reference frame parameters. We note the work underway in the community to developed improved atmospheric drag models for satellite applications.

Historically the DORIS recoveries for geocenter have been characterized by reasonable recoveries in X and Y, but large signals in Z. For example *Feissel-Vernier et al.* (2006) for three sample series find annual signals of ± 5 mm in X and Y but ± 20 mm in Z. In the DORIS geocenter time series, the prime signals occur at the annual period, but also at the solar beta prime (draconitic) period for TOPEX/Poseidon. This was the key clue that indicated mis-modelling of radiation pressure was aliasing into geocenter recovery for DORIS. *Gobinddass et al.* (2009) showed that by tuning the solar radiation pressure reflectance coefficient ($C_r$) for each satellite (in effect scaling the macromodel), and fixing it in the orbit solutions, it was possible to mitigate the radiation pressure mis-modelling and recover a cleaner geocenter signal, particularly in the Z component. The problem is particularly acute for DORIS as many members of the satellite constellation are sun-synchronous, and so the radiation pressure mis-modelling will alias directly into an annual signal. In the new IGN solutions, the Z component in geocenter is more in line with the expected annual amplitude predicted by geophysical models. We are pleased to report that the time series of *Gobinddass et al.* (2009) has been incorporated into the IDS combination, however not all the DORIS analysis centers have completed the same level of radiation pressure model tuning. A spectral analysis was completed of the geocenter signals of all the IDS AC's, and strong Z amplitudes at the annual period (365 days) and TOPEX draconitic period (120 days) were present in several of the series. In future work, all the AC's will be encouraged to upgrade their models and data processing.

Drag modelling and parameterization of drag coefficients are also a key issue for DORIS satellite POD, particularly in solar storms and other overall periods of high solar activity (*Willis et al., 2005*). The drag mis-modelling effects can be mitigated by increasing the drag parameterization (i.e. adjusting an empirical drag coefficient more frequently for the low altitude satellites such as the SPOT's and ENVISAT). The habit had been to adjust such $c_d$'s every four to six hrs, however more frequent adjustments improve the station repeatability and EOP recovery during high drag periods *(Gobinddass and Willis, 2008*). Of the DORIS analysis centers, for the IDS-1 Combination prepared for ITRF2008, only IGN and ESA parameterized drag at the higher levels (1-2.4 hrs) (*Valette and Yaya, 2009*). As a consequence, when the WRMS (weekly RMS repeatability wrt. a cumulative position velocity solution) was computed, a spike was observed in late 2001 to 2002. This was found to coincide nearly exactly with the increase in solar flux around the peak of the solar cycle, and the increase in the RMS of fit in the DORIS satellite arcs (*Yaya and Valette, 2009*). Thus, the analysis centers were asked to reprocess their data from the Autumn of 2001 to the Spring of 2002 with a higher drag parameterization. The GAU, GSC and LCA analysis centers complied with this recommendation, and the result is that in IDS-2 ITRF2008 test combination, the peak in the

WRMS around the peak of the solar maximum has been much reduced from 26 mm with IDS-1 to 20 mm in IDS-2. We note that the GOP analysis center is probably not as affected by atmospheric drag as they use the Bernese software and solve for frequent stochastic parameters as a routine part of their OD solutions (*Stepanek et al., 2006*). The more frequent $c_d$ adjustment (in the ESA, IGN, GSC, GAU and LCA satellite orbits) is made possible by applying a weak constraint on the estimated $c_d$'s and/or a time-correlation with exponential decay time constant and a process noise sigma between adjacent $c_d$ parameters.

We note that work is underway in the community to upgrade atmosphere models. These include the group at the GRGS/CNES who are analyzing accelerometer data from GRACE and CHAMP for inclusion into new atmosphere models (cf. *Bruinsma and Forbes, 2007*; *2008*). In addition teams led by US. Naval Research Lab have developed improved drag models built upon the long history of MSIS models (*Picone et al., 2002*). The NRL is leading an experiment with the ANDE satellite, to study the Earth's thermosphere and gather further data to improve drag models (*ILRS/ANDE, 2009; Thomas, 2008*). The model developed by *Bowman et al.* (2008) is particularly interesting, as it relies on solar indices that track more closely how the Sun deposits energy into the thermosphere of the Earth. These indices are in the Far Ultraviolet and Extreme Ultraviolet, as opposed to the standard F10.7 proxy that has been used for years. The development of these models is very encouraging, however in any given orbit determination software it is easier to adjust new parameters than integrate a new orbit determination model, which requires manpower, testing and possibly adherence to standards of configuration control.

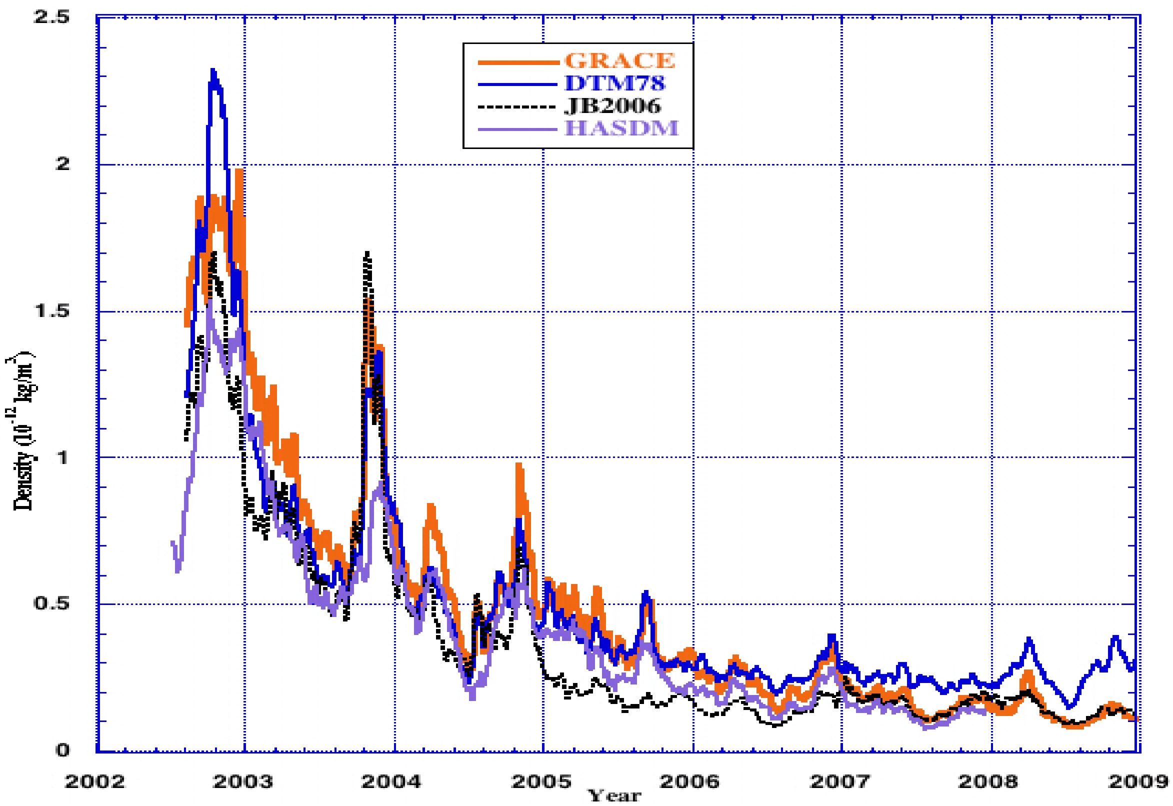


Figure 1: Density comparisons from 2002 to 2009 from atmosphere density models and from GRACE.

Atmosphere density estimates based on GRACE accelerometer data have been used to validate various density models, including the 1978 Density Temperature Model (DTM78), the Air Force Space Command's High Accuracy Satellite Density Model (HASDM) and the Jacchia-Bowman 2006 (JB2006) model (*Cheng et al., 2007, 2008; Tapley et al., 2007).* Figure 1 shows that the models tend to under-predict the density when solar activity is high (except for DTM78 over some periods) but agree better (especially for HASDM) with GRACE densities during low solar activity (starting from early 2006). The earlier empirical DTM78 model appears to over-predict the density as compared to the GRACE measurements after 2006 where the solar activity was decreasing. The extreme density values in during 2003 are due to the high solar activity and geomagnetic super-storm that occurred during the period of October-November 2003.

We also note that while at present the issue of drag modelling and parameterization affects primarily the IDS contribution to the reference frame, atmospheric drag is a strong signal on the Starlette and Stella satellites. These SLR cannonball targets are not typically used for reference frame work although some preliminary work has been done in this regard (*Govind et al., 2007*). The addition of further satellites, in particular targets with a tight SLR target signature (cf. see *Otsubo and Appleby, 2003* for a discussion of this issue) could benefit the SLR solutions. In particular prior to 1993, the addition of Starlette would strengthen the SLR reference solutions when Lageos was the only contributor. However many issues other than proper drag modelling and parameterization need to be resolved before these new satellites can be added to SLR reference frame solutions.

In this report period, working group members have tested improved radiation pressure models developed at the University College London (UCL) for the Jason-1 and ENVISAT satellites (*Ziebart et al., 2005; Sibthorpe, 2006*). ENVISAT is one of the members of the DORIS satellite constellation. Jason-1 does not presently contribute to the DORIS reference frame solutions as the data are omitted due to the instability of the DORIS Ultrastable Oscillator and its radiation sensitivity (*Willis et al., 2004*). However, development of an improved radiation pressure model is important first of all for oceanographic and mean sea level applications, as analysis of the CNES/GDR-C orbits has revealed a draconitic signature (beta-prime, or Sun-related) in the altimeter data (*Leuilette et al., 2009*). The UCL models were tested at NASA GSFC. For Jason-1, they find a systematic improvement in the SLR residuals, and a reduction in the magnitude of the empirical accelerations (*Lemoine et al., 2009*). The NASA GSFC std0905 orbits to be released to the Jason-1/Jason-2 Science team will use this modelling (*Lemoine et al., 2009*). Although Jason-1 is not part of DORIS reference frame solutions at present there is always the possibility the USO DORIS problem may be mitigated in the future by more detailed modelling (e.g. *Lemoine JM and H. Capdeville, 2006*). In addition the Jason-1 spacecraft carries an SLR retro-reflector and GPS receivers. While the prime and backup GPS receivers each in turn have failed, the long time span of SLR and GPS data available mean that Jason-1 could make an interesting satellite with which to attempt joint GPS/SLR reference frame solutions, should some group wish to make those experiments in the future. A prerequisite would be minimizing the errors due to the non-conservative forces, including radiation pressure and in this context, the UCL radiation pressure model for Jason-1 would be particularly useful.

The NASA GSFC team also tested the application of the UCL model on ENVISAT. It was found that the amplitude of the daily empirical accelerations showed a notable improvement (a factor of two to five). *Doornbos et al.* (2002), who applied a proprietary model, ANGARA, to orbit determination for ENVISAT, found that during periods of intense solar activity, deficiencies in the drag model, in particular the atmosphere response function to high flux or geomagnetic indices was the dominant source of error. We note that Le Bail et al. (2009) saw in 2003 a 27 day, solar-rotation-related, periodicity in the recovered ENVISAT along-track empirical acceleration amplitudes. At low solar flux conditions, the drag and radiation pressure model errors were found to be at a comparable level. In the future it would be interesting to intercompare the recovered 1opr accelerations from the different analysis centers that analyze ENVISAT data, as well as the *computed* drag and radiation pressure perturbations, in order to see what each orbit determination software is actually doing. The UCL model for ENVISAT has also been implemented in the GIPSY/OASIS software at JPL, and we expect that further tests with the IGN and/or INA DORIS analysis centers will be possible in the near future.

Advances in GPS orbit modelling have also been accomplished by members of our working group. An issue that has been present in GPS analyses is a putative bias in the SLR residuals to GPS satellites. In addition *Urschl et al.* (2007) found that the range residuals derived from the various GNSS orbits show similar periodic variations, which are correlated with eclipsing seasons and the sun's elevation above the orbital plane, indicating orbit or attitude modelling deficiencies. *Ziebart et al.* (2008) have made progress in this area. They observe that the bias can reach 4-5 cm around an arc on the dark side of the Earth (affecting primarily the satellites that experience eclipse). They find that modelling planetary radiation pressure can reduce this bias and that modelling antenna thrust further reduces the SLR residuals. The UCL team have experimented with different parameterizations of the albedo, and with detailed radiation pressure models for the GPS satellites (e.g. for the Block 2A and the Block 2R series of GPS satellites). These model developments are promising and offer the prospect of improving the GPS processing potentially for the next ITRF. Another avenue of radiation model improvement for the GPS satellites is suggested by *Herring* (2009). In his EGU paper, he showed the radiation signature in the GPS orbits, and demonstrated the correlation with the empirical terms used in orbit adjustment. As in Gobinddass et al. (2009) for the DORIS satellite orbits, he showed how the effect could be mitigated by a proper tuning of the parameterization. Taken together, these model and analysis developments are promising and offer the prospect of improving the GPS processing potentially for the next ITRF (i.e. ITRF2011 or ITRF2012). However, further testing is required and the working group will need to enlist the involvement of GPS analysis centers to carry out detailed tests (meaning processing a long time series of orbits and analyzing the daily station time series).

In the coming year, the working group will continue to focus on surface force model improvement for the ENVISAT and SPOT satellites, and we will also address modelling for Jason-2 (in orbit since June 2008) and Cryosat (scheduled for launch in late 2009) which will likely become strong contributors to the IDS reference frame in the future. Both satellites carry the DGXX DORIS receiver which can track up to seven DORIS beacons. Thus the quantity of DORIS data available will drastically increase in coming years.

Another possible activity would be to ascertain how we might improve the orbits of LEO satellites during periods of high solar activity through better forward modelling. If time and resources permit, we will evaluate the JB2006 atmosphere density model, and another atmosphere model upgrades that might be available.

We note that we have not addressed so far how the GPS reference frame might be affected by non-conservative force mis-modelling. A draconitic signature is evident in the GPS orbits, and is imputed to be due mis-modelling of the non-conservative forces.

We envisage a special session at the EGU General Assembly Meeting 2010 as a means to focus community attention on the precision determination and reference frame issues.

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# Inter-Commission Working Group 1.3: Concepts and Terminology Related to Geodetic Reference Systems

*Chair: Claude Boucher (France)*

The objective of the WG was to establish a report describing basically a recommended nomenclature, together with all useful comments for a better reader's understanding. The working group intended to expand towards the geodetic community the work recently achieved by the International Astronomical Union, and to provide material for the IERS Conventions. A detailed report can be found on the IAG Commission 1 website. Also a summary paper is planned for publication in a journal.

*Recommended terminology*

The following terms were considered by the WG. The terms with * are the terms recommended for preferred use:

- Conventional Terrestrial Reference Frame (CTRF)
- Conventional Terrestrial Reference System (CTRS)
- Geocentric Terrestrial Reference System (GTRS)*
- Geodetic Reference System
- International Terrestrial Reference Frame (ITRF)*
- International Terrestrial Reference System (ITRS)*
- Terrestrial Reference Frame (TRF)*
- Terrestrial Reference System (TRS)*
- Vertical Reference System*

# Inter-Commission Working Group 1.4: Site Survey and Co-locations

*Chair: Pierguido Sarti (Italy)*

## Goals and Objectives

The WG should spread the knowledge related to local surveys and their adjustment among the national agencies in charge of co-location sites maintenance.

*1. Site surveys standards:*

a. Revise the local tie surveying activity developed so far. Identify open issues and promote research and discussion.

b. Set guidelines related to in field operations.

c. Spread the know how among the community and the national agencies in charge of co-located sites maintenance.

*2. Tie vector* estimation:

a. Set guidelines on tie vectors computational standards and their transformation into global frame.

b. Provide local tie vectors with full variance-covariance information in SINEX format.

c. Develop a concrete action plan to improve local ties for future ITRF realizations.

*3. Site surveys activities:*

a. Promote local tie surveying wherever needed.

b. Remotely assist site surveying activities.

c. Provide computational support.

*4. Coordination and research:*

a. Liaise with technique combination centres.

b. Liaise with technique services.

c. Promote a joint effort aimed at focusing on the most recent combination residuals of the global frame for investigating local inconsistencies at co-location sites and identify actions to be taken to improve the performances of tie vectors within ITRF like combinations.

Complete charter at: http://iag.ign.fr/index.php?id=55

## Meetings

*The first WG meeting took place during the AGU Fall Conference on Wednesday, December 16th, 2009 at Hotel Palomar in San Francisco (USA). The following items were discussed.*

***Site Survey Standards***

*Guidelines for surveyors:* During the meeting the necessity of defining the guidelines regarding local tie practice has been pointed out several times. This would assure a minimum standard in tie vector measurements with the aim of estimating eccentricities to the highest precision achievable. Several methods nowadays exist and different groups claim to possess the know-how for optimal tie vector computation. Nowadays only a few tie vector surveying methods have been compared and proved to be consistent. As a matter of fact, tie vectors are submitted to ITRF Combination Centres adopting a variety of non homogeneous methods which largely depend on the know-how of the local teams carrying out the local surveying operations. The issue must be discussed in the next Vienna meeting during EGU 2010 in order to agree on common surveying methods which may be routinely adopted as conventional IERS reference procedures for tie vector computation. Specific guidelines must be described, supplied and circulated in a document which should be used as quick reference manual. Operatively, the WG must identify a sub-group of WG members experts on tie surveying technical issues for the compilation of a reference manual.

***Tie Vector Estimation***

*Software:* Exchange of tie vector estimation software has to be promoted among the local tie groups and existing software must be made readily available. A validation phase must precede the former step and has to be supported.

***Site Surveys activities***

*Critical co-location sites:* ITRF2008 residuals will provide verification of critical co-locations in need of urgent actions such as re-measurements/re-computation of the tie vector. Specific action will be taken accordingly to support new local tie measurements or re-analyse data with existing software.

***Coordination and Research***

*Who does what?* The role of local agencies and their surveyors must be harmonised with IERS standards and combination requirements. Technique Services are crucial to endorse documentation eventually produced by this WG and must be actively involved in the finalisation of conventional IERS reference procedures related to tie vector estimation.

*Output format:* Software should allow to save and to output the full tie vector information (components and full variance-covariance matrix) in the native topocentric frame. Also, when available, information on local geoid undulation should be provided. These aspects are crucial to align topocentric and local geodetic frames and to carry out a thorough investigation on combination residuals.

*Alignment:* Local to global frame tie vectors alignment remains an aspect which needs deep and further investigation.

*Terminology:* As research progresses, the lack of a univocal reference terminology on local tie issues is evident. Definitions are needed on specific procedures, items and quantities which relate to tie vector surveying, estimation and alignment. Particularly, the definition of space geodetic instrument reference point is ambiguous (e.g. stochastic, conventional, electronic). This part can be treated and included in the reference manual.

*PCV & technique-dependent biases:* As the knowledge of gravitational deformations of VLBI telescopes improves, a new lexicon on phenomena and quantities must be clearly set. PCV files similar to GPS might be needed in the future for VLBI in order to account for gravitational deformation of VLBI telescopes. This task can be fulfilled liaising with IVS and other services. Finally range biases in SLR and their signature in the mis-closure between terrestrial and space geodetic results must be investigated in the near future. It is agreed that these corrections are responsibility of the technique services and cannot be relied upon tie surveying and computation procedures, i.e. the tie aims at connecting conventional-to-conventional reference points.

*The second meeting of the WG took place in Vienna, during the EGU 2010 meeting, May 4$^{th}$, 2010, 19.00 h-20.00 h at the Vienna International Centre venue, Meeting Room SM3. The minutes of the meeting are under preparation.*

The interest on the topics covered by the WG chart is high in the geodetic community, as shown by the remarkable number of invitees that participated in both the first and second WG meeting.

## Ongoing activity

During the Vienna meeting, the discussion partially focused on the possibility to write *guidelines for surveyors* to be resumed *in a reference manual* for practical on field operations. Although time consuming, a drafting of such document is feasible and would be useful under certain circumstances. Nevertheless, as chair of the working group, I have to stress the *complete lack of agreement on the methods to be adopted for tie vector surveying* among the groups involved in local tie surveying. This certainly jeopardizes the efforts spent on the preparation of a reference manual and it compromises its significance and validity.

As the *local ties* are performed mostly by local on-site surveyors, the *methods are highly site dependent* and may differ considerably one another. Nevertheless, a *harmonization* of the different surveying method *is needed to* dominate and *control* several factors that impact on the *accuracy of* the *tie vector*. In addition, the different *homemade software* which are used specifically to reduce and condition indirect terrestrial observations *must be inter-compared* and tested. To my knowledge, *only one test* was successfully carried out inter-comparing two indirect-method software and it *proved* their *consistency* (Dawson et al. 2007, J Geodesy). *This* mandatory *phase* of the harmonization process was identified as *crucial* during the San Francisco WG meeting *but* had *no follow up*.

*Tie vectors residuals* were recently released as a *by-product* of the recent *ITRF2008 combination*. Their values *are currently* being *investigated* for assessing critical situations at the co-location sites. A close *cooperation* with the Product and *Combination Centres* is compulsory and is part of the ongoing investigation.

The *WG needs closer cooperation with the single technique services* in order to investigate further the role of PCV to connect the Electronic and Conventional reference points of the different geodetic instruments and remove the possible biases. *Particularly,* the cooperation with *IVS, IDS and ILRS must be strengthened.*

### *Miscellaneous*

During the EGU2010, the session "The Global Geodetic Observing System: Tying and Integrating Geodetic Techniques for Research and Applications" attracted contributions that covered several aspects relevant to the WG activity. Twelve oral and twenty one poster contributions were eventually presented and helped outlining the state-of-the-art on the WG activities.

### Survey activities

In August 2009 John M. Gipson (NVI Inc.) issued an invitation for a proof-of-concept demonstration involving a Robotic Total Station and a VLBI antenna at the Goddard Geophysical Observatory in Greenbelt, Maryland. The demonstration was carried out on Wednesday, September 23 at 2:00 and aimed at illustrating a 1 hour automated, straight-forward, fast, and, unassisted method for measuring the position of the VLBI/SLR conventional reference point.