Commission 1 - Reference Frames

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President: Zuheir Altamimi (France)
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Structure

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Overview

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.

Introduction

The main activities of Commission 1 during the period 2007-2009 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 president's sub-commissions and sub-component to reflect changes and continuous activities of all commission entities.
- A Steering Committee meeting was 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.
- Participation in COSPAR GA held in Montreal, July 2008 and in Hotine Marussi symposium in Rome, July 2009.
- It goes without saying that the main activities were undertaken by the commission sub-components as presented in the rest of this mid-term 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 main activities of SC-1.2 are: increase of the number of GNSS permanents stations within the 6 regional sub-commissions; the establishment within SIRGAS of five associated analysis centres under the responsibility of Latin American and Caribbean institutions; for NAREF, realization of densifications of the ITRF and IGS global networks by weekly combinations of six different regional weekly solutions using different GPS processing software packages; for AFREF, creation of an Operational Data Centre (ODC) for AFREF with an open data policy, expected to be operational within the second half of 2009; for Asia & Pacific, 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; and finally for Antarctica, the realization of SCAR GPS Campaigns in

2008 and 2009 where the data of 34 Antarctic sites are collected in the SCAR GPS database beginning with the year 1995.

Additionally, one of the main new initiatives of SC-1.3 is the creation of an inter-regional 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. A first set of preliminary regional combined solutions is prepared for June 2009. The preliminary solution resulting from the combination of the preliminary regional SINEX solutions with long-term solutions from global networks will serve to identify problems and help to set strategic choices and guidelines. Some problems encountered up to now are being solved. A new solution is expected to be issued in 2010-2011.

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

The main highlight of SC-1.4 activities includes the analysis of ICRS definition in view of the latest development in astrometry and space geodesy as well as the analysis to generate the next realization of the ICRS (ICRF2) at microwave frequencies using VLBI data.

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.

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 Geosciences 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 geocentre 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), geocentre 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.
- JPL is studying a satellite project specifically dedicated to the co-location of the space geodetic techniques onboard a new satellite. This will be complementary to the co-location efforts on the ground.
- A new IERS Working Group has been formed 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.

Working Group SC 1.1 - WG 1: Comparison and Combination of Precise Orbits Derived from Different Space Geodetic Techniques

Chair: Henno Boomkamp (Germany)

The main interest of the Working Group remains to improve techniques of comparing and combining precise orbit solutions based on different space geodetic techniques, in support of the more generic objectives of IAG Commission 1 and GGOS. As a result of propositions and discussions held during the reporting period, a new approach is proposed in this field and will be the main subject of this report.

The DANCER project

The DANCER system forms an internet-based solution approach to construct least squares estimation processes for an *unlimited* station network size. In this method, the normal matrix contributions from individual geodetic instruments are accumulated on a local PC at the ground station. All station-dependent parameters (station coordinates, clocks, troposphere delays, etc.) are pre-eliminated from the normal equation system by the local estimation process (see Figure 1 and Eq. 1). The remaining global normal matrix partition is exchanged among all participating computers via internet, using a highly efficient scheme called *square dancing*. This algorithm provided the name DANCER, which also reflects a close relation to the DIGGER project that will be revisited further below. After the square-dance matrix accumulation process, all PCs in the network hold the same global matrix partition. This allows every individual computer to solve the global parameter corrections $\vec{x}_A$ for Earth rotation parameters and satellite parameters. The global solution vector $\vec{x}_A$ is substituted in the pre-elimination equations (1) to find the local parameter corrections $\vec{x}_C$ of the station. The entire least squares solution is iterated to convergence.

The outcome of this distributed estimation process is mathematically identical to a single least squares solution for all involved observations and parameters, but can include many thousands of stations. While no individual analysis centre would be able to handle such a large estimation process, the DANCER processing effort at individual tracking stations is rather modest. The involved internet traffic is in the order of 50 megabytes per station per solution, which is a trivial load for modern internet connections. The DANCER solution process can span an arc of e.g. the most recent 48 hours and is repeated at regular intervals, e.g. every two hours, in analogy to current IGS products.

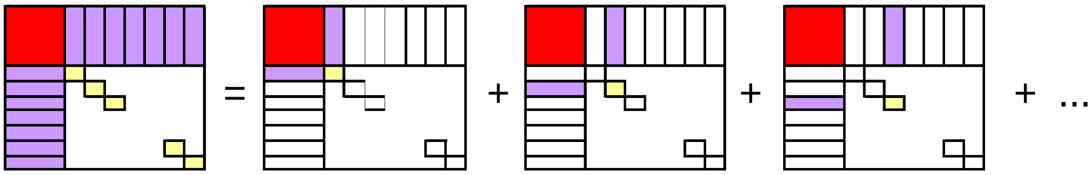

Figure 1: Normal matrix of a least squares process, written as the sum of contributions from individual geodetic instruments. The global (red) partition requires summation of many contributions, but other partitions (yellow, purple) are only relevant to a single receiver. These station-dependent partitions are pre-eliminated and only the global partitions are exchanged.

$$\begin{pmatrix} A & B \\ B^t & C \end{pmatrix}\begin{pmatrix} \vec{x}_A \\ \vec{x}_C \end{pmatrix} = \begin{pmatrix} \vec{b}_A \\ \vec{b}_C \end{pmatrix} \Rightarrow \begin{cases} A\vec{x}_A + B\vec{x}_C = \vec{b}_A \\ B^t\vec{x}_A + C\vec{x}_C = \vec{b}_C \end{cases} \tag{1}$$
$$\vec{x}_C = C^{-1}\left(\vec{b}_C - B^t\vec{x}_A\right) \Rightarrow \left(A - BC^{-1}B^t\right)\vec{x}_A = \vec{b}_A - BC^{-1}\vec{b}_C$$

Eq. 1: Pre-elimination of a station-dependent vector $\vec{x}_C$ provides an equation for the global parameter corrections $\vec{x}_A$ only. Matrix A corresponds to the red partition of Figure 1, matrix B is the purple correlation block, and matrix C is a yellow station-dependent partition.

Square dance method

It is clear that the DANCER solution depends on the efficiency with which the global normal matrix information can be exchanged via internet. This turns out to be remarkably simple with an accumulation method called square dancing. In this approach, pairs are formed among all computers in the network. The two computers in each pair exchange their matrix contributions and add the incoming matrix to their own matrix (step 1 of Figure 2). New pairs are now formed between pairs of the first cycle (step 2 of Figure 2). Each computer exchanges its matrix with a computer of the other pair, and adds the incoming matrix to its own matrix. The four computers in the *pair of pairs* now hold the same sum of the four original matrix contributions.

In a third cycle, new pairs are formed between clusters of four computers from the previous cycle (step 3 in Figure 2), etc. It will be clear how this pair-wise exchange can be repeated as many times as necessary. Each consecutive cycle doubles the size of clusters with identical matrix sums. For a network of size N, only $^2\log N$ complete cycles are required to accumulate the global sum of all initial matrix contributions at all participating computers. In practice, the network size will not be an exact power of two, but this problem is easily solved. For instance, in a network of N = 10,000 computers, we find that $2^{13} < N < 2^{14}$. The largest power of two for which a complete exchange process is possible is 2^{13} = 8192. To form a sub-network of exactly this size, 1908 computers simply upload their matrix to another computer in the network at the start of the process. The receiving computers add the incoming matrix to their own matrix, after which only 8192 independent matrix contributions remain that are added together in 13 square dance cycles. After completion, the 1908 computers that were left out of the process download the global sum, which already includes their own contribution.

Because of the exponential rate with which the normal matrix information disperses through the network, the square dance approach is insensitive to an increase in network size. As shown above, an individual computer in a network of 10,000 computers will perform at most 14 exchange cycles to obtain the global sum of *all* matrix contributions. For a network of 80,000 computers, only three additional cycles would be required (2^3 = 8). This adds just a few minutes to the communication process, which is irrelevant in comparison to the overall process duration and its repeat rate (~hours). Individual computers only need to contact about

15 different computers in the network, which means that the involved socket connections can be kept open throughout the solution process for reducing wait states. The overall complexity and data volume involved with the square dance matrix accumulation process is comparable to that of reading a newspaper on the internet.

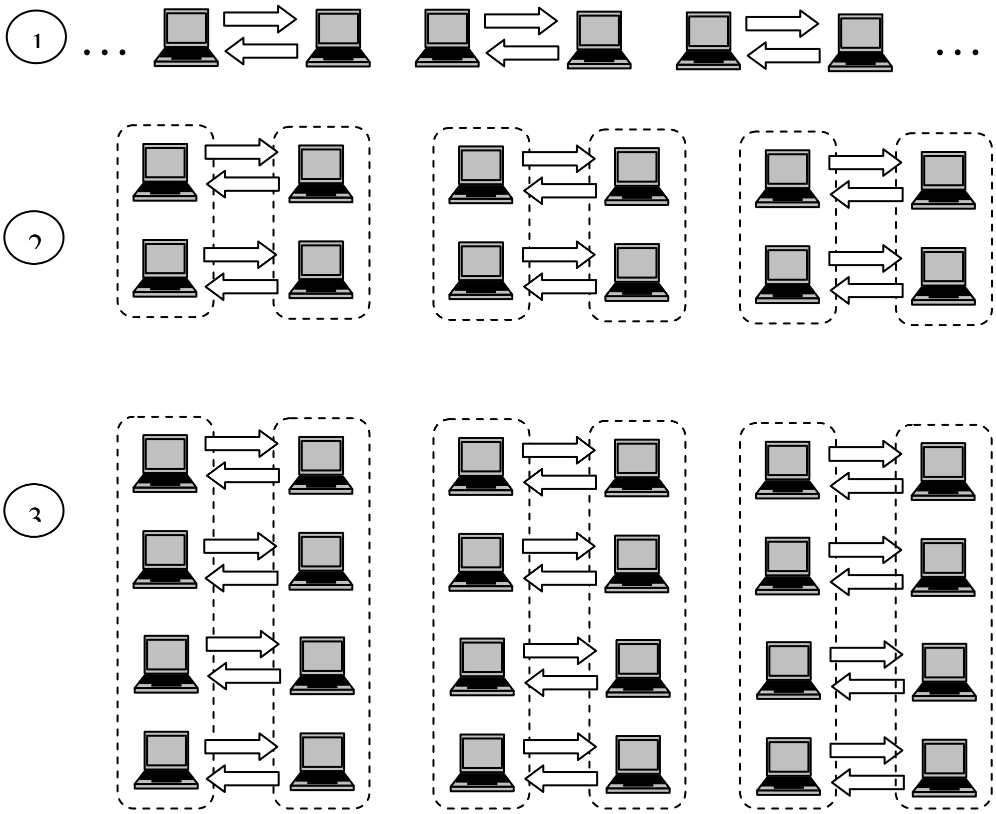

Figure 2: Square dance accumulation logic among a network of computers.

The above sections explain the basic concepts behind the DANCER solution, without going into all details. In practice, there are various complications that took some time to be solved. For instance, multiple layers of pre-eliminations and square dance exchanges are needed to cope with epoch-dependent parameters (GNSS clocks) and satellite-dependent parameters. A slightly different exchange mechanism is needed in support of GNSS ambiguity resolution. The DANCER system also involves a few centralized internet sites (hubs) where stations can *check-in* if they want to be part of the next global solution. The process needs various safety mechanisms, to cope with computers that go off-line in the middle of a solution process - etc. The concept is in fact conveniently redundant, because clusters of computers with the same intermediate matrix can immediately provide backup in case of unexpected loss of an individual computer, and spare computers can usually be found in a pool of unused participants (in the example above, there are 1908 spare computers). Such details fall outside the scope of this report, and do not change the principle of a distributed estimation process.

Consequences to IAG / GGOS

In terms of efficiency and possible solution size, distributed processing is expected to be orders of magnitude more powerful than the traditional centralized processing approach at Analysis Centres. The DANCER system does not really have any network size limit, because it is perfectly scalable: every new receiver brings its own computer, so that the workload for individual computers is only affected by a possible increase in exchange cycles – however, this will only add a few percent to the process duration. It could therefore be concluded that the centralized product generation of the current IAG services could benefit from such solutions and that in the long term such distributed estimation software could even be fully integrated with the software of high-end GNSS receivers and similar geodetic instruments: global estimation products like Earth rotation parameters will then become output products *of the receivers*.

The implications of a distributed processing approach for the current IAG and its services can be profound. Some effects will be:

- *All* permanent geodetic GNSS receivers in the world can be included in a single, coherent ITRF solution. The differences between regional networks and global networks disappear: all receivers become part of the same global GNSS network. This can lead to ITRF solutions based on ten thousands of receivers, as opposed to currently only 400. This solves most of the network densification issues.
- Most elements of the centralized IAG Services (data centres, analysis centres, product centres) could significantly benefit. The DANCER software transforms an individual geodetic instrument into a mini data centre, a mini analysis centre, and a mini product centre. Data and products may still be published by the station operator on a voluntary basis, but stations can also participate *anonymously* in the DANCER solution, sharing neither their data nor their products. It seems obvious that stations that want to be in a formal ITRF solution must always publish their data and their position coordinates, in order to allow independent validation.
- Combination solutions seem no longer required if all observations can be processed in a single, mathematically clean least squares solution. The DANCER solution may provide perfectly coherent estimation products for all involved receivers and tracking stations, and consistency between local and global estimation products.
- With DANCER, all GNSS processing is expected to be possible at a higher data rate than what is typically done by the IGS Analysis Centres today. This improves the signal-to-noise ratio and therefore the solution quality. A data rate of 30 seconds is foreseen, which also allows inclusion of data from orbiting receivers. To this purpose, the LEO download stations can run the DANCER software and the LEO orbit parameters become pre-eliminated "station" parameters. This conveniently avoids LEO data distribution issues (data publication latency) that in the past have lead to many discussions: the data does not have to be published at short latency, but can nonetheless contribute to the estimation of the pole in near real-time.
- High-end GNSS users anywhere in the world can run the DANCER software on their own PC, and join the next available global solution via internet. The user data is treated in exactly the same way as the observations from the reference sites (with the exception that no-net-rotation conditions etc. should only be derived from properly monumented geodetic sites). This means that users obtain precise ITRF coordinates and UTC time offsets for their own receiver from a *global* solution process, at accuracy levels that are currently only available to IGS stations. In other words: DANCER offers *direct access* to the ITRF and to UTC anywhere on the planet, maybe even replacing current techniques such as short-baseline differential GPS.
- Other geodetic instruments, in particular SLR stations, DORIS download stations and VLBI correlation centres can also join the global solution with their own data. These stations will then observe the *same* polar motion parameters that are estimated by the GNSS network, while their estimated station coordinates are subject to the *same*

Helmert constraints as the GNSS receivers. This global solution then provides perfect consistency among all space geodetic techniques, which forms the main objective of IAG Sub-Commission 1.1.

- *All* formal objectives of WG 1 may be accomplished simultaneously if the geodetic reference sites start using the DANCER software once available. The DANCER system would implement a true Global Geodetic Observation System by making all geodetic instruments *work together* via internet. This turns the network of instruments into a single sensor for polar motion, satellite orbits and other global parameters.

Implementation status of DANCER and DIGGER

The DIGGER project has been introduced via a previous report of the WG 1.1.1. (2007), and in a report to the IGS Governing Board (December 2007). It aims at fast reprocessing of space geodetic data by means of distributed processing (grid computing) on internet. DIGGER uses an iterative *conjugate gradient* solution to split a huge least squares process (spanning ~15 years of data) into thousands of manageable tasks. It uses a data exchange scheme similar to, but slightly different from, the DANCER square dance method to exchange the involved solution vectors.

The data traffic involved with DANCER is highly *in*sensitive to network size, but very sensitive to the size of the global matrix partitions. It would for instance be prohibitive to estimate a gravity field model with DANCER, while it is not a problem to include many thousands of stations in one solution. This means that DANCER is mainly suitable for computing large network solutions in near real-time, generating most of the typical products that are currently generated by IGS and other services, such as station coordinates, troposphere parameters, satellite orbits and polar motion parameters. DIGGER does not have a practical limitation on the number of global model parameters, as long as a sufficiently large number of computers participate in the process. This makes DIGGER suitable for estimating large geophysical models from long data periods (gravity field, tides, station velocities). The two projects are therefore complementary.

The implementation of the internet-based applications DIGGER and DANCER may be realised in C++ or JAVA, preferably in close collaboration between IAG Analysis Centres and industry.

The main element of both, DIGGER and DANCER, is compact, efficient and highly portable parameter estimation software. In fact, DIGGER really requires a single-binary / single control-file layout in order to be supported by the Berkeley Open Infrastructure for Network Computing (BOINC), which has been selected as the driver of the grid computing process for various strong reasons. For DANCER it is merely *convenient* if the software is as compact as a single binary, but this would not be strictly required. For both projects it is essential that the orbit estimation software is under strict configuration control, and that automatic updating via internet is supported. There are obvious advantages in using the same core parameter estimation software for DIGGER and DANCER:

- One development trajectory requires less effort than two separate trajectories
- The same modelling standards will automatically be used in re-processing and operational product generation
- Changes in (e.g.) IERS conventions or other processing standards only need to be implemented once and will always be consistent between the two systems

- The same computers that will be using DANCER might as well be used in the DIGGER project. If each station archives its own data, it can later reprocess that data for a DIGGER process, whenever requested. This means that a complete merge of the two systems may be an option in the long-term.

A suitable single binary orbit estimation system (ROBOD) is currently being implemented on behalf of ESOC, using state-of-art software engineering methods and several independent design optimizations. By the time of the previous IAG report (2007), this project was just moving from its prototype stage at ESOC towards formal implementation by industry. At the time of the current report, a first version was delivered, currently undergoing a critical design review. As soon as all relevant state-of-art precision levels are accomplished, such software could form the core of the DIGGER project. In fact, the prototype software had already been installed successfully under the BOINC grid computing software, showing the feasibility of the concept. However, a more comprehensive demonstration under realistic conditions combined with a thorough verification and validation campaign would be required in order to assess the full potential of the proposed solution.

Conclusion

Because the DANCER and DIGGER projects can accomplish most if not all objectives of WG 1 of Sub-Commission 1.1, and most objectives of other IAG sub-commissions and GGOS, it seems recommendable to pursue these two strategic targets further.

Working Group SC 1.1 - WG 2: Interactions and consistency between Terrestrial Reference Frame, Earth rotation, and gravity field

Chair: Detlef Angermann (Germany)

Objectives

Working Group 2 of Sub-Commission 1.1 "Coordination of Space Techniques" is a joint WG with Commission 2, Commission 3, and the Global Geodetic Observing System (GGOS).
The main research topics are:

- Study the theoretical and practical interactions/relationships between parameters and models describing the terrestrial reference frame (TRF), Earth rotation and the gravity field (e.g., low-degree spherical harmonic coefficients).
- 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

During the period of this report various activities related to the integration of geometry, Earth rotation and gravity, and the interactions between these three fields were carried out. 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. Two projects, that address various topics of this WG, are explicitly mentioned below:

- Within the GGOS-D project (funded by BMBF, 2005 – 2008), homogeneously processed observation time series have been generated for the different space geodetic observation techniques, as the basis for the computation of a GGOS-D terrestrial reference frame and for the generation of consistent, high-quality time series of site coordinates, Earth rotation parameters, quasar coordinates and low-degree harmonics of the Earth's gravity field. The project involves four institutions: GeoForschungsZentrum Potsdam (GFZ), Bundesamt für Kartographie und Geodäsie (BKG), Institut für Geodäsie und Geoinformation, Universität Bonn (IGG), and Deutsches Geodätisches Forschungsinstitut (DGFI), see Rothacher et al. (2007).

In the framework of 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" improvements have been achieved regarding the combination of geometric and gravimetric observations. A major focus was on the analysis of geophysical contributions to Earth rotation changes determined from geometric, gravimetric and altimetric space observations as well as from geophysical models (see for example Göttl and Seitz, 2009). The project started in 2006 and is now in the second funding period (2009-2012).

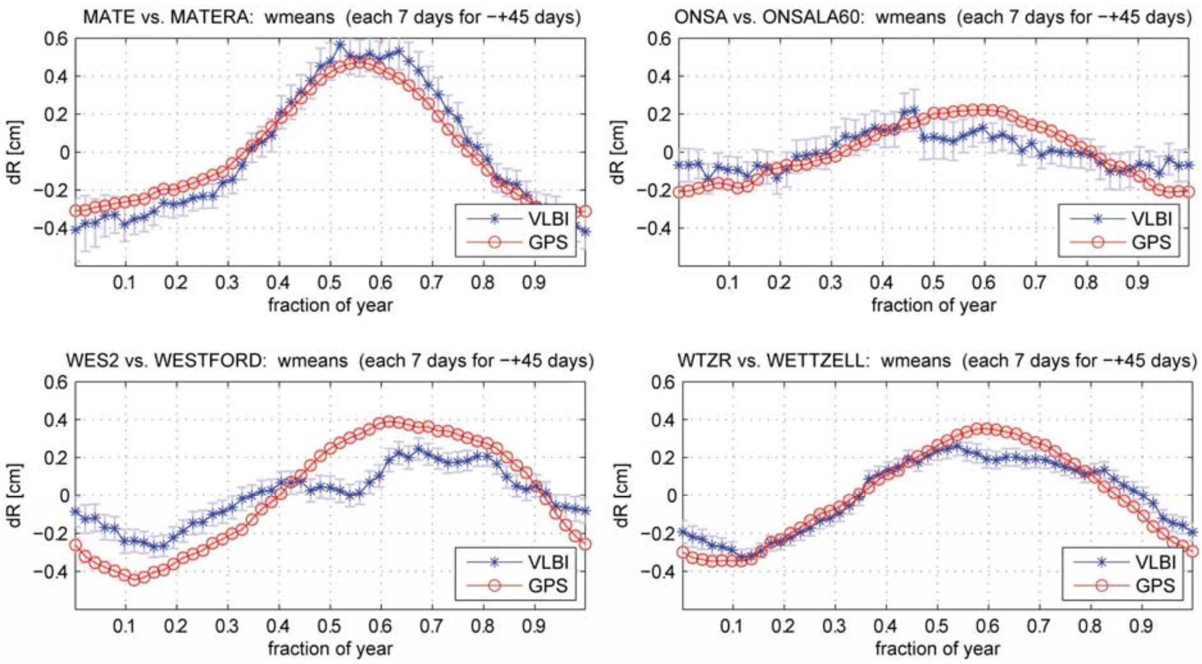

Fig. 1: Mean annual behavior of homogeneously processed VLBI (blue stars) and GPS (red circles) height time series at four co-location sites. The figures illustrate 90 days moving weighted means and their formal errors, computed each 7 days from the daily height estimates.

As an example for the working group activities we provide some results of the GGOS-D project. The time series analysis of station positions has shown non-linear variations of station positions, especially in the height component. Fig.1 shows the mean average of such annual variations for four GPS-VLBI co-location sites. The results were obtained from consistently processed VLBI and GPS observation time series, which have been generated in a joint effort by DGFI, GFZ Potsdam and Technische Universität München. The observed seasonal signals may be caused by atmospherical, hydrological and non-tidal oceanic loading effects, which are not reduced from the original observations.

A deficiency regarding the current strategy for the computation of long-term solutions is, that the temporal variations of station positions are described only by constant velocities. Deviations of the station motions from a linear model (e.g., seasonal variations) will produce errors in the products for the three fields (geometry, Earth rotation and gravity). A suitable handling of these seasonal variations in station positions is a challenge for the future.

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Working Group SC 1.1 - WG 3: Comparison and combination of atmospheric information derived from different space geodetic techniques

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.

As already summarized in the last Working Group 3 Report (Rothacher et al., 2007), 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. Snajdrova et al. (2005), Ichikawa et al. (2006), and Krügel et al. (2007) for the 15-days continuous VLBI campaigns CONT02 and CONT05, or Steigenberger et al. (2007) and Heinkelmann et al. (2007) for long time series from VLBI and GPS. In recent years, a common research project by several German institutions has dealt with the *Integration of Space Geodetic Techniques as the Basis for a Global Geodetic-Geophysical Observing System* (GGOS-D, Rothacher et al., 2009). More information about this project is available at the webpage *http://www.ggos-d.de*.

Some PhD. theses (partly in German) were finished in the last 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, and some results are extracted from them.

Troposphere delay comparisons

The best agreement of zenith delays between two techniques is found for GPS and VLBI with a standard deviation of about 5 mm, and it is shown by Schmid et al. (2005) and Schmid (2009) that the biases between the techniques decrease when using absolute phase centre patterns for GPS. However, there remains a significant influence on the zenith delays at those GPS antennas covered by a random.

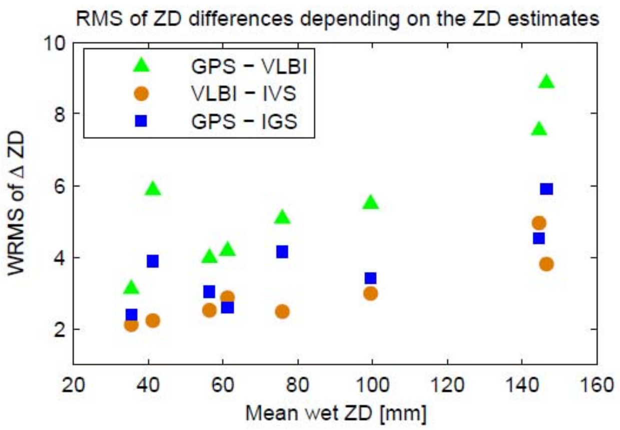

Figure 1 (from Thaller, 2008). WRMS of the zenith delay differences depending on the size of the estimated wet zenith delays. IVS refers to the combined solution of the International VLBI Service for Geodesy and Astrometry, VLBI is a dedicated VLBI solution using exactly the same geophysical models as the dedicated GPS solution.

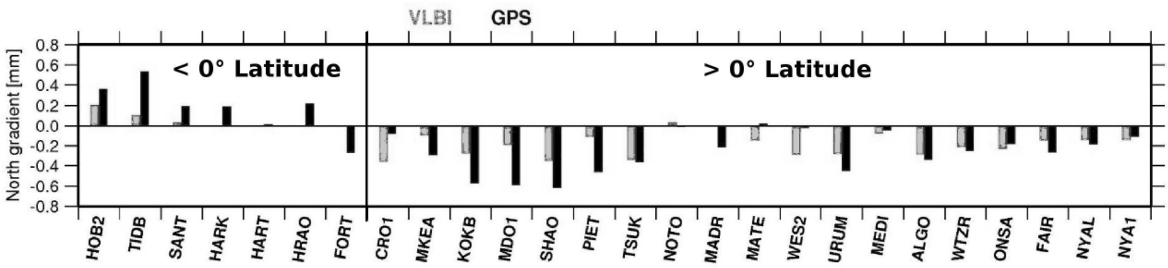

Figure 2 (from Nothnagel et al., 2009). Mean gradients in north-south direction of co-located VLBI and GPS stations.

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 recently developed GPT model (Boehm 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 (Boehm et al., 2006a) are more accurate, but new empirical mapping functions like GMF (Boehm 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.

For the combination of troposphere parameters from different space geodetic techniques, the normal equations have to be set up properly: the time intervals for the troposphere parameters should start at integer hours (e.g. 18:00 UTC) and at integer fractions of it (e.g. 18:15, or 18:30, ...), offset and rate should be set up for each interval, and the time intervals should be rather short because they can be concatenated at a later stage if necessary (Thaller, 2008). It is recommended to use piecewise linear offsets for the representation of troposphere parameters because these can easily be combined at a later stage.

Thaller (2008) concludes in her PhD. 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 dualfrequency techniques should determine similar TEC values at the same line of sight or Vertical (VTEC) values above a point on the Earth surface.

Within the 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. A first comparison between STEC values predicted by the IGS combination and the observed ones by DORIS (on board JASON) resulted in a standard deviation better than 1 TECU over all latitudes (Hernándes-Pajares, 2005). Hobiger et al. (2006) provided comparisons of TEC values between GPS and VLBI over the VLBI radio telescopes. They found a mean bias (VLBI minus GPS) above all sites of −2.8 TECU and an RMS of ±10 TECU.

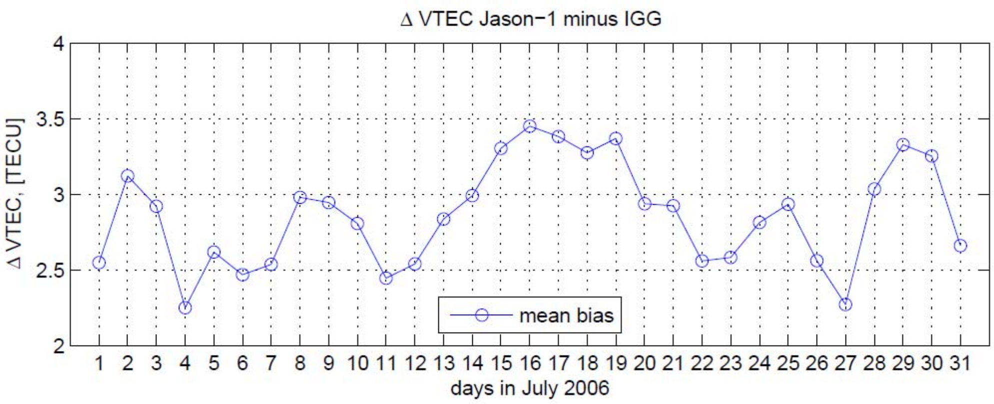

Figure 3 (from Todorova, 2009). Daily mean VTEC of the difference Jason-1 minus IGG VTEC in July 2006.

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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.
- 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.

The GGOS-D project has started some work at these frontiers, but 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 1n 2003 as a part of the new structure of the International Association of Geodesy (IAG).

Terms of Reference and Objectives for 2007-2010

Sub-Commission 1.2 is engaged in scientific research and practical aspects of the global reference frames. It investigates the requirements for the definition and realization of the terrestrial reference systems (TRS) and frames (TRF), addresses fundamental issues closely related to TRS, such as multi-technique global geodetic observatories (local ties, site effects, interdisciplinary use…) or methods for the combined processing of heterogeneous observation data. The work will be done in close cooperation with the International Earth Rotation and Reference Systems Service (IERS), in particular with the ITRS Product Centre, the other relevant IAG services (IGS, ILRS, IVS, IDS), and the IAG Global Geodetic Observing System (GGOS). Theoretical aspects (e.g., quality measures, relativistic modeling) will be investigated in cooperation with the Inter-Commission Committee on Theory.

The following research topics will form the fundamental objectives during the next period:

- Basic concepts and related terminology
- Improvement of relativistic modeling
- Fundamentals of the realization of the global terrestrial reference frames: co-location problems, local ties, datum problems (origin, scale and orientation, time evolution), coordinates origin, geo-centre, time series approach, long-term consistency with EOPs and ICRF…
- Analysis of strengths, weaknesses and systematic differences (biases) of individual techniques (VLBI, SLR, GPS, DORIS) related to their contribution to global combined TRF
- Combination methodologies of individual techniques' solutions and analysis of the underlying models, parameters, datum definitions etc.
- TRF by multi-technique data analysis
- Global Geodetic Observatories, concepts and practical implementation

Structure

President: Claude Boucher (France)

The sub-commission has an open membership. Current list is given in the list of members given below. Details about its activities will be given in its web page accessible through the IAG links.

Study Groups and Working Groups linked to SC1.2 :

IC-SG1: **Theory, implementation and quality assessment of geodetic reference frames** (jointly with ICCT) Chairman: Sakis Dermanis (Greece)

IC-WG3: **Concepts and terminology related to Geodetic Reference Systems** Chairman: Claude Boucher (France)

IC-WG4: **Site Survey and Co-location** (jointly with IERS) Chairman: Perguido Sarti (Italy) Link to IAG Commission 1: http://iag.ensg.ign.fr/

Activities for the period 2007-2009

This report provides only summaries of activities related to the Sub-commission. For more details or references, visit the web pages hosted by the IAG Commission 1 website.

Terminology

The IC-WG2 was specifically devoted to this subject. The group published a summary report detailed as a separate report in this document. In addition, a scientific paper is under preparation.

The new release of the IERS Conventions actually implement this terminology, through the active contribution of several members of the SC, either in drafting or within the IERS Convention Advisory Board chaired by Jim Ray.

Site survey and co-locations

This IERS Working Group is considering to reactivate its involvement in research topics, and therefore its re-link with the SC activities, thanks to Perguido Sarti who is now chairing this group.

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 geosciences 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 in the frame of 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.

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 in progress, ITRF2008.

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.

Members

Zuheir Altamimi (France)
Geoff Blewitt (USA)
Claude Boucher (France) President
Nicole Capitaine (France)
Xavier Collilieux (France)
David Coulot (France)
Sakis Dermanis (Greece)
Herman Drewes (Germany)
Johannes Ihde (Germany)
Sergei Klioner (Russia)
Gerard Petit (France)
Hans-Peter Plag (USA)
Jim Ray (USA)
Perguido Sarti (Italy)
Pascal Willis (France)

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 organisations.

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

In addition, 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 increase of the number of permanent GNSS tracking sites in Europe, (more than 200 EPN stations operated in 2009 by national European institutions) and of the number of sites which record GLONASS data simultaneously to GPS data and which stream real time data.
- The release of official updates of the ITRS/ETRS89 coordinates/velocities of the EPN (EUREF Permanent Network) stations in a regular mode, as a result of the ITRF densification in Europe.
- The creation of the EUREF Special Project "EPN Reprocessing" with the goal of reprocessing the long time series of numerous EPN stations, aiming on a consistent processing strategy and thus to receive more reliable results.
- The computation and publication of a new realization of the EVRS (European Vertical Reference System) under the name EVRF2007. This realization was proposed for adoption by the European Commission as the vertical reference for pan-European geoinformation.
- 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) and in 2009 (Florence).

Sub-Commission 1.3 b: South and Central America

- The establishment of five associated analysis centres under the responsibility of Latin American and Caribbean institutions, and an additional experimental associated centre for computing ionospheric information based on the SIRGAS-CON.
- The organization of SIRGAS-CON in two hierarchical levels, the first one for providing the primary link to ITRF and the second one for densification at national level.
- The reprocessing of the SIRGAS-CON weekly solutions with absolute phase centre corrections and IGS05 as reference frame and the release of multiyear solutions.
- The start of a systematic study aiming at the improvement of the realization of the SIRGAS datum by three different strategies.
- The systematic adoption of official geodetic reference system at national level based on SIRGAS.
- The development of actions in order to promote SIRGAS in the countries that didn't adopt it yet, in particular the support to the establishment of new experimental associated analysis centres and the organization of the SIRGAS School on Reference Systems, under the sponsorship of the IAG and PAIGH.
- The Executive Committee met in Bogotá (2007) and in Montevideo (2008); the SC1.3b second workshop was held in Montevideo (2008).

Sub-Commission 1.3 c: North America

- The realization of densifications of the ITRF and IGS global networks by weekly combinations of six different regional weekly solutions using different GPS processing software.
- 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 centre variation models is underway.
- The continuation of the efforts aiming at the definition of a plate-fixed regional reference frame for North America stable at the sub-mm level. An updated version of the frame is currently under development and is expected to be released mid-2009. Two workshops on this subject were realized.
- The continuation of the activities related to the definition and maintenance of the relationships between international and North American reference frames/datums. Recent 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 one was a joint meeting held in June 2008 in Johannesburg which brought together representatives from the fields of seismology, meteorology, space weather, geophysics and geodesy.
- The progress made with the installation of permanent GNSS reference stations. These have been installed by National Mapping Agencies, Universities and research groups.
- The creation of an Operational Data Centre (ODC) for AFREF with an open data policy, expected to be operational within the second half of 2009.
- The realization of two training courses in 2007 and 2008 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. A similar course is to be held in August 2009 but with a greater emphasis on the practical aspects of the project.
- The application for funding submitted to the African Union Commission (AUC) and European Union (EU) for inclusion within the EU/ AU Lighthouse Projects.

Sub-Commission 1.3 e: Asia-Pacific

- 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 focussed on GPS observations but incorporated also other geodetic techniques, SLR and VLBI.
- The realization of additional annual, regional, GPS campaigns in 2007 and 2008, for both scientific research and local applications. Results from these campaigns have been submitted to the IAG Working Group on "Regional Dense Velocity Fields.
- 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 promotion of the application of new geodetic adjustment techniques and datum transformation parameters for regional spatial data integration and for geo-referencing cadastral information
- The support for the densification of continuous GPS installations in areas of earthquake and tsunami hazard.
- The meetings held in Seoul (2007), Kuala Lumpur (2008); the next meeting is planned for Bangkok (2009).

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. A first set of preliminary regional combined solutions is prepared for June 2009.
- The preliminary solution resulting from the combination of the preliminary regional SINEX solutions with long-term solutions from global networks will serve to identify problems and help to set strategic choices and guidelines. Some problems encountered up to now are being solved. A new solution is expected to be issued in 2010-2011.
- The WG met in Miami Beach (2008), San Francisco (2008) and Vienna (2009). 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.

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.

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". (www.euref-iag.net)

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 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 Euro-Geographics. The EUREF symposium 2008 took place in Brussels, Belgium and in 2009 in Florence, Italy.

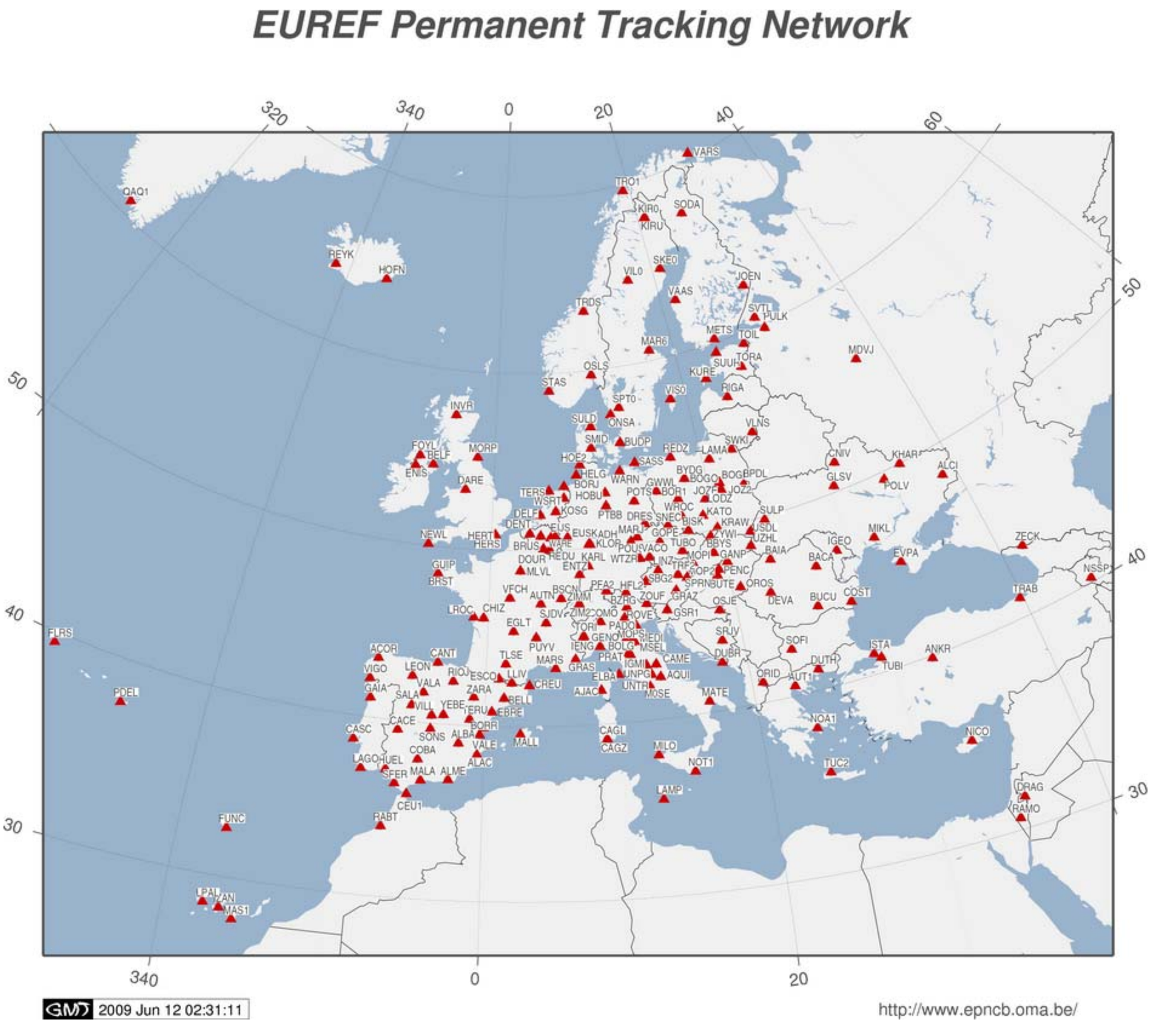
EUREF Permanent GNSS Network (EPN)

The EPN is a permanent GPS network created by the IAG Sub-commission for Europe (EUREF). Its primary objective is the creation and maintenance of the European Terrestrial Reference System 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 consists of a well-determined structure including GPS 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). As such, the EPN uses the same standards and exchange formats as the IGS.

Special Projects are set up by the EPN Coordination Group in order to introduce new applications into the EUREF Permanent Network 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. (www.epncb.oma.be)

The number of permanent GNSS tracking sites in Europe has grown considerably, more than 200 EPN stations are operated in 2009 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.



EUREF Permanent GNSS Network EPN

EUREF Densification of the ITRF

Even while the number of permanent GNSS tracking sites in Europe has grown considerably (more than 200 EPN stations in 2009), only a selection of these sites (mostly the ones belonging to the International GNSS Service – IGS) have coordinates included in recent ITRF realizations.

The latest realization of the ITRS, 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. In addition, the ITRF2005 has been computed with relative GNSS antenna models and coordinate offsets between solutions based on absolute antenna models and the ITRF2005 are significant. This problem will be resolved with the release of the ITRF2008 (expected for 2009) which will be compatible with absolute GNSS antenna models.

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 regular official updates of the ITRS/ETRS89 coordinates/velocities of the EPN stations. A first step in this process consisted in a densification of the ITRF2005 using all EPN data up to Dec. 2005 (the same observation period as covered by the ITRF2005). This release (Kenyeres, 2008) known as EPN_C1355 (ITRF2005) for the ITRS and the corresponding EPN_C1355 (ETRF2000) for the ETRS89 has been distributed to the EUREF community through EUREF mail 4142 on Dec. 12, 2008. As decided at the EUREF TWG meeting of Feb. 26-27 2009 in Budapest, this densification is replaced each 5 weeks by a new EUREF realization of the ITRF. The advantage of regularly updating the realization is that the most recent EPN results are taken as much as possible into account.

EPN reprocessing activities

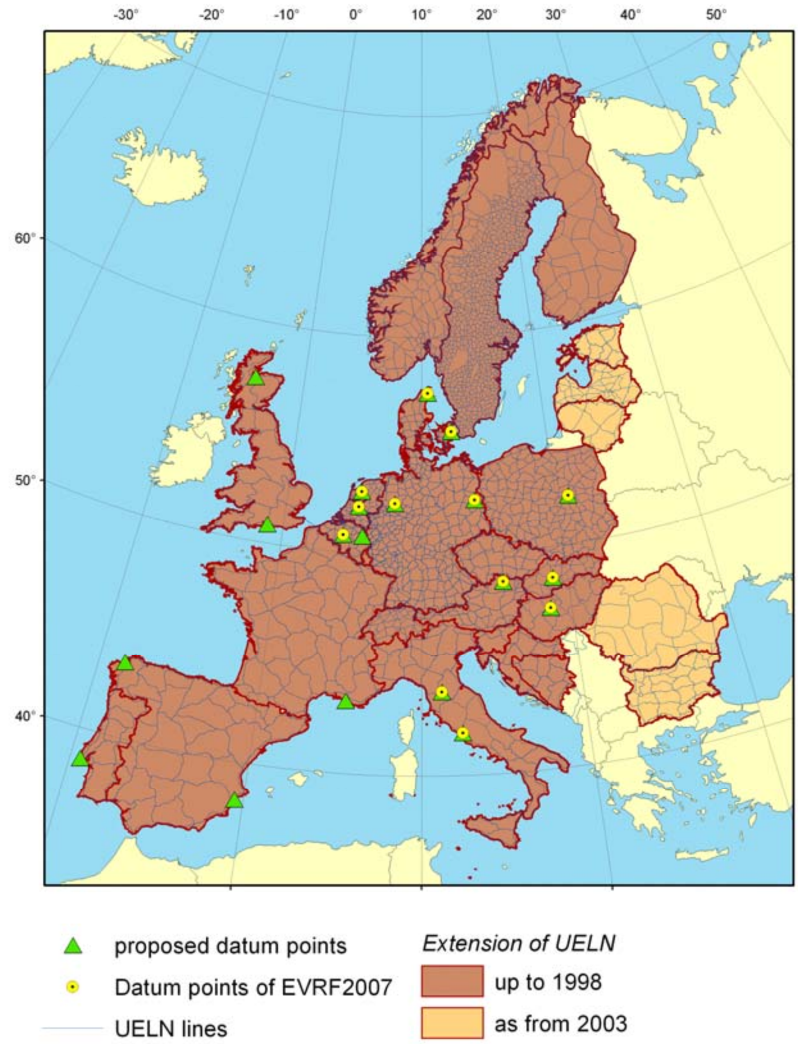
Inconsistencies in the long coordinates and time series are occurring, especially after changes of the modeling parameters. The plan to reprocess the long time series of numerous EPN stations aims on a consistent processing strategy and thus to receive more reliable results. A first attempt for reprocessing has been carried out by the Potsdam-Dresden-Group for the data sets from 1994 to 2007. On a call for participation all invited LACs declared to be willing to participate in this project. The majority of the EPN LACs is using the Bernese Software, some; however, make their data processing by other software packages. The comparison of the results basing on identical input data would be of special interest. The TWG finally decides to define a new EUREF Special Project "EPN Reprocessing". It is agreed that possibly several steps of subsequent solutions will be necessary to yield a satisfying result. The TWG has formed a Working Group with about 10 members (LACs, members of large) to investigate this problem in detail. A call for participation should be sent out inviting everybody who is interested and ready to contribute is invited to participate.

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). Half 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 which proposes to the European Commission that EVRF2007 is adopted as the vertical reference for pan-European geo-information.

The availability of EVRF2007 necessitates an update of the Geodetic Information and Service System CRS. Transformation parameters between national height systems and EVRF2007 will be calculated and provided at http://crs.bkg.bundde/crs-eu/ before the end of 2008. After providing the EVRF2007 results the development of the UELN will be continued.

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.



EVRF2007

ECGN continuation

The ECGN is considered as a European contribution to the IAG Project Global Geodetic Observation System (GGOS). The primary concern of the project consists in connecting the height component with the gravity determination while allowing for measuring data that are acquired in the European coastal regions and above adjacent seas. As objectives of the ECGN as an integrated European Reference System for Spatial Reference and Gravity are to be noted:

- maintenance of a long term stability of the terrestrial reference system with an accuracy of 10'-9 for Europe especially in the height component,
- in-situ combination of geometric positioning (GPS) with physical height and other Earth gravity parameters in 1 cm accuracy level,

- modeling of influences of time-dependent parameters of the solid Earth, of the Earth gravity field, the atmosphere, the oceans and the hydrosphere for different applications of positioning.
- the modeling of gravity field components to validate the satellite gravity missions CHAMP, GRACE and GOCE,
- present a platform for further geo-components (GMES, GEOSS. GGOS).

As input data the records of techniques such as VLBI, SLR, GNSS, DORIS, leveling, tides gauges, gravimeters (absolute, superconducting, spring) are mentioned. Initially about 70 stations were selected to form the ECGN, later the number was reduced to about 50 as the other ones turned out to be not suitable.

Sub-Commission 1.3b: Regional ReferenceFrame 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 unified 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 two opportunities for evaluating the ongoing and forthcoming activities. The first meeting was held in Bogotá (Colombia), on June 7 – 8, 2007 (reported in SIRGAS Newsletter No 12); and the second one in Montevideo (Uruguay), on May 28 – 30, 2008 (reported in SIRGAS Newsletter 13). In addition, the SC1.3b – WG1 held its second workshop in Montevideo (Uruguay), on May 26 – 27, 2008, intended to improve the strategy used by the associated analysis centres.

As already informed in the previous report of this SC, during the first SC1.3b – WG1 workshop (Rio de Janeiro, Brazil, August 16 – 18, 2006), five associated analysis centres were established under the responsibility of Latin American and Caribbean institutions, namely: IGN and IGG-CIMA (Argentina), IBGE (Brazil), IGAC (Colombia), and INEG (Mexico). Soon after, an experimental period started aimed to assess the reliability of those centres (in the meantime, the DGFI continued to be in charge of the official processing of the entire network as IGS – RNAAC – SIR). An additional experimental associated centre was established at the UNLP (Argentina) for computing ionospheric information based on the SIRGAS continuously observing GNSS network (SIRGAS-CON).

The results of the above mentioned experiment were evaluated during the second SC1.3b – WG1 workshop. Based on that assessment, the SIRGAS Executive Committee approved the following actions items that were immediately translated into the practice:

1. The status of the IGG-CIMA, IBGE, IGAC and UNLP associated analysis centres was changed from experimental to official.
2. SIRGAS-CON was divided in two hierarchical levels (Figure 1.3b.1): a core one (SIRGAS-CON-C), intended to provide the primary link to ITRF; and a densification one (SIRGAS-CON-D), which encompasses all the fundamental stations of the national networks and facilitates the accessibility to the reference frame. The D-network was further divided in three sub-networks identified as North (N), Middle (M) and South (S). All the stations included in C and Ds networks match the ITRF requirements.

3. The computation of the C-network was in-charged to DGFI, while the computation of the D-networks was in-charged to IGAC (D-N), IBGE (D-M), and IGG-CIMA (D-S).
4. All the networks (C+Ds) are weekly combined in a common solution by a combination centre under the DGFI responsibility; a second combination centre under the IBGE responsibility provides redundancy and back-up.

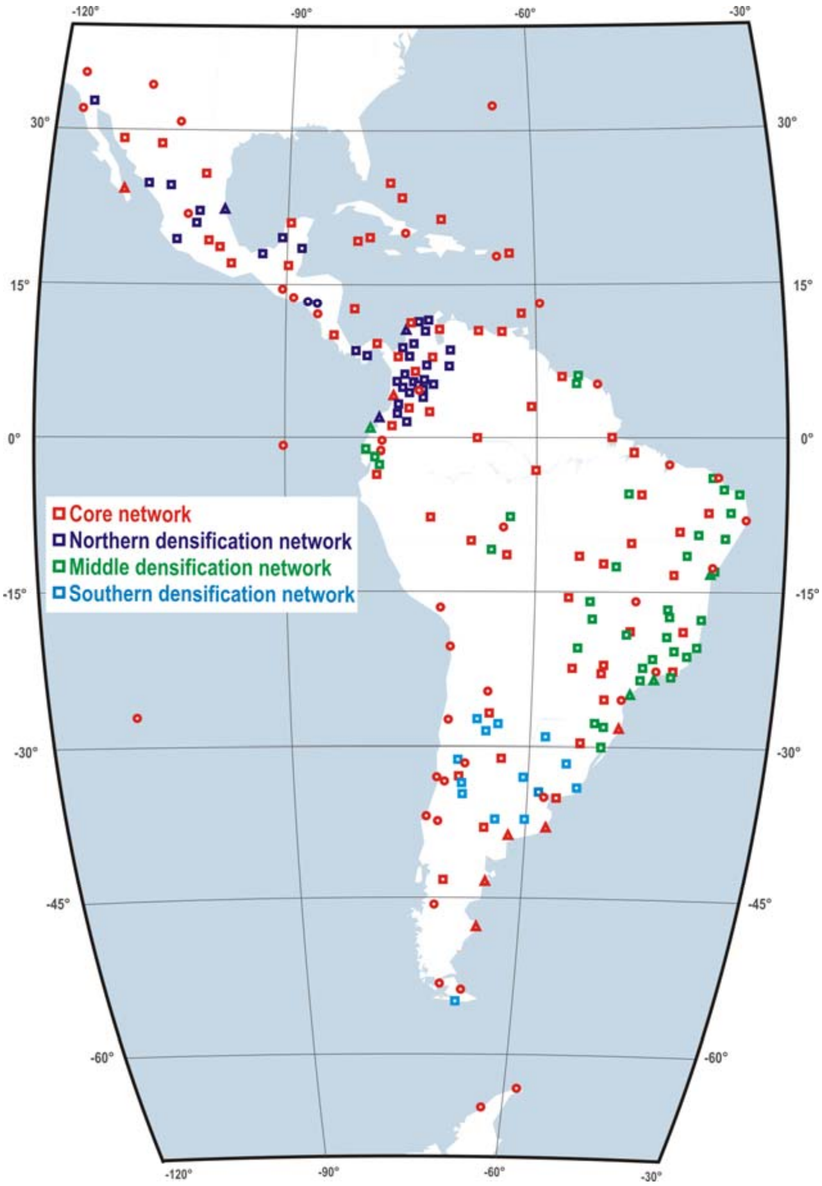


Figure 1.3b.1: SIRGAS-CON network: core and densification sub-networks.

Since August 31, 2008, each associated analysis centre delivers to the combination centres loosely constrained solutions for the assigned sub-network. All the sub-networks are individually aligned to the IGS05 reference frame by applying NNR + NNT conditions, and compared to IGS weekly values and to each other, in order to identify and reduce possible outliers from the individual normal equations. Later on, individual normal equations are accumulated and solved for computing a loosely constrained weekly solution for station coordinates, which is submitted to IGS for the global polyhedron and used to compute multiyear solutions for SIRGAS. Besides, a weekly solution constrained to IGS weekly coordinates is also computed and delivered to users.

At present, the main weakness of this strategy are caused by the facts that: i) SIRGAS-CON stations are unequally weighted in the weekly combinations because not all of them are included in the same number of individual solutions; ii) the redundancy to ensure that each station is processed by at least three processing centres is not fulfilled; iii) all the analysis centres use the same processing software. Actions are being undertaking for overcoming these limitations in the near future.

The SIRGAS-CON weekly solutions from January 2000 to November 2006 computed with relative phase centre corrections and referred to former ITRF solutions have been reprocessed including absolute phase centre corrections and IGS05 as reference frame. This provides homogeneously precise point positions and velocities for all SIRGAS-CON stations.

Periodically, as in-charged of the IGS-RNAAC-SIR, DGFI computes a new multiyear solution. The latest one, identified as SIR09P01, was released on June 2009 and encompasses all the weekly solutions provided by the associated analysis centres from January 2, 2000 (GPS week 1043) to January 3, 2009 (GPS week 1512). It is referred to IGS05 at 2005.0, precision was estimated to be better than ±0.5 mm (horizontal), ±0.9 mm (vertical) and ±0.8 mm/a (linear 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.

Recently, SC1.3b – WG1 performed a systematic study aimed to improve the realization of the SIRGAS datum. Three different strategies (NNR + NNT, constrained coordinates, and fixed coordinates) in combination with two different kinds of control coordinates (IGS weekly solutions, and IGS05 + linear velocities) were applied to a time series spanning from October 2006 (GPS week 1395) to December 2008 (GPS week 1512). Preliminary results have been described in an internal report that is being considered by the SIRGAS Steering Council with the aim of presenting some recommendation to the Executive Committee, during the next meeting that will be held in Buenos Aires, in conjunction with the IAG General Assembly.

At present, 13 of the 18 countries that participate in SC1.3b adopted an official geodetic reference system based on SIRGAS (Figure 1.3b.2). A great and successful effort is being carried out in order to increase the involvement in SC1.3b of a few South American countries and the majority of Central America and Caribbean countries, whose participation has not been as intense as desired. The expected target is that all the countries in the region can implement in-house facilities to maintain their national reference frames according to modern Geodesy the state-of-the-art. Two major actions are being performed in order to achieve that objective:

1. Promoting and supporting the establishment of new experimental associated analysis centres under the responsibility of Latin American and Caribbean institutions. At present, there are five centres in this category, namely: INEG (México), IGN (Argentina), IGM (Ecuador), LUZ (Venezuela), SGN (Uruguay). SC1.3b supports this enterprise by institutional agreements that facilitate the acquisition of processing software and providing training on its use. Training courses of this type have already taught for the experimental analysis centres installed or being installed in Ecuador, Uruguay, Peru and Chile.
2. The SIRGAS School on Reference System, which aims to provide the attendant with fundamental concepts needed for the appropriate generation and use of fundamental geodetic data. The first edition of this school will be held in Bogotá (Colombia), from July 13 to 17, 2009, under the sponsorship of the IAG and PAIGH. The program covers: i) geodetic reference systems; ii) coordinates determination from Global Navigation Satellite Systems (GNSS); iii) link between heights obtained from GNSS and those based on spirit levelling; iv) Geocentric Reference System for the Americas (SIRGAS); and v) spreading and application of SIRGAS products.

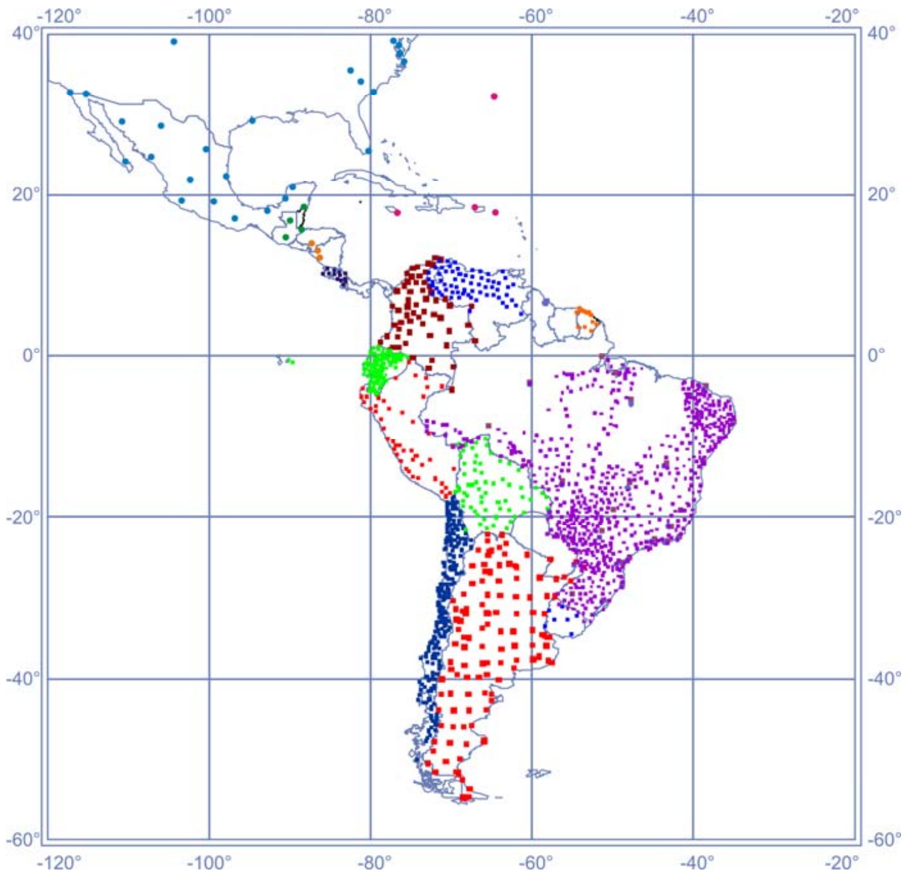


Figure 1.3b.2: National densification of SIRGAS.

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 neighbouring countries and the levelling of the 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.

SC1.3b has been represented in the following meetings:

SIRGAS: an international collaborative enterprise of the geodetic community in Latin America and the Caribbean. C. Brunini, L. Sánchez, H. Drewes, W. Martínez. In: 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.

SIRGAS: ITRF densification in Latin America and the Caribbean. L. Sánchez, C. Brunini, S. Costa, V. Mackern, W. Martinez, W. Seemüller, A. da Silva. In: European Geosciences Union, General Assembly 2009 (EGU 2009). Vienna, Austria. April 19 - 24, 2009.

SIRGAS: Base para las Geociencias, la Geoinformación y la Navegación. C. Brunini, L. Sánchez, H. Drewes. In: Reunión Científica 24 de la Asociación Argentina de Geodesia y Geofísica (AAGG). Mendoza, Argentina. April 14 - 17, 2009.

SIRGAS: Basis for Geosciences, Geodata, and Navigation in Latin America. C. Brunini, L. Sánchez. In: Semana Geomática Internacional. Barcelona, Spain. March 3 - 5, 2009.

SIRGAS report on the activities related to the IAG Working Group 'Regional Dense Velocity Fields' . L. Sánchez. In: Informal meeting of the IAG Working Group 'Regional Dense Velocity Fields'. AGU Fall Meeting. San Francisco, USA. December 15 - 19, 2008.

SIRGAS: reference frame for the GNSS applications in Latin America. L. Sánchez, C. Brunini. Presented by R. Neilan. In: Third Meeting of the International Committee on Global Navigation Satellite Systems (ICG). Pasadena, California, USA. December 8 - 12, 2008.

SIRGAS: Basis for Geosciences, Geodata, and Navigation in Latin America. L. Sánchez, C. Brunini. In: International Symposium on Global Navigation Satellite Systems, Space-based and Ground-based Augmentation Systems and Applications. Berlin, Germany. November 11 - 14, 2008.

Global vertical datum unification based on the combination of the fixed gravimetric and the scalar free geodetic boundary problems. L. Sánchez. In: IAG International Symposium on Gravity, Geoid and Earth Observation. Chania, Crete, Greece. June 23 - 27, 2008.

The Geocentric Reference System of the Americas (SIRGAS). C. Brunini, L. Sánchez. In: United Nations/Colombia/United States of America Workshop on the Applications of Global Navigation Satellite Systems. Medellin, Colombia. June 23 - 27, 2008.

IAG Sub commission 1.3b SIRGAS reference system: Ongoing activities. C. Brunini, L. Sánchez. Presented by M. Craymer. In: AGU 2008 Joint Assembly. Fort Lauderdale, Florida, USA. May 27 - 30, 2008.

The new position and velocity solution DGF07P01 of the IGS Regional Network Associate Analysis Center for SIRGAS (IGS RNAAC SIR). W. Seemüller, M. Krügel, H. Drewes, A. Abolghasem. In: AGU Fall Meeting. San Francisco, USA. December 10 - 14, 2007.

SIRGAS operations and the regional local cores network scene. S. A. Costa. In: 6th FIG Regional Conference. San Jose, Costa Rica. November 12 - 15, 2007.

SIRGAS: Sistema de Referencia Geocéntrico para las Américas C. Brunini. In: 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: Richard Snay (USA), Michael Craymer (Canada)

This sub-commission is composed of three active working groups and one inactive working group to be reactivated in 2009. The following summarizes the activities of each. For more information and publications related to these working groups, visit the regional Sub-Commission web site at <http://www.naref.org/>.

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

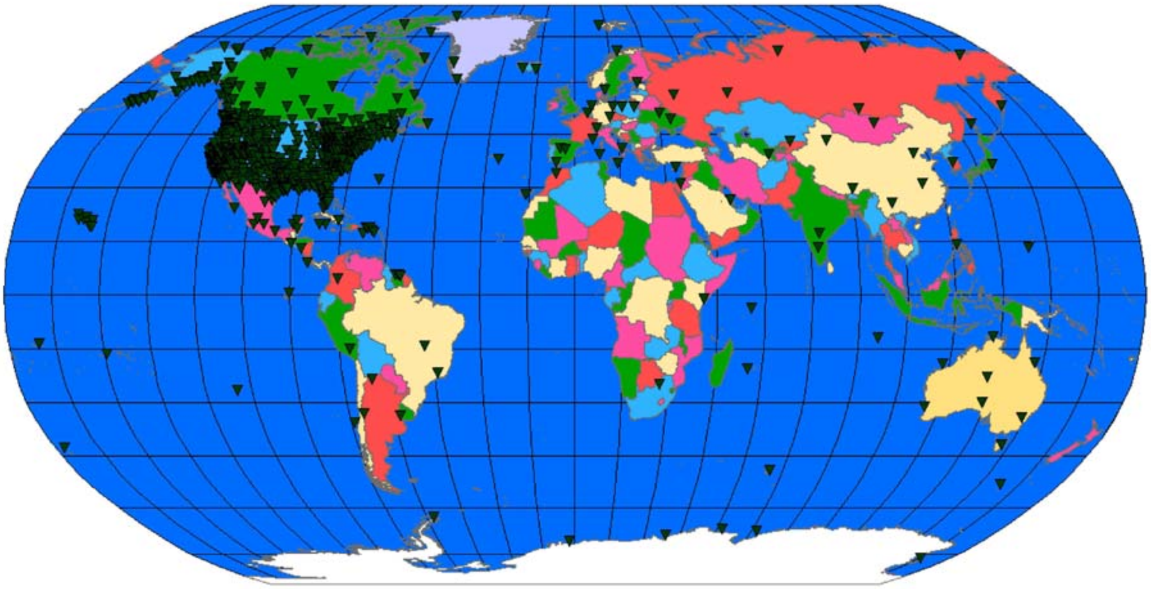
The objective of this WG is to densify the ITRF and IGS global networks in the North American region. The densification consists of weekly combinations of six different regional weekly solutions across the entire continent using four different GPS processing software. Current contributors and some details of their solutions are given in the following table.

NAREF weekly regional coordinate solution contributions.

Contributor	Software	Region	No. Stations (approx.)
MIT	GIPSY & Bernese Combo	Western North America	1100+ (~520+ used)
NGS	PAGES	US & territories & exico (CORS network)	1200+
NRCan/GSD	Bernese	Canada & border areas of US & Greenland	200
NRCan/GSD	GIPSY	Canada	45
NRCan/GSC	Bernese	Western Canada	75
Scripps	GAMIT	North America	1100+ (~625 used)

A number of sites have been omitted from the combination of submitted contributions due mainly to problems with antenna heights. Investigations are being planned to resolve these issues. Many other stations have been removed from the MIT and Scripps solutions because of 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. To better align the NAREF combinations to the ITRF, a subset of global sites have been included in all but the NRCan/GSC solutions since GPS Week 1400. Due to delays in submissions of some of the regional solutions since GPS Week 1400, the weekly combinations are not yet up to date. These weekly combination solutions are available from the IGS and the NAREF FTP archive.
To date, cumulative solutions (coordinates and velocities) based on the weekly NAREF combinations have been generated on an as required basis but the intention is to produce new solutions on an annual basis. The last cumulative solution based only on data up to GPS Week

1399 due to the change in IGS processing procedures and their adoption of absolute antenna phase centres.



NAREF network since GPS Week 1400 with global sites used to align with ITRF.

A major reprocessing effort of regional solutions prior to GPS Week 1400 is presently underway by Scripps and NGS using the new IGS procedures and absolute antenna phase centre variation models. These regional solutions have essentially been a densification of their global reprocessing efforts for the IGS. Both have already reprocessed several years of data. The other contributors plan to begin reprocessing their regional solutions using the final reprocessed IGS orbits once they become available.

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

Significant efforts continued under this joint working group 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 geodynamics studies throughout the continent. Nine workshops to define the reference frame have been held since 2004, including two during this reporting period.

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 is currently under development using several improved velocity solutions from the members of the WG, including the last official NAREF solution up to GPS week 1399. This version of SNARF is expected to be released mid-2009. In addition to a reference frame (coordinates and velocities) with uncertainties, a model for glacial isostatic adjustment and plate rotation rates with respect to ITRF2000 will also be provided.

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 fourteen parameter transformation from ITRF96. 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. Recent activities have focused more on education and outreach efforts.

Later in 2009 it is expected that a new ITRF2008 will be introduced. At that time, a revised version of the NAD83-ITRF transformation will be determined for use in both Canada and the U.S.

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.

This sub-commission has been inactive since the inception of the NAREF sub-commission. However, with 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, it has been decided to re-activate the working group in the near future to address the issued faced in adopting a new geoid-based IGLD.

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. Although stations have been installed in the name of AFREF, some groups are withholding data for their own use which defeats the objectives and principles of the IGS which are also the fundamental principles of AFREF.

At a recent AFREF Steering Committee meeting in Addis Ababa in April 2009, the Chief Directorate: Surveys and Mapping in South Africa offered to take on the role of Operational Data Centre (ODC) for AFREF. This will create a single data base for AFREF which will have an open data policy. Data will be mirrored to the Regional Data Centre at the Hartebeesthoek Radio Astronomy Observatory and one of the IGS Global Data Centres. It is trusted that the AFREF ODC will be operational within the second half of 2009.

Meetings and Training Courses

A number of Steering Committee meetings were held during the reporting period but perhaps the most significant was a joint meeting held in June 2008 in Johannesburg which 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.

Two training courses were held, one in August 2007 and the second in Aug 2008 both 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. A similar course is to be held in August 2009 but with a greater emphasis on the practical aspects of the project.

Funding for AFREF

Funding 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 partially successful but still requires refinement. 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 from receiver manufacturers.

Sub-Commission 1.3e: Regional Reference Frame for South-East Asia and Pacific

Chair: Shigeru Matsuzaka (Japan)

Overview and Organisation

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 GPS 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 GPS installations in areas of earthquake and tsunami hazard and strongly encourage nations to make their geodetic data readily available.

Outputs

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 focussed 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). In the period 2007-2009, four geodetic VLBI campaigns have been undertaken in the region for the APRGP, namely APSG-20 (11 Sep 2007) APSG-21 (10 Oct 2007), APSG-22 (09 Sep 2008) and APSG-23 (08 Oct 2008).

Two additional annual, regional, GPS campaigns were undertaken in 2007 and 2008. APRGP campaigns were coordinated by Geoscience Australia (GA) and the campaign data (1997 – 2008) 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. The processing of the APRGP data sets, from the years 1997 to 2006 inclusive, was undertaken by Geoscience Australia. Results from these campaigns have now been submitted to the IAG working group on regional dense velocity fields.

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 will be held in Bangkok, Thailand in October, 2009.
- 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 has commenced the AuScope Initiative, which includes the construction and operation of 3 new VLBI stations and 100 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 and 2009 were carried out in the austral summers 2008 and 2009. 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.

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 1st of March 2007 and ended at 28th 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).

Working Group SC 1.3 - WG 1: Regional Dense Velocity Fields

Chair: Carine Bruyninx

Objectives and Membership

Because of accuracy, ability to provide results in a global reference frame, and low cost of receivers and versatility, Global Navigation Satellite Systems (GNSS) are presently the main sensor of the Earth's surface deformation. Consequently, GNSS networks have been installed all over the world and repeated GNSS campaigns are conducted to monitor ground deformations. In addition, a large number of Continuous Operating GNSS Reference Stations (CORS) are operating today for multi-disciplinary applications ranging from surveying to numerical weather prediction.

The regional sub-commissions within IAG sub-commission 1 "Regional Reference Frames" have already made a first step in coordinating these activities in order maintain their regional reference systems.

This Working Group on "Regional Dense Velocity Fields" 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. For that purpose the WG has set up the following goals:

- define specifications and quality standards for the regional SINEX solutions and relevant meta-data;
- collect SINEX solutions and their meta-data ;
- study in-depth the individual strengths and shortcomings of local/regional and continuous/epoch GNSS solutions to determine site velocities;
- define optimal strategies for the combination of regional and global SINEX solutions;
- provide dense regional velocity fields;
- provide the densification of the ITRF2005 (or its successor);
- encourage participation in related symposia;
- implement a web site in order to provide information on the activities and access to the products of the WG
- and prepare recommendations and a comprehensive final report on the WG activities.

The Working Group brings together representatives of the regional sub-commissions and experts in the combination of SINEX files. Working Group members are Altamimi Z. (France), Becker M. (Germany), Bruyninx C. (Belgium), Craymer M. (Canada), Combrink A. (South Africa), Combrinck L. (South Africa), Dawson J. (Australia), Fernandes R. (Portugal), Dietrich R. (Germany), Govind R. (Australia), Herring T. (US), Kenyeres A. (Hungary), King B. (USA), Kreemer C. (USA), Lavallée D. (the Netherlands), Legrand J. (Belgium), Sánchez L. (Germany), Sella G. (US), and Woppelmann G. (France).

Activities

The goal of the WG is to provide regional dense GNSS-based velocity information in a common reference frame. The working group is linking its activities with the regional sub-commissions within IAG sub-commission 1 "Regional Reference Frames" (AFREF, Asia &

Pacific, Antarctica, NAREF, SIRGAS, and EUREF). Their expertise, coordination role for their region, and their capability to generate a unique cumulative solution for their region including velocity solutions from third parties (even campaigns) is essential for the WG.

The WG thus divided the world in different regions corresponding to the regions of the different sub-commissions and appointed for each region a region coordinator. The region coordinators are gathering velocity solutions for their region (in accordance with the WG requirements) and combine the submitted velocity solutions with GNSS solutions from the regional sub-commissions to produce one regional combined velocity solution. In addition to the individual regions, cumulative SINEX solutions from global networks as TIGA are also used. A first set of preliminary regional combined solutions is prepared for June 2009. Two working group members have agreed to combine the preliminary regional SINEX solutions with long-term solutions from global networks such as the IGS and tie the result to the ITRS anticipating a preliminary WG solution in time for the IAG 2009 meeting in Buenos Aires. This main goal of this preliminary solution will be to identify the problems that will arise and help to set strategic choices and guidelines for the future. These guidelines will be used to issue a new solution in 2010-2011.

The WG issued a call for participation at the end of 2008. Figure 1 shows on a map the solutions that have been proposed to the Working Group up to date. Not all of them have been received at this moment at it is expected that some of them will only be available end of 2009.

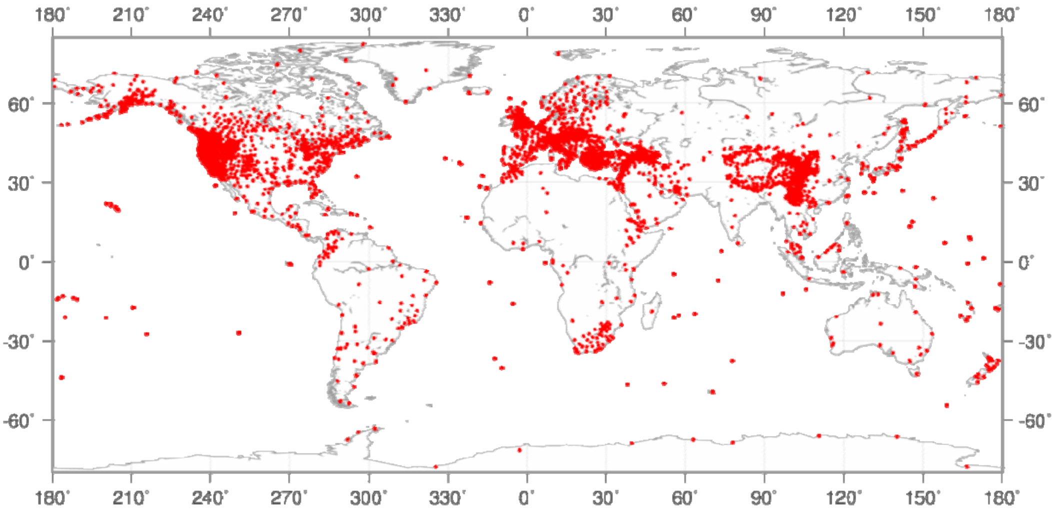


Figure 1 - Map of the velocity solutions proposed to the Working Group to date. In total about 6000 sites are included.

The following problems have been encountered up to now:

- *Domes numbers & station names:* Not all sites included in the contributing solutions have official domes numbers attributed by the IERS and this can make SINEX combination software fail. A coordinated approach for attributing virtual domes numbers will therefore be necessary. In the case of duplicates station names, a new station 4 char-ID and virtual DOMES number will also have to be assigned in a coordinates way avoiding overlaps duplicates and inconsistencies between the different regions.
- *Solutions with only precise velocity estimates and no precise coordinates:* The implication being that inter-site correlations (negligible in many cases, not so in others) are not included and some programs designed to merge SINEX files could fail.

- *Inconsistent solution numbers:* The WG recommended in the guidelines that: "For IGS sites the timing of offsets should be identical to those in use by the IGS". However, this does not help when solutions have already been produced. A dedicated approach for this problem will have to be investigated.

Working Group Meetings

- June 4, 2008, Miami Beach, US (during IGS Analysis Centres Workshop), the minutes are available from http://www.epncb.oma.be/IAG/documents/minutes/Minutes_20080604.pdf
- December 18, 2008, San Francisco, US (AGU 2008 Fall Meeting), the minutes are available from http://www.epncb.oma.be/IAG/documents/minutes/Minutes_20081218. pdf
- April 20, 2009, Vienna, Austria (EGU 2009), the minutes are available from http://www.epncb.oma.be/IAG/documents/minutes/Minutes_20090420.pdf

Outreach

A web site has been set up providing a gateway to the WG activities, including the submission guidelines, call for participation, list of contributors, etc... It is available from http://www.epncb.oma.be/IAG/.

Members of the Working Group have presented the activities of the WG at the following meetings:

- Sensitivity of the Reference Frame Definition in a Regional Network, C. Bruyninx, J. Legrand; *AGU Fall Meeting 2007, December 10-14, 2007, San Francisco, US*
- Sensitivity of the Reference Frame Definition in a Regional Network, Legrand J., Bruyninx C., Pottiaux E.; *EGU General Assembly 2008, April 14-18, 2008, Vienna, Austria*
- IAG Working Group "Regional Dense Velocity Fields": Objectives and Future Plans, C. Bruyninx, 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; *IGS Analysis Centres Workshop, June 2-6, 2008, Miami, US*
- IAG Working Group "Regional Dense Velocity Fields": Objectives and Future Plans, C. Bruyninx, 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; *AFREF Workshop, June 17-18, 2008, Johannesburg, South Africa*
- Objectives and Challenges of the IAG Working Group "Regional Dense Velocity Fields", C. Bruyninx, 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; *EUREF 2008 Symposium, June 18-21, 2008, Brussels, Belgium*
- EPN Reference Frame Alignment: Consistency of the Station Positions, Legrand J., Bruyninx C.; *EUREF 2008 Symposium, June 18-21, 2008, Brussels, Belgium*
- Objectives and Challenges of the IAG Working Group "Regional Dense Velocity Fields", 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. Sanchez, G. Sella; *EUREF 2008 Symposium, June 18-21, 2008, Brussels, Belgium*
- Towards the Provision of Regional Dense Velocity Fields in a Global Reference Frame, C. Bruyninx, Z. Altamimi, M. Becker, M. Craymer, L. Combrinck, A. Combrink, R. Fernandes, R. Govind, T. Herring, A. Kenyeres, B. King, C. Kreemer, D. Lavallée, J. Legrand, M. Moore, L. Sánchez, G. Sella, G. Woppelmann; *WEGENER 2008 General Assembly, September 15-18, 2008, Darmstadt, Germany*

- IAG Working Group "Regional Dense Velocity Fields": Objectives and Future Plans, C. Bruyninx, Z. Altamimi, M. Becker, M. Craymer, L. Combrinck, A. Combrink, J. Dawson, R. Fernandes, R. Govind, T. Herring, A. Kenyeres, R. King, C. Kreemer, D. Lavallée, J. Legrand, L. Sánchez, G. Sella, G. Woppelmann; *AGU Fall Meeting, December 15-19, 2008, San Francisco, US*
- Influence of the Reference Frame Alignment on Station Positions and Velocities: Global or Regional?, Legrand J., N. Bergeot, C. Bruyninx, G. Wöppelmann, M.-N. Bouin, Z. Altamimi; A*GU Fall Meeting, December 15-19, 2008, San Francisco,*
- Progress of the IAG SC1.3 Working Group in Providing a Dense Global Velocity Field Based on GNSS Observations, C. Bruyninx, 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, Z. Shen, G. Sella, G. Woppelmann; *EGU General Assembly, April 19-24, 2009, Vienna, Austria*
- Reliability of Regional and Global GNSS Network Solutions Expressed in the Global Reference Frame, J. Legrand, N. Bergeot, C. Bruyninx, G. Wöppelmann, M.N. Bouin, Z. Altamimi; *EGU General Assembly, April 19-24, 2009, Vienna, Austria*
- Progress of IAG SC1.3 Working Group in Providing a Dense Global Velocity Field Based on GNSS Observations, C. Bruyninx, 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, Z. Shen, G. Sella, G. Woppelmann; *EUREF symposium, May 27-30, 2009, Florence, Italy*
- A Dense Global Velocity based on GNSS Observations: Preliminary Results, C. Bruyninx, 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; *IAG 2009 Scientific Assembly, 31 August – 4 September 2009, Buenos Aires, Argentina*
- Comparison of Regional and Global GNSS Position and Velocity Solutions, J. Legrand, N. Bergeot, C. Bruyninx, G. Wöppelmann, A. Santamaria-Gomez, M.N. Bouin, Z. Altamimi; *IAG 2009 Scientific Assembly, 31 August – 4 September 2009, Buenos Aires, Argentina*

and the following papers have been written:

- Bruyninx C., Z. Altamimi, M. Becker, M. Craymer, L. Crombrinck, A. Crombrink, R. Fernandes, R. Govind, A. Kenyeres, B. King, C. Kreemer, D. Lavallée, J. Legrand, L. Sanchez, G. Sella, Objectives and Challenges of the IAG Working Group "Regional Dense Velocity Fields", Proc. EUREF symposium, July 2008, Brussels (in press)
- Legrand J., Bruyninx C., EPN Reference Frame Alignment: Consistency of the Station Positions, Submitted to Bulletin of Geodesy and Geomatics (in press)
- Legrand J., N. Bergeot, C. Bruyninx, G. Woppelmann, M.-N. Bouin, Z. Altamimi , Impact of the Reference Frame Definition on Geodynamic Interpretations, Submitted to Journal of Geodynamics (in press)
- Progress of IAG SC1.3 Working Group in Providing a Dense Global Velocity Field Based on GNSS Observations, C. Bruyninx, 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, Z. Shen, G. Sella, G. Woppelmann, Proc. EUREF symposium, Florence, Italy (in press)

and WG members have been co-chairing of session

- "Multi-GNSS & regional combined IGS products" at IGS Analysis Workshop, Miami Beach, June 2008

Sub-Commission 1.4: Interaction of Celestial and Terrestrial Reference Frames

President: Harald Schuh (Austria)

The main objective of the 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, S. Klioner, D. MacMillan, J. Sokolova, O. Titov, V. Zharov, ex officio: H. Schuh, Chair 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 1.4.1 activity are the following:

1. Analysis of ICRS definition in view of the latest development in astrometry and space geodesy.
2. Effect of 2000, 2003, and 2006 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.

A part of the results outlined below and related to the construction of the next ICRF realization, ICRF2, will be included in detail in the IERS Technical Note 35 which is due for the IAU General Assembly 2009. This work is a result of joint activity with the dedicated IAU and IERS/IVS Working Groups and the IERS ICRS Product Center.

1. *Analysis of the 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 Report to the IAU 2006 General Assembly. No substantial progress has been achieved since that report. However, the ICRF definition becomes not well understood and consistent when moving to the modern observations e.g. VLBI and GAIA. To solve arisen problems a set of new considerations is needed on such issues as general relativity and acceleration of the solar system barycentre.

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

These issues are summarized in Capitaine (2007, 2008). Further analysis is planned.

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

To be investigated.

4. *Alignment of ICRF to ICRS*

A procedure for final aligning of the ICRF2 has been developed by the group at Paris Observatory. This procedure mainly follows the procedure used in the 1990s 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 the stability of the ICRF2 axes, in particular through a choice of the optimal set of core sources.

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 radio source position catalogues using various data sets, software and analysis options. Comparison of these catalogues allowed us to draw 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 investigate on),
- Atmosphere pressure loading (no 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 were conducted:

- Investigation of systematic and individual (peculiar) source motion,
- Analysis of the consistency of CRF realizations at different frequency bands,
- Methods of assessment of absolute accuracy and systematic errors of CRF catalogues.

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

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

7. *Impact of the ICRS and ICRF problems on geodesy*

Although geodesy mainly deals with measurements on and of the Earth, it is closely connected with and depends on measurements on the sky, at least in two aspects:

- Many geodetic measurements are made through observations of sky objects,
- Many applied and fundamental geodetic results are obtained from the common adjustment of the TRF, EOP, and CRF parameters.

For this reason an impact of the adopted ICRF on geodetic results is anticipated, and the consequences of moving from ICRF to ICRF2 should be investigated after completing and publishing the ICRF2.

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, 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 of the Working Group*

Produce ICRF2 for IERS / IVS consideration and for submission to the corresponding IAU Working Group

2. *Charter and purpose*

The purpose of Working Group 1.4.2 (which is identical with the corresponding IERS/IVS Working Groups) is 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) will apply state-of-the-art astronomical and geophysical models in the analysis of the entire relevant S/X astrometric and geodetic VLBI data set. It will carefully consider the selection of defining sources and the mitigation of source position variations to improve the stability of the ICRF. The goal is 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.

3. Activities in the period 2007 to mid 2009

In the period 2007 to mid 2009 WG 1.4.2 undertook the analysis to generate the next realization of the ICRF at microwave frequencies using VLBI data. The WG concentrated on several main areas: time series of source positions to determine stable and unstable sources, compilation of source structure snapshots and evolution to supplement the time series, determining the effects of variations in modeling, data and analyst choices, generation of source catalogues using the best available geophysical and astronomical models, and orientation to the ICRS as realized by the current ICRF. The WG met a number of times: April 2007 in Vienna, September 2007 in Paris, March 2008 in St. Petersburg, September 2008 in Dresden, December 2008 in Washington and March 2009 in Bordeaux. The work for the catalogue to be proposed to the IAU is being compiled as IERS Technical Note No. 35.

WG 1.4.3 Interaction between Celestial and Terrestrial Reference Frames

Chair: Sébastien Lambert (since mid 2008)

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

This report summarizes research activities in link to IAG WG 1.4.3 between mid 2008 and mid 2009, i.e. since S. Lambert became Chair of the WG.

1. Effects of CRF realization on EOP and TRF

1.1. Influence of the CRF datum and analysis configuration

During a typical VLBI solution, station coordinates and velocities and radio source coordinates are estimated as global parameters, while EOP are estimated as arc parameters. The first version of the ICRF (Ma et al. 1998) proposed 212 sources to define the ICRS axes. Since then, other subsets have been investigated. Feissel-Vernier et al. (2006), MacMillan and Ma (2007), Titov (2007), Lambert et al. (2008), and Lambert and Gontier (2009) investigated the effects of the selection of reference radio sources and of the analysis configuration in geodetic products. In this context, analysis configuration deals with the split between global and arc radio source coordinates (e.g., downgrading very unstable sources as arc parameters, or keeping them as global but not using them in the no net rotation (NNR) condition). These studies showed that the choice of the defining sources mainly influences the bias of the nutation series. However, the analysis configuration can produce changes in estimates of long-period nutation spectral components at the level of 10 microarcseconds. This does not affect geophysical results like the Earth's outer core resonant frequency in a significant way.

1.2. Work w.r.t. the ICRF2

A number of IVS Analysis Centers are participating to the construction of the new realization of the ICRS. The ICRF2 is now in its final stage and should be delivered by mid-2009 for the IAU General Assembly. It will provide new coordinates for about 3800 sources, and a set of defining sources to replace the 212 ICRF defining sources. This work has been done within the IERS/IVS Working Group "Second Realization of the ICRF", chaired by C. Ma which as IAG WG 1.4.2 also reports to IAG. The consequences of using the ICRF2 in calculation of other geodetic products will have to be treated after its complete release. Besides, a number of scientific results including effects of the analysis configuration (station handling, models) in CRF realization will be reported in the IERS Technical Note 35.

2. Effects of the TRF realization on EOP and CRF

A study performed by Z. Malkin (2009) showed that the VLBI-derived EOP accuracy primarily depends on the VLBI network geometry and to a lesser extent on other factors, such as recording mode, data rate and scheduling parameters, whereas these factors have a stronger impact on the EOP precision. The study proposes a 'geometry index' for VLBI networks based on the network volume.

3. Geophysical or technique modeling issues

3.1. Atmosphere delay

Kouba (2009) and Steigenberger et al. (2009a) studied the impact of different mapping functions (GMF and VMF1) and hydrostatic a priori zenith delays (GPT and ECMWF) on GPS-derived station positions. Whereas Kouba (2009) used the Precise Point Positioning (PPP) approach, Steigenberger et al. (2009a) used homogeneously reprocessed double-differenced global network solutions. The station height differences between terrestrial reference frames computed from these reprocessed solutions with GMF/GPT and with VMF1/ECMWF are in general below 1 mm. Both authors found, that the application of GPT-derived a priori delays results in a partial compensation of atmosphere loading.

3.2 Antenna phase center variations

Steigenberger et al. (2009b) computed four TRF solutions with different GPS antenna phase centre models from 11 years of reprocessed GPS observations. The station coordinate changes due to different phase centre models can reach 5 mm for the horizontal and up to 16 mm for the vertical component. The velocity changes are 1 mm/yr and 2.5 mm/yr, respectively.

Bibliography 2007–2009

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Inter-Commission Project 1.2: Vertical Reference Frames

Chair: Johannes Ihde (Germany)

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

The IAG Inter-Commission Project 1.2 studied during the period 2003 – 2007 the possibilities of the definition and 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.

The results of the work of the Inter-commission Project 1.2 are documented in **Conventions for the Definition and Realization of a Conventional Vertical Reference System (CVRS)**. 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. Parts of the IERS 2003 conventions are the basis for the CVRS conventions.

Open topics are concepts for the

- Establishment of an information system describing the various regional vertical reference frames and their relation to a GVRS,
- Determination of transformation parameters between regional vertical reference frames and the unified global height system as well as
- Relationship between a GVRS and the International Terrestrial Reference System.

Objectives in the period 2007 - 2011

- 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

Program of Activities

- Study of information on regional vertical systems and their relations to a global vertical reference system for practical applications;
- Study of combination procedures of height data sets from different techniques;
- Development of the basic relationships between ITRS and IVRS conventions, parameters, realization, models
- Unification of regional (continental) height systems
- Preparation of a pilot project for the realization of a GVRS.

2. The Realization Concept

The realization of an IVRS is a typical item of the IAG project GGOS, mainly as a 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 and if possible of GNSS/levelling with a global gravity model (GGM); which is named as the geodetic boundary value problem (GBVP) approach. This approach is the combination of different components:

- A global permanent GNSS network of stations connected with levelling networks, optionally supplemented by permanent (SG) and/or periodical (AG) gravity observations at selected stations
- A global gravity model (GGM) with continental and regional densifications using the remove restore technique.

As result of this approach we have available physical heights or geopotential numbers related to a geoid/quasigeoid $\boldsymbol{T_{p\,RRT}}$ which is related to a conventional zero level of the potential of the Earth gravity field W_{0C}. W_{0C} is a parameter of the mean Earth ellipsoid which shall used for all realization procedures of the WHS.

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

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

A further approach which can be used for the unification of vertical reference frames bases 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.

In general the realization und unification is a combination of the different elements based on a set of consistent conventional numerical standards. The accuracy of WHS realization depends in the first order from the resolution of the gravity model. A service providing all relevant information would be useful.

3. WHS Pilot Project

The pilot project (WHS-PP) could start with a case study of combination of available elements:

(1) The global gravity model EGM07 with continental and national densifications

(2) For GNSS the IGS TIGA-PP, which monitors vertical movements of globally distributed tide gauge stations

(3) Continental and national levelling networks linked to IGS TIGA stations

(4) The tide gauge stations observations linked to IGS TIGA stations which are a product of the PSMSL

(5) Absolute and super conducting gravity meter measurement at selected IGS TIGA stations

(6) A global sea surface topography model

(7) The numerical standards of IERS conventions 2003

Partners for the WHS-PP are inside the IAG the IGFS for GGM, absolute and super conducting gravity meter measurements, IGS for TIGA, SC2.4 for continental and regional desification of a GGM and GLOSS for PSMSL and a global sea surface topography model.

4. Proposed continuation

The IAG 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.

Proposed items for continuation:

- Discussion of the results of ICP1.2 (GGOS action)
- Initiation of a pilot project for an IVRS realization on the basis of the IGS TIGA-PP, GGP and IGFS for AG and a CGGM (call for participation as an IGFS action)
- Further development of the CVRS conventions
- Decision about numerical standards as task of GGOS in cooperation with International Astronomical Union (IAU) and international hydrological and oceanographic organisations.

The project continuation shall be realized in cooperation with other organizations, especially the International Association of Hydrological Sciences (IAHS), the International Association for the Physical Sciences of the Oceans (IAPSO), Global Sea Level Observing System (GLOSS) the International Hydrographic Organisation (IHO), the International Federation of Surveyors (FIG), and the Inter-service Geospatial Working Group (IGeoWG) of NATO.

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.

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 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. 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 are also mandatory. 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 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 loading services currently available.

long-term biases in the reference frame -- Because environmental models do not yet conserve overall mass or properly account for exchange of fluids between states, 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. 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 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 field of corrections used must be reported in new SINEX blocks that will need to be documented. The availability of such information will permit only an approximate removal of the non-tidal corrections, though, if the applied sampling is finer than the geodetic integration interval.

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 bureau, 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.

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. 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") should also be reduced. 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. The result would be a long-term frame for each technique consisting of the usual reference positions and velocities. 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. 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 geocentre 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.

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.

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 geocentre 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 geocentre 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 geocentre 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 macro-model), and fixing it in the orbit solutions, it was possible to mitigate the radiation pressure mis-modelling and recover a cleaner geocentre 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 geocentre 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 centres have completed the same level of radiation pressure model tuning. A spectral analysis was completed of the geocentre 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 centres, 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 w.r.t. 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 centres 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 centres 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 centre 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 has 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.

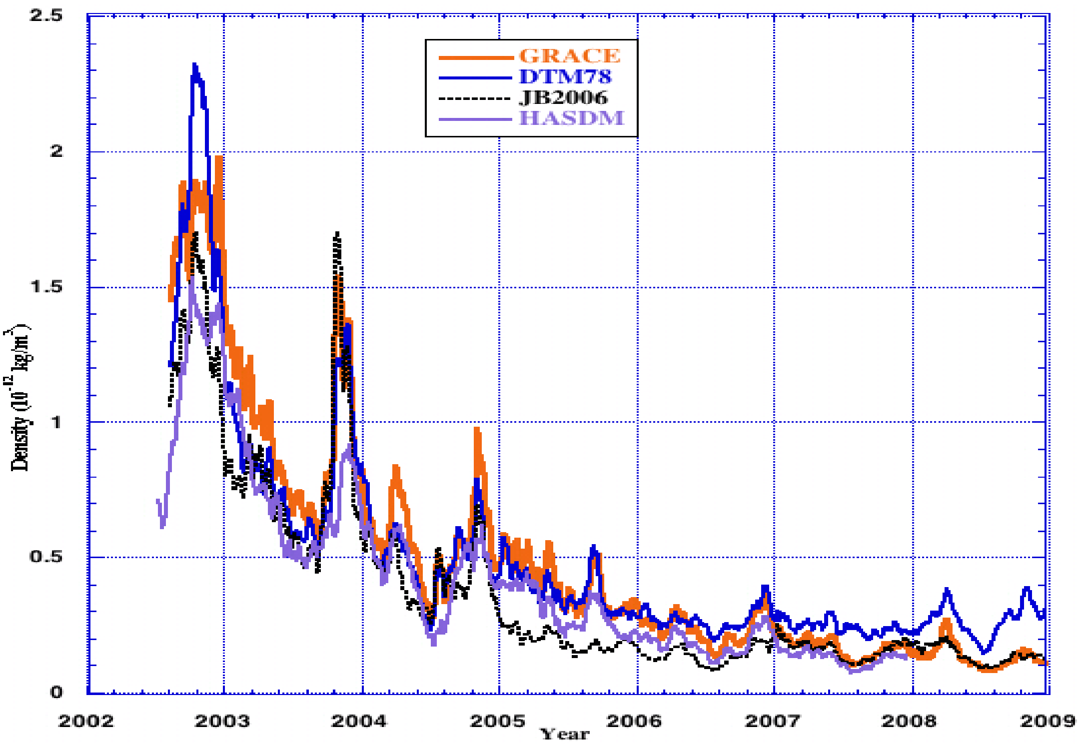

Figure 1: Density comparisons from 2002 to 2009 from atmosphere density models and from GRACE.

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 Ultra-stable 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 (eg. *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-sconservative 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 inter-compare the recovered 1opr accelerations from the different analysis centres 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 centres 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 (eg 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 centres 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)

Recommended nomenclature related to Geodetic Reference Systems

V06 feb 2009

Introduction

The recommended nomenclature is composed of a set of selected terms, associated with definitions, as listed in the lexicon given below in alphabetical order. In this introduction, we present in a narrative format all selected terms, as well as other terms currently used, but not or no more recommended. Recommended terms are written in bold .

The concept of *Geodetic Reference System (GRS)* is used here to designate any reference system of metrological quality specific to Geodesy. It must be distinguished from the specific use of this term traditionally adopted by the IAG and consisting of four fundamental constants (such as GRS80) and the derived models (ellipsoid, normal gravity…). Nevertheless, we do not consider it as part of the formal nomenclature, but as a background concept, in which we must adopt a common understanding of the term "reference system".

The general understanding of a reference system adopted here is the set of data necessary to unambiguously determine numerical quantities, in addition to measurable quantities. In other words, one can estimate unambiguously some quantities of interest, such as the coordinates of points, by a combined use of relevant measurements and the choice of a GRS. Several aspects can be considered related to a GRS:

- At the "ideal" level, a GRS is identified with objects of some physical model, such as a local coordinate system of the relativistic space-time, or an affine frame of Newtonian physics.
- The unique identification of a given GRS requires a set of rules, numerical constants and algorithms, designated as a *Conventional GRS*.
- At the so-called realization level, or the translation from the physical model to the estimation model, the GRS follows two main approaches:
    a) The application of a Conventional GRS, which permits a unique estimation of the relevant quantities. In other words, they are the necessary and sufficient data and rules which enable a proper estimation of parameters from measurements.
    b) A conventional selection of quantities estimated according to those rules.

The primary example of a GRS is the ***Terrestrial Reference System (TRS***) understood as a spatial reference frame co-moving with the Earth in space.

The physico-mathematical model of a TRS is the spatial part of a system of Earth-linked space-time coordinates within the framework of General Relativity, or alternatively an affine Euclidian reference frame in the framework of Newtonian Physics. The general purpose of such a system is to define coordinate systems in which points of the Earth are only slowly changing, and to describe the motion of any object of the Earth's environment (such as an artificial satellite). If needed, one can be more specific by using the expression "ideal TRS".

The conventional rules to identify a TRS or its realizations were traditionally designated by the expression *Conventional Terrestrial Reference System (CTRS)*. We no longer recommend the use of this expression, which is not clear enough for a wide community.

The main characteristics of a TRS are its origin, orientation and scale. These can be considered either at the physical level, or at the estimation level.

At the physical level, for a given TRS:

- The origin is modeled by the event (t,0,0,0) of the local coordinate system in relativistic physics, or by the origin point of the affine frame in Newtonian physics.
- The orientation can be represented by the unit vectors tangent to the spatial coordinate axes in relativistic physics, or by the ortho-normal basis of the affine frame in Newtonian physics.
- The scale is related to the way the metrology of lengths is handled. It is a choice not to allow any scalar factor with regard to the SI unit of length, or to allow a choice of unit of length depending on the TRS.

At the estimation level, we introduce the concept of ***Terrestrial Reference Frame (TRF)*** as a realization of a TRS, clearly identifying the origin, orientation and scale..

Usually, such a realization is done by a set of identifiers of physical points (geodetic markers, tracking instrument reference points, center of mass of artificial satellites…) with corresponding numerical coordinate information (values, derivatives, tabulation…) expressed in a selected coordinate system linked to a specific TRS. Such a set was designated by the expression *Conventional Terrestrial Reference Frame (CTRF*), which is no longer recommended either. TRF is the unique preferred term to designate the realization of a TRS.

Two major types of TRS are currently used in Geodesy:

- the local TRS well designed to map a small area of the topographic surface, as used by laboratory experiments or topographers
- the geocentric TRS, designed to map the whole Earth as well as its motion in space

For a local TRS, the origin is located on or near the topographic surface and the orientation is local (horizontal and vertical).

For a geocentric TRS, the origin is at or near the geocentre and the orientation is equatorial. If needed, one can distinguish between truly geocentric (see after) and quasi-geocentric, for the TRS underlying classical terrestrial networks using fundamental points and for which the origin may be displaced from the actual geocentre by several hundred meters.

For the astro-geodetic community, the ***Geocentric Terrestrial Reference System (GTRS)*** is the fundamental strictly geocentric Terrestrial Coordinate System, now formally recognized by the IAU and the IUGG.

The spatial part (3d) of the 4d GTRS is therefore a geocentric TRS.

Since 1988 a specific geocentric TRS has been selected and progressively formally adopted by the international scientific community, and beyond. It is the ***International Terrestrial Reference System (ITRS).***

ITRS is currently under the responsibility of the IERS which establishes its primary realization by producing a specific TRF designated as ***International Terrestrial Reference Frame (ITRF).***

Concerning vertical frameworks, the primary concept is the ***Vertical Reference System (VRS).***

Lexicon

Geocentric Terrestrial Reference System (GTRS)

Geocentric Terrestrial Reference System is defined jointly by IAU and IUGG as "a system of geocentric space-time coordinates within the framework of General Relativity, co-rotating with the Earth and related to Geocentric Celestial Reference System by a spatial rotation which takes into account the Earth orientation Parameters."

International Terrestrial Reference Frame (ITRF)

Primary realization of the ITRS developed and published by the IERS. ITRF is therefore the primary TRF related to the ITRS.

International Terrestrial Reference System (ITRS)

ITRS is the spatial tridimensional part of the specific GTRS for which the orientation is operationally maintained in continuity with past international agreements (so-called BIH orientation). Since 1988, this task has been assigned by the international scientific astro-geodetic community to the International Earth Rotation and Reference Systems Service (IERS).

Terrestrial Reference Frame (TRF)

Realization of a TRS through the numerical realization of its origin, orientation and scale, and their time evolution. This is currently obtained through a set of identifiers of physical points (geodetic markers, tracking instrument reference points, center of mass of artificial satellites…) with corresponding numerical coordinate information (values, derivatives, tabulation…) expressed in a selected coordinate system linked to a specific TRS

Terrestrial Reference System (TRS)

Spatial reference frame co-moving with the Earth in space. The physico-mathematical model of a TRS is the spatial part of a system of Earth-linked space-time coordinates within the framework of General Relativity or an affine Euclidian reference frame in the framework of Newtonian Physics.

Vertical Reference System

A specific height system, associated with a specific equipotential surface of the Earth's gravity field (geoid).

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

Chair: Gary Johnston (Australia), Pierguido Sarti (Italy)

Background

The IAG Sub-Commission 1.4 Site Survey and Co-locations operates jointly with the

IERS, Working Group on Site Survey and Co-location. The major goals and objectives of the WG are to:

Develop site survey and standards, including:

- Develop, test, compare and set standards on site survey methods, including observational techniques, network design, classical adjustment, geometrical modelling and/ or direct measurement techniques for invariant point determination, reference frame alignment, software implementation and SINEX generation. This will include the development of a standards document for undertaking site surveys;
- Undertake test campaigns to be used for the comparison of different approaches to local tie surveys addressing each of the technical elements;
- Develop standards for the documentation of site surveys, including survey report content and format; and
- Suggest a pool of expertise to provide advice to survey teams, as required, on standards for site surveys.

Assist in global local-tie coordination, including:

- Liaise with local and international survey teams undertaking site surveys at important co-location sites;
- Liaise with the technique combination groups to ensure WG site survey products meet user requirements;
- Coordinate as required and make recommendations to observatories as to survey scheduling and re-survey frequency;
- Develop and distribute software tools to the community to assist in the generation of site survey products, including SINEX generation software; and
- Provide a forum to raise the profile of site survey as a critically important independent geodetic technique.

Undertake site survey research, including:

- Investigate new site survey methodologies, including observational techniques, observational modelling, invariant point definition, geometrical modelling and/or direct measurement techniques for invariant point determination, reference frame alignment and structural deformation analysis.

Consider future planning issues, including:

- The WG makes recommendations for the future in respect to the ongoing site survey needs of the community and how these needs will be met in the long term (to address issues outside of the scope of this WG).

- Develop recommendations as to how the community can provide the IERS database with all information relevant to inter-technique combination and to the maintenance of the ITRF.

Meetings and Activity

A meeting was held in 2007, at EGU in Vienna, jointly with the GGOS Networks and communication working group. Copies of presentations from that meeting can be found at http://www.iers.org/MainDisp.csl?pid=68-40.

A meeting was held in 2008, at the AGU2008 meeting in San Francisco, US, jointly with the GGOS Networks and communication working group. The meeting was well attended and presentations from a number of speakers illustrated current topics of interest. A particular emphasis was placed on attempting to establish a new methodology for monitoring collocation vectors in near real time. The current survey methodology is episodic and as such will not pick up variations to the collocation vector between surveys. The need to continually refine accuracies was also discussed. With the GGOS aim of refining the accuracy of the ITRF below the 1mm level it becomes imperative that component accuracies are well below that level of accuracy. Current local tie accuracies are at the 1 – 5mm level and as such need to be refined further. As usual the meeting also stressed the need to continue to develop the concept of Local Ties as a key component of the technique combinations and reference frame definition and to ensure all collocated sites have up to date tie information.

Change of Working Group Chair

The chair of the Working Group on Site Survey and Co-locations was changed at the end of April 2009 from Gary Johnston (Geoscience Australia) to Pierguido Sarti (IRA-INAF, Italy).
The new charter of the working group was prepared in April 2009. It was endorsed by the IERS Directing Board on the 19th April 2009 in Vienna and is reported below:

Introduction

Tie vectors are nowadays fundamental for the computation of global terrestrial reference frames: the combination of the individual techniques-specific reference frames relies on the accuracy of tie vectors as well as the number and distribution of co-location sites. In order to be useful, tie vectors must be provided with full variance covariance information and must be accurate to the 1 mm level. Variance covariance computation strictly attains to the data processing phase of the tie vector; it can be rather simply achieved and should be regarded as a mandatory task of any local tie. An accurate estimation of the tie vector is more difficult to obtain and many efforts must be taken during the whole local tie process. The accuracy of a tie vector is usually (and indirectly) assessed through a comparison with the space geodetic solutions in the combination phase: the residuals of the combination are analyzed and used to identify discrepancies between space geodetic and terrestrial measurements. If, on one hand, these discrepancies simply highlight a disagreement for a specific co-location site, on the other hand, they are the starting point for a rigorous investigation on the wide variety of causes that might originate from technique specific problems. It should be noticed that the whole process is characterized by the unavoidable complication of reliably coupling measurements of different nature (space geodetic and terrestrial) related to different reference points (electrical and conventional points, respectively).

Local tie surveys are usually performed combining terrestrial measurements of angles, distances and height differences and aim at computing differential coordinates (local ties) between space geodetic instruments expressed in a topocentric frame. In order to do so, terrestrial measurements are performed and combined according to a geometric model (whose complexity and flexibility can vary considerably) apt at realizing the *conventional* definition of the instrument's reference point. Regardless of the way the observations are acquired, processed and conditioned (all these aspects obviously impact the tie vector estimation) it should be noticed that it is impossible to directly observe the instrument's electrical reference point with terrestrial techniques (i.e. the antenna's phase centre for GPS, VLBI and DORIS and the photo-detector for SLR). Furthermore, the tie vector is naturally expressed with respect to a topocentric frame and, in order to be useful, it must be accurately transformed into a global frame.

Space geodetic observations are acquired at the electrical reference point and are commonly referred to the conventional reference point by means of specific corrections and models that are assumed to properly realize the connection. Many factors may influence the stability of the electrical point and any inconsistency related to this very delicate connection phase obviously reflects on the combination's residuals. Addressing, investigating and understanding electrical point instabilities has been a major concern for the whole geodetic community and it is a mandatory task when tie vectors and space geodetic measurements are combined.

The WG on site surveys and co-locations aims at enhancing the cooperation between the groups involved in local tie surveys and their adjustment, the combination centres, the users of tie vectors and the space geodetic techniques services (i.e. IGS, ILRS, IVS and IDS), with the purpose of bringing together all necessary capabilities apt to improve present day situation.

Cooperation with GGOS activities and its branches should be sought and established.

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 focussing 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.

The list of WG members and the schedule is currently being finalized and will be ready soon.

Other Activities

Geoscience Australia continues to undertake monitoring surveys at the Australian sites. A new calibration pier at Mt Stromlo has been constructed in an attempt to refine the accuracy of the Minico near real time IVP monitoring system. The IVP was showing an apparent seasonal motion through the Minico system. It is believed that the tallest of the four calibration piers was actually moving seasonally and this was biasing the IVP results at the 0.5mm level.

Plans are also being developed for local tie infrastructure at the Yarragadee site which will have a 12m VLBI telescope installed in 2009. A methodology for surveying the relationship between the VLBI dish, Moblas 5 system, Proposed NGSLR system and the variety of GNSS sites is being developed.

IGN is now undertaking routine local tie surveys at numerous sites and offers this service to observatory operators who are unable to complete their own surveys.

Pierguido Sarti from the Italian Istituto di Radioastronomia (IRA) reports that in 2007 they have completely re-surveyed Medicina VLBI-GPS eccentricity and Noto elevation axis using terrestrial observations.