Commission 1 – Reference Frames

http://iag.geo.tuwien.ac.at/c1/

President: Geoffrey Blewitt (USA)
Vice President: Johannes Böhm (Austria)

Structure

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Overview

Commission 1 activities have been dealing with the theoretical aspects of how best to define reference systems, and how such reference systems can be used for practical and scientific applications. The reader is referred to the Geodesists Handbook 2016 for further details on the objectives of Commission 1 and its components. Commission 1 has been closely interacting with other IAG components including Commissions, ICCT, Services, and GGOS, where reference system aspects are of concern. Many of these interactions are facilitated by Joint Study Groups and Joint Working Groups of Commission 1. This report summarizes the work performed during 2015-2019 by the various components of Commission 1, including the Sub-commissions and their Working Groups, and Joint Working Groups who have their primary affiliation with Commission 1.

In addition to the work performed by the components of Commission 1, the following summarizes activities in 2015-2019 that were performed on behalf of the entire Commission:

- A web site for Commission 1 was established at http://iag.geo.tuwien.ac.at/c1/.
• The terms of reference and structure of Commission 1, and membership.descriptions of its components were detailed in our contribution to the Geodesists Handbook 2016.

• The Steering Committee of Commission 1 has met annually, in accordance with the IAG bylaws:
  1. Vienna, Austria, April 2016;
  2. Kobe, Japan, August 2017;
  3. Pasadena, USA, July 2018; and

• Commission 1 leadership convened four IAG Symposia:
  1. at the IAG-IASPEI Joint Assembly in Kobe, Japan, July-August 2017;
  2. “Reference Frames for Applications in Geosciences” (REFAG) at the COSPAR 42nd Assembly in Pasadena, California, USA, July 2018;
  3. at the IUGG General Assembly in Montreal, Canada, July 2019, with 5 oral sessions and one poster session scheduled; and
  4. at the COSPAR 43rd Assembly in Sydney, Australia, in August 2020, which will be chaired by Heike Peter (Germany), Chair of the Technical Panel on Satellite Dynamics (PSD).

• Considering that Commission 1 is defined to be identical with Sub-commission B2 of COSPAR, symposium 2 and symposium 4 listed above serve to reinvigorate the connection between IAG and COSPAR.

• Commission 1 was represented at all the IAG Executive Committee Meetings, at which progress reports were presented:
  1. San Francisco, USA (2015);
  2. Potsdam, Germany (2016);
  3. Vienna, Austria (2017), and
  4. Washington DC, USA (2019), and
  5. Montreal, Canada (2019)

• Commission 1 was represented at the IAG Strategic Planning Meeting in Potsdam, Germany, 2016.

The following pages now provide reports for all IAG components that are primarily affiliated with Commission 1 and its Sub-commissions.
Sub-commission 1.1: Coordination of Space Techniques

Chair: Urs Hugentobler (Germany)

Overview

Sub-commission 1.1 focusses on the coordination of research related to the geodetic space techniques with emphasis on co-location aspects at fundamental geodetic observatories as well as on co-location targets in space, considering common parameters such as coordinates, troposphere parameters, clock parameters.

The GGOS Working Group “Performance Simulations and Architectural Trade-Offs (PLATO)” was installed in 2013. In the IAG structure 2015-2019 PLATO acts as an IAG Joint Working Group in IAG Sub-Commission 1.1 in order to establish a link for the study and assessment of co-locations in space as a very relevant topic in the context of coordination of space geodetic techniques. In 2016 PLATO was converted into a “Standing Committee” in the GGOS framework in order to allow studies on a time frame extending the usual duration of working groups.

In addition to a large variety of SLR, LLR and VLBI simulations covering different aspects related to the design of ground- and space-based architecture of measurement systems, to improved analysis methods, and to observation scenarios and their impact on TRF accuracy and stability, PLATO members contributed important simulation results for the proposal for the EGRASP/Eratosthenes mission proposal in reply of ESA’s Earth Explorer-9 call prepared under the lead of Richard Biancale.

Working Group 1.1.1 on co-location using clocks and new sensors was set up. A position paper was prepared focusing on the relevance of precise time and frequency distribution at fundamental stations and corresponding closure measurements as a method to monitor local ties. A meeting is planned addressing the next generation geodetic stations and metrology concept. Activities of the ESA Topical Team on Geodesy, Clocks and Time Transfer exploit synergies with the IAG WG 1.1.1.

Terms of Reference

Space techniques play a fundamental role for the realization and dissemination of highly accurate and long-term stable terrestrial and celestial reference frames as well as for accurate monitoring of the Earth orientation parameters linking the two fundamental frames. The current space geodetic techniques contributing to ITRF and ICRF, i.e., Very Long Baseline Interferometry (VLBI), Satellite and Lunar Laser Ranging (SLR/LLR), Global Navigation Satellite Systems (GNSS) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) have particular strengths and technique-specific weaknesses.

Strengths of the techniques are exploited by combining them making use of fundamental sites co-locating more than one technique. Sub-commission 1.1 focusses on the coordination of research related to the geodetic space techniques with emphasis on co-location aspects at fundamental geodetic observatories as well as on co-location targets in space, considering common parameters such as coordinates of stations and satellites, troposphere parameters, and clock parameters.
Working Groups of Sub-commission 1.1:

WG 1.1.1: Co-location using Clocks and New Sensors

Chair: Ulrich Schreiber (Germany)

Members
• Sten Bergstrand (Sweden)
• Srinivas Bettadpur (USA)
• Rüdiger Haas (Sweden)
• Younghee Kwak (Germany)
• David McCormick (USA)
• Markku Poutanen (Finland)
• Ivan Prochazka (Czech Republic)

Activities and publications during the period 2015-2019

The establishment of accurate local ties of different space geodetic techniques at fundamental geodetic observatories poses a long-standing problem. While geometric ties can be determined at sub-millimeter-level, the relation to physical phase centers of the instruments and temporal stability of such offsets are usually known with significantly lower precision. This working group evaluates novel ways for inter-technique cross-calibration at geodetic sites using existing and new sensors and technologies, such as highly accurate time and frequency transfer, ultra-stable clocks, and co-location targets. The activities of the working group are closely related to IAG JWG 2.1 on Relativistic Geodesy. A corresponding coordination meeting took place in Hannover, Germany, on April 12, 2017.

1. Position Paper

A position paper addressing the main topics of the working group was formulated stimulating the discussions among the WG members. The position paper addresses the issue of local ties at geodetic observatories and highlights a concept allowing to access the physical phase center of SLR as well as VLBI and other space geodetic instruments through closure measurements of travel times. The concept involves precise time distribution of timing signals between the instruments and a common calibration target through compensated optical fibers.

Figure 1.1.1 shows the concept of a demonstrator that is developed at the Geodetic Observatory in Wettzell allowing to cross-calibrate the reference points of several VLBI telescopes. A precisely time-tagged signal is broadcast by a reference target and received by the radio telescopes through standard receive channels. The signal is registered with respect to a reference signal (p-cal and formatter) with precisely known time relation to the broadcast signal. The concept thus allows to precisely relate the geometric free space travel distance from the reference target to instrument reference point through time closure measurements.

The highlighted concept is currently built up at the Geodetic Observatory Wettzell in the framework of the research unit FOR 1503 funded by the German Science Foundation (DFG). Similar concepts and performance and implementation issues for the other space geodetic techniques are discussed in the context of the working group.
Fig 1.1.1. Concept for precise cross-calibration of the reference points of VLBI telescopes through time closure measurements.

2. Meeting on Next Generation Geodetic Stations and Metrology

A workshop on Next Generation Geodetic Stations and Metrology is planned by Srinivas Bettadpur at Center for Space Research at University of Texas at Austin for late summer 2017. Background is the operation of the McDonald Geodetic Observatory as a multi-technique geodetic observatory within the NSAS’s Next Generation Space Geodesy Network. The goal of the workshop is to develop a list of areas of attention and research that bear the potential for leading to an idealized geodetic observatory supporting the needs of a future terrestrial reference frame.

The effort attempts to reassess the available knowledge from the viewpoint of metrology science and its implementation with the needs defined by the next generation reference frame. Topics of discussion are in particular the contribution of distribution of precise time and frequency between the different systems at an observatory, concepts of inter-system surveys at ppm-level, contribution of gravity measurements, and requirements for characterization of the environment.

3. ESA Topical Team on Geodesy, Clocks and Time Transfer

In the framework of the ESA Topical Team on Geodesy, Clocks and Time Transfer a workshop is in planning focussing on distribution of precise time between geodetic observatories using space techniques. The topical team is chaired by Ulli Schreiber and receives funding from ESA for the organization of workshops. It consists of an international group of experts and coordinates the activities of different research groups working on topics related to clocks and time transfer for geodetic applications, activities that are relevant in the context of the tasks of IAG WG 1.1.1. The topical team identifies scientific problems and relevant new technologies and organizes topical workshops. A main focus is the exploitation of the Atomic Clock Ensemble in Space (ACES) that will be launched in 2020 to the International Space Station.
JWG 1.1.2: Performance Simulations and Architectural Trade-Offs (PLATO)

Chair: Daniela Thaller (Germany)
Vice Chair: Benjamin Männel (Germany)

Members
• AIUB (Astronomical Institute, University of Bern, Switzerland)
• BKG (Bundesamt für Kartographie und Geodäsie, Germany)
• CNES (Center National d’Études Spatiales, France)
• DGFI-TUM (Deutsches Geodätisches Forschungsinstitut, TU München, Germany)
• ETH Zürich, Switzerland
• GFZ (GeoForschungsZentrum Potsdam, Germany)
• GRGS (Group de Recherche de Géodésie Spatial, France)
• GSFC (Goddard Space Flight Center, USA)
• IfE (Institut für Erdmessung, University of Hannover, Germany)
• IGN (Institut National de l’Information Géographique en Forestièr, France)
• JCET (Joint Center for Earth Systems Technology, USA)
• JPL (Jet Propulsion Laboratory, USA)
• NMA (Norwegian Mapping Authority)
• TU Berlin, Germany
• TU München, Germany
• TU Wien, Austria

Activities and publications during the period 2015-2019

The terrestrial reference frame (TRF) is the foundation for virtually all space-based and ground-based Earth observations. Positions of objects are determined within an underlying TRF and the accuracy with which objects can be positioned ultimately depends on the accuracy of the reference frame. In order to meet the anticipated future needs of science and society GGOS has determined that the accuracy and stability of the ITRF needs to be better than 1mm and 0.1mm/y, respectively. The current ITRF is at least an order of magnitude less accurate and stable than these goals. Further improvements of the ITRF are thought to be achieved by:
• Developing next generation space-geodetic stations with improved technology and system performance;
• Improving the ground network configuration in view of global coverage and co-locations;
• Improving the number and accuracy of surveys between co-located stations;
• Deploying, improving and optimizing space-based co-locations.

This joint working group aids these activities and helps to evaluate the impact on the accuracy and stability of future ITRFs. To this purpose a variety of aspects related to design of ground- and space-based architectures of measurement systems and their impact on TRF accuracy and stability are investigated. WG members develop improved analysis methods using all existing data and co-locations and carry out extensive simulations for future improvements and optimization of ground network, space segment and observation scenarios.
Organization

On the meeting of the GGOS Bureau of Networks and Observations during EGU in April 2016 it was decided that PLATO will be a “Standing Committee” in the GGOS framework in order to allow studies on a time frame extending the usual duration of working groups. In the IAG structure 2015-2019 PLATO acts also as an IAG Joint Working Group in IAG Sub-Commission 1.1 in order to establish a link for the study and assessment of co-locations in space as a very relevant topic in the context of coordination of space geodetic techniques. This report overlaps with the corresponding Traveaux report for the GGOS Bureau of Networks and Observations.

In June 2016 Richard Gross (JPL) who co-chaired PLATO since 2013 handed over the co-chair to Benjamin Männel (GFZ).

Members of PLATO are informed about ongoing and planned activities with a newsletter.

1. Meetings

In regular meetings in conjunction with the EGU, Vienna (annually in April), WG members report about the progress of the work related to PLATO including performed and planned studies, results from simulations and analysis of real data and the results of the groups have been compared.

2. Achievements

Several members were successful in acquiring funding for simulation studies (DGFI-TUM, AIUB, TU Vienna, GFZ). Several geodetic software packages have been augmented by the capability to carry out realistic simulation scenarios (VieVS, DOGS, Bernese, Geodyn). The following sections give information on achievements related to specific areas.

SLR Simulations

Simulations for improved global SLR station network were carried out. Simulations for an SLR station in Antarctica (Syowa, co-located with VLBI) showed the benefit for geocenter parameter determination. Simulations for improved SLR tracking of GNSS satellites started.

LLR Simulations

Simulations related to more LLR data assuming millimeter ranging accuracies (up to three future single-prism reflectors on the moon and two additional LLR sites on the southern hemisphere) were carried out. The effect on the lunar reflector coordinates, the mass of the Earth-Moon system and two relativistic parameters (temporal variation of the gravitational constant and equivalence principle) was studied. Especially, the measurements to the new type of reflectors would lead to an improved accuracy of the estimated parameters up to a factor of 6 over a decade of new measurements.
VLBI Simulations

Simulations (and analysis of data as far as available) for new VGOS telescopes employing next generation broadband VLBI technology, showed that the GGOS requirements of 1 mm accuracy and 0.1 mm/year stability will likely be fulfilled for the reference frame. Simulations and analysis of VLBI tracking data of GNSS satellites and the Chinese APOD cube-satellite (i.e. using co-locations in space) were carried out using the Australian VLBI antennas for several sessions during 2016.

Local Ties

The impact of the Local ties on the reference frame products were studied regarding different stochastic models of the LT, selection of the LT, and the impact of systematically wrong LT. It was shown that the LT standard deviations of 1 mm or better lead to the best datum realization of an SLR+VLBI-TRF. Simulating wrong LT indicate Wettzell, Badary and AGGO as important LT sites in the SLR and VLBI combination.

E-GRASP/Eratosthenes

PLATO members were actively participating on the preparation E-GRASP/Eratosthenes proposal lead by Richard Biancale. The proposal was submitted in 2016 in response of the ESA Earth Explorer-9 call. After good scientific assessment by ESA a revised version of the proposal was submitted 2017 EE9 call. The satellite mission proposed co-locates all fundamental space-based geodetic instruments, including GNSS and DORIS receivers, laser retro-reflectors, and a VLBI transmitter on the same satellite platform on a highly eccentric orbit with particular attention on the time and space metrology on board.

A variety of simulations were performed by PLATO members both for discriminating the best orbital scenario according to many geometric/technical/physical criteria and for assessing the expected performances on the TRF according to GGOS goals.

3. Recommended Future Work

It is recommended that future work include the examination of trade-off options for station deployment and closure, technology upgrades, impact of site ties, etc. Simulation studies related to ground infrastructure are planned to assess impact on reference frame products of network configuration, system performance, technique and technology mix, co-location conditions, site ties while simulation studies related to space infrastructure are planned to assess impact on reference frame products of: co-location in space, space ties, available satellites.

Work to project future network capability over the next 5- and 10-year periods using projected network configuration in new system implementation is recommended. Improved analysis methods for reference frame products by including all existing data and available co-locations should be developed and analysis campaign with exchanged simulated observations.
4. Conferences

PLATO is present at the main geodetic. Presentation were given at the IGS Workshop in Sydney in Feb. 2017, IVS General Meeting in Johannesburg in March 2016, the EGU General Assembly in Vienna in April 2015 and April 2016, the IUGG General Assembly in July 2015, the ILRS Workshop in Potsdam in October 2016, at the AGU Fall Metting in San Francisco in December 2016. A presentation was given at the IAG Scientific Assembly July, 30 - August 4, 2017 in Kobe, Japan with title “The GGOS Standing Committee on Performance Simulations and Architectural Trade-Offs (PLATO)” highlighting results of ongoing studies and giving first recommendations.

5. Publications


Sub-commission 1.2: Global Reference Frames

Chair: X. Collilieux (France)

Overview

Sub-commission 1.2 focuses its activity on the definition and realization of the terrestrial reference system (TRS). Since 2016, it includes the link to world height system (WHS). It studies fundamental questions and more practical aspects that can improve current terrestrial reference frame (TRF) determinations.

Numerous activities are actually realized in other IAG-related structures, namely:
• Sub-commission 1.3 on “Regional reference frames”, including EUREF, SIRGAS…
• International Earth Rotation and Reference Systems Service (IERS)
• Other relevant IAG services (IGS, ILRS, IVS, IDS)
• IAG Global Geodetic Observing System (GGOS)
• Inter-Commission Committee on Theory.
We therefore encourage the reader to refer to their individual reports.

At first, this report highlights recent works with respect to the relativistic modelling of reference frames. Thus, it presents the ITRF2014, the latest realization of the International Terrestrial Reference System (ITRS), which is published by the International Earth Rotation and Reference Systems Service (IERS). It provides the coordinates of a set of points at the Earth and delivered in a self-consistent Terrestrial Reference Frame with their variance-covariance information. Those are computed for more than 35 years of observations from the four space geodetic techniques, namely: DORIS, GNSS, SLR and VLBI. The report also presents the work of the IERS combination centers which conduct researches on Terrestrial Reference Frame determination. Whereas vertical coordinate reference system was up to now realized at the continental scale, work is underway to realize a world height system. This activity is summarized in this report. Such a realization should be interoperable and consistent with the current geometric determination of the Terrestrial Reference System. Recent Researches on local ties and space ties are then summarized. Finally, undergoing work on ISO standardization and conventions is summarized.

Summary of the Sub-commission’s activities during the period 2015-2019

Contributors to this report:
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Relativistic modelling

Relativistic reference frames are based on a network of clocks in space linked with time transfer technologies. Such realized frames are entirely decoupled from ground fixed stations and could be used to reference any point on the Earth's surface.

Recent work by Kostić et al. (2015) is worth reporting here. They have presented a new method for implementing a relativistic positioning system with a GNSS. The spacetime metric is described with a perturbed Schwarzschild metric, while the dynamics is completely solved using a first order perturbation approach, including perturbations due to Earth multipoles (up to the 6th), the Moon, the Sun, Venus, Jupiter, solid tide, ocean tide, and Kerr rotation effect. The authors find that positioning in this perturbed spacetime is highly accurate and time efficient already with standard numerical procedures and laptop.

Within IAG, relativistic modelling is investigated in JWG 2.1 “Relativistic Geodesy: First Steps Towards a New Geodetic Technique”. See the Commission 2 report for more details.

ITRS center and ITRF2014

Overview

The main activities of the ITRS Center during the period 2015-2019 include the maintenance of the ITRF network, database and website. The full report is available in the report of the ITRS center in the IERS section of the travaux. Main points are summarized in the following.

Activities and publications

A) The main activities of the ITRS Center related to research analysis during this period include:

- The ITRS Product Center collects all new surveys operated by either Institut national de l’information géographique et forestière (IGN) or the hosting agencies of ITRF co-location sites. At the occasion of the ITRF2014 analysis, several new local tie SINEX files and corresponding reports were submitted to the ITRS Center. These new survey results were made available via the ITRF website after the release of the ITRF2014.
- The operational entity of the ITRS Center at the IGN Survey department has prepared a document describing the IGN current practice of local survey that could help surveyors who do not know how to proceed and are not used with mm precision.

B) Publication of ITRF2014:

- During the preparation of ITRF2014, various tests and combined coordinate sets have been processed by IERS combination centers (see below).
- The final ITRF2014 solution was published in January 2016, with a dedicated website: <http://itrf.ign.fr/ITRF_solutions/2014/>.
- A full ITRF2014 article was published in Journal of Geophysical Research (Altamimi et al., 2016).
- the ITRF2014 is available for download at the dedicated website: <http://itrf.ign.fr/ITRF_solutions/2014/>.
The ITRF2014 is an improved realization of the International Terrestrial Reference System (ITRS) and is demonstrated to be of higher quality than the past ITRF versions. It involves two main innovations dealing with the modelling of station non-linear motions, namely seasonal (annual and semi-annual) signals present in the time series of station positions and post-seismic deformations for 124 sites that were subject to major earthquakes. In order to illustrate the performance of the modelling of the non-linear station motions, figure 1.2.1 shows, as an example, the trajectory of Tsukuba (Japan) site after the Tohoku earthquake, where GNSS and VLBI instruments are co-located. The Post-Seismic Deformation parametric model fitted to the GPS data was then applied to the VLBI time series. Figure The de-trended residuals of both stations are also shown, after removing the linear velocity and annual and semi-annual signals.

![Fig. 1.2.1. Left) Site trajectory of Tsukuba (Japan), GNSS. Right) De-trended residuals of Tsukuba (Japan), GNSS](image)

**IERS Combination center**

Report of the IERS components can be found in the IAG report. Relevant components of the report are summarized in this document since they are related to Terrestrial Reference Frame computation strategy that is a field of research.

**IERS Combination center: DGFI**

Deutsches Geodätisches Forschungsinstitut - Technische Universität München (DGFI-TUM) is acting as one of the ITRS Combination Centers within the IERS since 2001.

DGFI-TUM's latest realization of the ITRS is the DTRF2014. The DTRF2014 is an independent realization of the ITRS based on the same input data as the realizations ITRF2014 and JTRF2014 (see section IERS combination center: JPL). While the ITRF2014 is based on the combination of solutions, the DTRF2014 is computed by the combination of
normal equations. DTRF2014 is the first ITRS realization corrected for non-tidal atmospheric and hydrological loading. However, all information to reconstruct the real station positions at each observation epoch is delivered. DTRF2014 is available for download at <http://www.dgfi.tum.de/en/science-data-products/dtrf2014/>. In addition to this work, the impact of the joint station coordinates and EOP combination on the ICRS realization was object of new research.

**IERS Combination center: IGN**

The members of the IGN Combination Center, often in cooperation with other scientists, conduct research and developments activities relating to the ITRF in particular and reference frames in general. R&D activities include ITRF accuracy evaluation, mean sea level, loading effects, combination strategies, and maintenance and update of CATREF software. Main contributions are report below:

- Specific new developments were achieved and validated in preparation for the ITRF2014: CATREF software was enhanced and upgraded to include periodic terms of the station position time series, such as in particular annual, semi-annual terms for all techniques and draconitic signals for satellite techniques, especially GNSS.
- Other developments were also finalized and validated, such as modelling of post-seismic deformations for sites affected by major Earthquakes, as well as an improved strategy for the detection of discontinuities in the technique station position time series.
- First and early results of the ITRF2014 input data analysis were presented at various conferences in 2015.
- A preliminary ITRF2014 solution called ITRF2014P was generated and submitted on September 09, 2015 to the Technique Centers of the four techniques for evaluation. A certain number of feedbacks were then received and all concerns were answered and taken into account for the final ITRF2014 solution.

**IERS Combination center: JPL**

The Jet Propulsion Laboratory (JPL) is developing a sequential estimation approach to determining combined, multi-technique terrestrial reference frames. An approach based on a Kalman filter/smoother was initially taken. Kalman filters are commonly used to estimate the parameters of some system when a stochastic model of the system is available and when the data contain noise. For the purpose of determining a terrestrial reference frame, the system consists of the positions and velocities of geodetic observing stations and associated EOPs along with their full covariance matrices. The data consist of time series of observed VLBI, SLR, GNSS, and DORIS station positions and EOPs along with the data measurement covariance matrices. In addition, measurements from ground surveys of the positions of reference marks of co-located stations are used as constraints to tie the technique-specific measurements to each other. JPL’s Kalman filter and smoother for reference frame determination (KALREF) combines these measurements to determine ITRF-like reference frames subject to constraints imposed on the allowed evolution of the station positions. KALREF includes options to model the station motion as linear, linear and annual, or linear, annual, and semiannual. Through the use of stochastic models for the process noise, the station positions can be constrained to exactly follow these models of the station motion (by setting the process noise to zero), to recover the observed station positions (by setting the process noise to a large value), or to follow a smoothed path (by setting the process noise to
Based upon the lessons learned in using KALREF to determine JTRF2014, JPL has decided to move from a Kalman filter/smoother-based approach to sequentially estimating TRFs to one based on a square-root information filter. Square-root information filters are numerically superior to Kalman filters and can more naturally account for degeneracies in the system of equations being solved. Unlike KALREF which had a 1-week fixed time step, the square-root reference frame filter (SREF) now being developed will have a variable time step, allowing measurements to be assimilated at the epoch of their observation. SREF will also include both dynamic and stochastic models of the EOPs to improve their prediction and will include a model for postseismic station displacements to improve the predictions of the motions of stations affected by large earthquakes. And SREF will be able to optionally assimilate VLBI-observed radio source positions to jointly determine terrestrial and celestial reference frames. SREF is currently being validated and is expected to be used to determine JTRF2020.

**Link to gravity**

The JWG 0.1.2 “Strategy for the Realization of the International Height Reference System (IHRS)” is working on specifying the International Height Reference System realization process, namely the determination of the International Height Reference Frame (IHRF). The working group has first determined the selection criteria of the IHRF stations. Among them, reference stations should be co-located with current ITRF multi-technique network, regional reference frame stations, national levelling benchmarks and tide gauges. About 170 stations distributed worldwide have been proposed. The estimation process of the gravitational potential values at those sites and their accuracy has been studied. Three comparison campaigns have been carried out by the working group: a first campaign based on common points but different input data; a second campaign based on a common set of input data and a minimum set of standards; a third campaign as a reprocessing of the second one. More details, discussions of the results and references can be found in the JWG 0.1.2 report.

**Local ties**

At co-location sites where several technique instruments are operating, the relative positions of the instrument reference points need to be known. They are called local tie vectors. Those are indispensable datasets for deriving and validating a Terrestrial Reference Frame. It is fundamental to support research for local tie determination to reach a 1-mm accuracy monitoring of the local tie vectors. Communication on the best practices for determining local tie vectors is also of the outmost importance since the determination a local tie vector is an expensive task. As mentioned above in the ITRS center report, a new IERS technical note has been published to report the procedures that have been defined at IGN France for surveying co-location sites (Poyard et al., 2017).

The research activity related to the derivation of local tie vectors is summarized in the JWG 1.1 Joint Working Group on “Site Survey and co-location” report.

**Space ties**

Up to now, Terrestrial Reference Frames are computed from separate technique coordinate sets and terrestrial local ties. However, the position of satellites that carry several positioning sensors (laser reflectors, GNSS antenna, DORIS antenna) can be determining by a simultaneous computation using all available data. In this case, the relative positions of the ...
instruments on board of the satellites (determined using measurement or known a priori) plays the role of a space tie in a Terrestrial Reference Frame processing at the observation level. This issue is discussed in the JWG 1.1.3 named “Performance Simulations and Architectural Trade-Offs (PLATO)”. During the two first years, the working group has conducted several studies based on simulated data to show the impact of including VLBI measurements on satellites, the effect for an improved SLR tracking to GNSS satellites and the interest of improving the SLR tracking network configuration. Please report to the report of the working group for more details and references.

**ISO standardization**

The standardization activity related to Terrestrial Reference Frames is studied in the GGOS Working Group "ITRS Standards for ISO TC 211", see the report of GGOS “Bureau of Products and Standards”. The group is presently working on a draft of the ISO TC211/19161-1 standard.

**Link to conventions**

The IERS conventions chapter 4, version 1.3.0, has been updated on 01 April 2019 for ITRF2014 release. All the versions of the IERS conventions, including the most recent are available at the IERS convention center web sites: <http://iers-conventions.obspm.fr/conventions_versions.php> or <http://maia.usno.navy.mil/conventions_versions.php>.

**References**


Sub-commission 1.3: Regional Reference Frames

Chair: Carine Bruyninx (Belgium)

Overview

Sub-commission 1.3 contains six regional Sub-Commissions (SC)
- 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
and one Working Group (WG) “Time-dependent transformations between reference frames”.

This final report gathers the contributions of the above regional sub-commissions and WG for the period 2015-2019. As stated in the Terms of Reference, IAG Sub-commission SC1.3 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 common key issues of interest to regional organizations.

In addition to the specific objectives of each regional Sub-commission, the main objectives of SC1.3 as a whole are to:
- Coordinate the activities of the regional Sub-commissions focusing on exchange of data, competences and results;
- Promote operation of permanent GNSS stations, in connection with IGS (international GNSS network) whenever appropriate, as the basis for the long-term maintenance of regional reference frames;
- Promote open access to the GNSS data from permanent GNSS stations used for the maintenance of regional reference frames and scientific applications;
- Develop specifications for the definition and realization of regional reference frames, including the vertical component with a special consideration of gravity and other data;
- Encourage and stimulate the development of the AFREF project in close cooperation with IGS and other interested organizations;
- Encourage and assist countries, within each regional Sub-commission, to re-define and modernize their national geodetic systems, compatible with the ITRF;
- Support the initiatives of the GGRF (Global Geodetic Reference Frame) WG of the UN-GGIM (United Nations Initiative on Global Geospatial Information Management).

The reports of the individual Sub-commissions and the WG are presented hereafter.
Sub-commission 1.3a: Europe (EUREF)

Chair: Markku Poutanen (Finland)

Introduction and structure

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

The results and recommendations issued by the EUREF sub-commission support the use of the European Reference Systems in all scientific and practical activities related to precise georeferencing and navigation, Earth sciences research and multi-disciplinary applications. EUREF applies the most accurate and reliable terrestrial and space-borne geodetic techniques available, and develops the necessary scientific principles and methodology. Its activities focus on a continuous innovation and on evolving user needs, as well as on the maintenance of an active network of people and organizations, and may be summarized as follows:

- Maintenance of the ETRS89 (European Terrestrial Reference System) and the EVRS (European Vertical Reference System) and upgrade of the respective realizations;
- Refining the EUREF Permanent Network (EPN) in close cooperation with the IGS;
- Improvement of the European Vertical Reference System;
- Contribution 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 meetings of the EUREF Technical Working Group (TWG), since 2017 EUREF Governing Board (GB), which take place three times a year, and at the annual EUREF Symposia. The symposia that place every year since 1990, with an attendance of about 100-120 participants coming from more than 30 European countries and other continents, representing Universities, Research Centres and NMAs (National Mapping Agencies). The organization of the EUREF Symposia is supported by EuroGeographics, the consortium of the European National Mapping and Cadastre Agencies (NMCAs), reflecting the importance of EUREF for practical purposes.


GB members

Elmar Brockmann (Switzerland)
Carine Bruyninx (Belgium)
Rolf Dach (Switzerland)
Jan Dousa (Czech Republic)
Rui Fernandes (Portugal)
Ambrus Kenyeres (Hungary, GB chair)
Juliette Legrand (Belgium)
Martin Lidberg (Sweden)
Tomasz Liwosz (Poland)
Martin Poutanen (Finland, EUREF chair, ex-officio)
Rosa Pacione (Italy)  
Martina Sacher (Germany)  
Wolfgang Söhne (Germany, EUREF secretary, ex-officio) 
Christof Völksen (Germany) 
Zuheir Altamimi (France), Alessandro Caporali (Italy), and João Torres (Portugal) are regularly participating to the GB meetings as honorary members. Andrzej Araszkiewicz (Poland) is regularly participating to the GB meetings as invited guest.

Activities and publications during the period 2015-2019

EPN – Tracking Network, Network Coordination, EPN Central Bureau

Over the last four years, the number of permanent GNSS tracking stations in Europe belonging to the European Permanent Network was growing from 265 by mid-2015 to 336 by mid-2019. The number of sites recording GLONASS data simultaneously to GPS data was significantly increasing from 70 % by mid-2015 to 94 % by mid-2019.

One focus was on the upgrade of the EPN towards a multi-GNSS network. By mid-2019, 210 stations (63 %) are recording Galileo data. Moreover, 169 stations are recording the BeiDou constellation, and 22 stations are recording the regional QZSS.

In Nov. 2016, the EPN Central Bureau (CB) launched a completely revised version of the web portal (http://www.epncb.oma.be). The navigation was re-arranged, and the portfolio was streamlined to remove old and no longer used items. Moreover, the access was made more flexible to be used also with modern equipment like, e.g., smartphones and tablets. In 2017, new multi-GNSS data quality checks were implemented, including the re-analysis of all historical RINEX 2 and 3 EPN data. Finally, the new “Metadata Management and Dissemination System for Multiple GNSS Networks” (M³G, available from https://gnss-metadata.eu), developed by the EPN CB, has reached in 2018 the level of maturity required for operational use in EUREF and consequently all EPN and EPN densification metadata were migrated to M³G.

The EUREF Regional Data Centre (RDC) and the Analysis Centre (AC) in Graz, Austria was closed in 2017. Therefore, in 2016 the Austrian colleagues started to build up a new RDC and a new AC at the Bundesamt für Eich- und Vermessungswesen (BEV) in parallel to the existing structure and took over full functionalities in 2017.

Most of the activities covering EPN are reported on an annual basis in the Technical Reports of the IGS. In addition to the overview and summary given here, see Bruyninx et al. (2015), Bruyninx et al. (2016), Bruyninx et al. (2017), and Bruyninx et al. (2018) for more details.
During the reporting period, the first EPN stations started providing real-time data in RTCM 3.2 and 3.3 format. In addition to GPS and GLONASS, most of the streams contain Galileo, BeiDou, QZSS and SBAS. The monitoring of the three EUREF broadcasters at the EPN CB was extended. In addition to the RTCM 2 and 3.1 format, also the RTCM 3.2 and 3.3 data stream contents are now verified against the proposed content of the sourcetable.

References:


EPN – Analysis Centre Coordinator, Troposphere Coordinator, Reference Frame Coordinator

The EPN Analysis Centre Coordinator (ACC) combines GNSS coordinate solutions provided by 16 EPN Analysis Centres into official EPN solutions.

In 2016, the ACC worked in the Working Group “EPN Reprocessing”. In the beginning of 2016, the EPN-Repro2 reprocessing was finalized. The ACC combined daily solutions computed by five EPN ACs (ASI, GOP, IGE, LPT and MUT) for the period 1996-2013; the results have proven high homogeneity of the individual AC solutions.

At the end of 2016, a methodology for creating weekly combined EPN solutions was changed (EPN LAC mail 2134). Up to and including week 1924, the weekly combined solutions were created directly from the AC weekly solutions. Since week 1925 (Nov. 27, 2016), the daily AC solutions have been used for that purpose; at first the daily AC solutions are combined for each day of the week, and then the seven daily combined solutions are stacked into a weekly solution. It was verified that the new approach allows to handle more consistently daily position outliers (for both AC and combined solutions), and helps to mitigate possible inconsistencies between AC solutions which could be observed when combining on a weekly level. Due to the change in the combination strategy, the EPN ACC website (http://www.epnacc.wat.edu.pl) has been updated. The website now contains graphs and maps presenting coordinate consistency of AC daily solutions with respect to the daily combined solutions for each station and day of the last combined week.

To be consistent with IGS products, since January 29, 2017 (GPS week 1934) the EPN ACs started to use the IGS14/epn_14.atx framework during GNSS data analysis. Since week 1934, also EPN combined coordinate solutions have been aligned to the IGS14 reference frame (Liwosz and Araszkiewicz, 2017).

Since week 1980 (Dec. 17, 2017) the troposphere modelling has been harmonized among EPN ACs, i.e., all ACs started to use the VMF1/ECMWF approach (before week 1980 9 ACs used VMF1/ECMWF, and 7 used the GMF/GPT approach). After week 1980 better consistency between AC coordinate solutions was observed for some stations. Also, the scale differences between the combined solution and solutions provided by three ACs (BKG, IGE and ROB), which used the GMF/GPT approach before week 1980, were noticeably decreased (Liwosz and Araszkiewicz, 2018).

At the EUREF symposium 2018 held in Amsterdam, the EUREF plenary adopted a resolution encouraging the ACs to build up the capabilities for processing Galileo observations and asking the EUREF community, GSA, ESA and the GNSS industry to provide the missing receiver antenna calibrations for Galileo signals. Following this resolution, some ACs started creating GNSS processing solutions including Galileo observations in addition to GPS and GLONASS, in parallel to the operational GPS+GLONASS solutions, and making them available to the Analysis Centres Coordinator and the Troposphere Coordinator, so that the impact of Galileo observations on the combination products could be analyzed.

In 2018, the ACC analyzed the impact of including Galileo observations in EPN AC products on combined EPN station positions. In the test phase (EPN LAC Mail no. 2344), eight ACs (BEK, BKG, IGE, ROB, UPA, NKG, SUT, WUT) provided solutions including Galileo observations (in addition to the operational solutions). In comparison with the operational combined solutions, mean position differences (over 33 weeks) for the majority of stations did not exceed 1 mm in the horizontal components, and 3 mm in the vertical component. For the troposphere, the differences in the total zenith delays were below 1 mm.
Since the impact of adding Galileo observations on combined positions was small, it was decided that starting with week 2044 (March 10, 2019) these observations may be included in the EPN operational products (EPN LAC Mail no. 2407).

Besides station coordinates, the 16 EPN ACs also submit Zenith Total Delay (ZTD) parameters and horizontal gradients on a routine basis in the legacy SINEX_TRO format that are used by the TC to deliver the EPN official tropospheric product. The EPN official tropospheric product is based on a combination of the contributing solutions using a generalized least square method (Pacione et al., 2011). Starting from GPS week 2034, in addition to the legacy format, the EPN tropospheric combined solution release in SINEX_TRO v2.0 format (Pacione and Dousa, 2017).

The ZTDs and horizontal gradients are delivered with a sampling rate of one hour, on a weekly basis, but in daily files. At the EPN Analysis Centres Workshop in Brussels in 2017, the harmonization of the troposphere modelling among the EPN ACs was proposed in order to increase the consistency between AC solutions. It was agreed that from GPS week 1980 onwards it would be mandatory to model the tropospheric delay using the VMF1 mapping function together with a priori hydrostatic delays from VMF1 grids (based on atmospheric pressure data from ECMWF).

The mean bias and standard deviation of the AC individual ZTD contributions with respect to the combined ZTD solution, http://epncb.eu/_productsservices/sitezenithpathdelays/, allow for monitoring of the agreement of the AC solutions versus the combination. Twice per year, the EPN multi-year tropospheric solution is updated and it is announced by means of a EUREF mail. Last update done in March 2019 and covering the period 1996-2018 (see EUREF mail 09770).

For each EPN station ZTD time series, ZTD monthly mean and comparison with radiosonde data (if collocated) plots are updated and available at the EPN Central Bureau http://www.epncb.oma.be/_productsservices/sitezenithpathdelays/.

In 2016, the TC worked in the Working Group “EPN Reprocessing” in close cooperation with the WG3 of the COST Action ES1206 ‘GNSS4SWEC’ (REF) being the availability of 20+ years of GNSS data is a valuable data set for the development of a climate data record of GNSS tropospheric products. The EPN-Repro2 tropospheric data set (Pacione et al., 2017; Pacione, 2016) is open to the user community and, on a European scale, it has been established as a reference data set for monitoring trend and variability in atmospheric water vapor.

Starting with the release of IGS14 in January 2017, the EPN multi-year position and velocity solution was replaced by a new version based on the daily EPN-repro2 solutions (from GPS week 834 to GPS week 1772) and the daily EPN routine solutions (from GPS weeks 1773 up to present). The solution is computed with the CATREF software (Altamimi et. al., 2007). It has a revised discontinuity list and incorporates the ITRF2014 post-seismic deformation models (ftp://itrf.ign.fr/pub/itrf/ITRF2014-psd-gnss.dat) for five stations belonging to the EPN: ANKR00TUR, BUCU00ROU, ISTA00TUR, REYK00ISL, TUBI00TUR. It is consistent with the epn_14.atx ground antenna calibrations and aligned to the IGS14 reference frame. In order to insure the consistency of the daily solutions with the IGS14/epn_14.atx, the positions prior to GPS week 1934 were corrected (using the latitude-dependent models from IGS, IGSMAIL-7399) for the position changes caused by the change from epn_08.atx to epn_14.atx. The EPN multi-year solution is updated each 15 weeks at EPN CB website. To guarantee the quality and reliability of the solution, several checks are performed at each release. The position time series are screened in order to look for outliers and discontinuities.
The agreement of the EPN solution w.r.t. IGS14 and the weekly updates of the IGS multi-year solution IGSYYYPWW is monitored. Hector software (Bos et al., 2013) is used to derive realistic error estimates and assess the quality and the reliability of the stations. In addition to the time series of the multi-year solution, extended time series are updated daily by adding the EPN daily combined solutions (operational and rapid) not yet included in the final combined EPN solution. Together with the RINEX data quality check monitoring performed by EPN CB, these quick updates allow to monitor the behaviour of the EPN stations and to react promptly in case of degradations at a station.

References:


Pacione R., Bruyninx C., Brockmann E., Söhne W. (2019) EPN data and products in support of atmospheric sounding, Presented at EGU General Assembly, Vienna, Austria, April 08-12, 2019

Working Groups – Multi-GNSS WG, Reprocessing WG, WG on European Dense Velocities, EPN Densification WG, Deformation Modelling WG

Thanks to the effort of the Multi-GNSS WG and the EPN CB, the number of stations submitting RINEX 3 files to the EPN increased significantly to 222 stations. In addition, the use of long RINEX filenames increased significantly to 199 stations. In 2016, the first EPN Analysis Centre (LPT, swisstopo) started processing Galileo and BeiDou data in addition to GPS and GLONASS on a routine basis. As of mid-2019, several other Analysis Centres included Galileo in their processing, at least in a parallel test-processing environment.

The second reprocessing of the EPN, Repro-2, was finalized in 2016. Covering the period 1996 to 2014, five analysis centres (ACs) were contributing. Three ACs processed the complete EPN using three different software packages (BSW 5.2, GAMIT 10.5 and GIPSY 6.2), two ACs processed large subnetworks with BSW5.2. The combinations were carried out by the Analysis Centre and the Troposphere Coordinators, respectively. The combination results for coordinates as well as for troposphere parameters are the basis for the new accumulated EPN solutions.

The WG on European Dense Velocities is collecting velocity results from many European countries and institutions. The inputs with detailed statistics, the combination results and the residuals of the individual contributions against the combined solution are regularly updated and presented on a dedicated web page (http://pnac.swisstopo.admin.ch/divers/dens_vel/index.html). More than 53000 individual values are stored in the database (status end of March 2019).

The EPN densification project is combining weekly SINEX solutions provided by European countries for their dense national active GNSS networks with the weekly EPN SINEX solutions, resulting in a cumulative position and velocity solution for more than 3300 stations (http://www.epncb.oma.be/_densification/).

Figure 1.3a.2. combined horizontal velocities from the WG on European Dense Velocities (left, http://pnac.swisstopo.admin.ch/divers/dens_vel/combvel_eu_all_cmb_basic_dh.jpg) and ETRF2000 velocities from WG on EPN Densification (http://www.epncb.oma.be/densification/coordinates/posvel_map.php).

Thanks to the inputs provided by both working groups, on European Dense Velocities and on Densification, the Deformation Modelling WG started working on the derivation of deformation models for Europe.
References:
European Terrestrial Reference System 89 (ETRS89)

The ETRS89 is intimately linked to the ITRS through a similarity transformation of 14 parameters. Consequently, for each ITRS realization (ITRFyy) a corresponding ETRS89 frame (ETRFyy) can be defined. The ITRF2014 was the occasion to propose an ETRF2014 where its origin coincides with that of ITRF2014, and therefore the seven transformation parameters are all zeros at epoch 1989.0, while their temporal rates are zeros, except the three rotation rates. The latter actually represent the three components of the Eurasian plate rotation pole in ITRF2014 (Altamimi, 2018).

The release of ITRF2014 imposed the question to the EUREF GB how to deal with the corresponding ETRS89 realization. The EUREF GB discussed three different options and solutions: a) to introduce an updated ETRS89 realization, called ETRF2014, b) to introduce ETRF2014 with an origin coinciding with the ITRF2014 origin, or c) to keep the ETRF2000 as it is. To get in advance a feedback from the user community, in 2016 EUREF Resolution No. 3 was approved to launch a questionnaire and to distribute it to the EUREF community, namely the NMAs. The feedback given by 35 replies from 29 countries to the questionnaire showed that the majority of the NMAs was in favor of keeping ETRF2000 but many countries explained reasons, which would justify an updated ETRS89 realization, e.g. crustal movement, land uplift, or inhomogeneous velocity field (Söhne et al., 2017).

The 2017 EUREF Resolution No. 1 recognizes the diverse requirements regarding national implementations of ETRS89, and respects the different countries’ decisions on adopting their preferred ETRS89 realizations (http://www.euref.eu/symposia/2017Wroclaw/06-01-Resolutions-EUREF2017.pdf).

References:
Altamimi Z. (2019) ETRS89 or ITRS and what are the user needs?, EGU2019-12673, Presented at EGU General Assembly, Vienna, Austria, April 08-12, 2019
European Vertical Reference System (EVRS)

The last realization of the European Vertical Reference System (EVRS) has been released in 2008 under the name EVRF2007. At the EUREF symposium June 2008 in Brussels, Resolution No. 3 was approved proposing to the European Commission the adoption of the EVRF2007 as the mandatory vertical reference for pan-European geo-information. EVRF2007 is based on the measurements of the Unified European Leveling Network (UELN). The datum is realized by 13 datum points distributed evenly over the stable part of Europe. The measurements have been reduced to the common epoch 2000 by applying corrections for the glacial isostatic adjustment (land uplift) in Fennoscandia, which are provided by the Nordic Geodetic Commission (NKG) under the name NKG2005LU.

In the meantime, UELN is continuously enhanced using additional or updated leveling data submitted by different countries (Fig. 1.3a.2). Since 2015, the network parts of Germany and Switzerland have been replaced by new measured leveling data. Also in 2015, the French scientific zero-order leveling network NIREF has been integrated in the UELN. NIREF was observed between 1983 and 2014 and is much more precise than IGN69 data, but not dense enough to replace completely these old data in UELN. Therefore, both networks were combined. Because of a known bias in the North-South direction the data of IGN69 were introduced with lower weights than NIREF data. The including of NIREF data in UELN allowed the first time to integrate the height difference between France and UK that had been measured through the Channel tunnel in 1994. Using the NIREF data and the tunnel measurement the computed UELN height in Dover (UK) changed by 140 mm.

In 2016, Estonia delivered new leveling data in a very high precision.

In 2017, UELN has been expanded by Belarus, which provided 1st order leveling data at the first time.

In 2018, Belgium, Italy and Slovenia delivered new measured leveling data of their countries. Furthermore, parts of the network of Czech Republic have been replaced by new measured leveling data. Moreover, the UELN could be enlarged by the leveling network of Ukraine.

Furthermore, between 2016 and 2018 some supplements or corrections were delivered by the Netherlands, Norway and Slovakia.

At the EUREF symposium in Tallinn 2019, a new realization of the EVRS was adopted. According to the EVRS definition, the EVRF2019 is in the level of Normaal Amsterdams Peil (NAP). The heights are normal heights in the zero-tide system. Unlike EVRF2007, the heights of EVRF2019 are additionally provided in the mean-tide system, in order to support users that need conformity of heights with the mean sea level, especially in the field of oceanography.
Figure 1.3a.3. Status of the United European Leveling Network (UELN)

References:
Sacher M. (2019) The European Vertical Reference System (EVRS) – development and latest results, Presented at EGU General Assembly, Vienna, Austria, April 08-12, 2019
Revision of EUREF Terms of References

During 2015 and 2016, the EUREF Terms of References (ToR) have been updated, discussed in EUREF 2015 and 2016 symposia as well as during the TWG meetings. The ToR were adopted in the EUREF 2017 symposium in Wroclaw. One visible change was the renaming of the Technical Working Group into Governing Board.

Cooperation with other organizations and international integration

GB members Z. Altamimi, C. Bruyninx, and M. Poutanen are participating to the work on the United Nations (UN) Global Geodetic Reference Frame (GGRF) and the permanent UN Subcommittee on Geodesy (SoG) within UN Committee of Experts on Management Global Geospatial Information (UN-GGIM). The implementation plan, based on the roadmap accepted in 2016, and the UN General Assembly resolution in 2015 on sustainable global geodetic reference frame, is presently under development.

M. Poutanen is chairing the UN-GGIM: Europe special expert group “GRF-Europe”. He also gave reports on EUREF activities at the meetings of the UN International Committee on Global Navigation Satellite Systems (ICG) in Boulder, USA (ICG10, 2015), Sochi, Russia (ICG11, 2016), Kyoto, Japan (ICG12, 2017) and Xi’an, China (ICG13, 2018).

The European Plate Observing System (EPOS) gathers input from geodesy, geology, seismology, volcanology, or geomagnetism to understand the complex dynamic Earth system. EPOS is approaching the end of its implementation Phase. EUREF’s activities, e.g. the EPN and its combined solutions will contribute to EPOS “GNSS Data and Products” services and, therefore, EUREF has been engaged in the preparation of the Operational Phase of EPOS, which should start in 2019-2020.

The cooperation between EUREF and the Central European GNSS Research Network (CEGRN) involves 33 Central European Countries and measurement campaigns every two years since 1996. The cooperation results in a strong support to the EUREF WGs on Densification, Dense Velocity Field and Deformation Modelling and joint publications in peer reviewed journals.

EUREF has been invited to participate to the Pan-European Ground Motion Service (EU-GMS) which is going to be established as a service using Copernicus, in particular Interferometric Synthetic Aperture Radar (InSAR) data of the Sentinel satellites of the Copernicus programme of the European Space Agency (ESA). EUREF’s contribution to the service would be to serve as a reference.

References:


Fernandes R. (and 30 co-authors) (2018) EPOS TCS GNSS, Presented at EUREF symposium, Amsterdam, The Netherlands, May 30 – June 01, 2018

Frei M. (2017) InSAR Based Ground Motion Service for Germany, Presented at EUREF symposium, Wroclaw, Poland, May 17-19, 2017


Outreach and capacity building

A dedicated EUREF-related session 2.3 “Applications and future of European references frames – (more than) 30 years of EUREF” was organized at the 2019 General Assembly of the European Geosciences Union (EGU) in Vienna. 20 presentations were given with 7 oral presentations and 13 posters

EUREF Governing Board resp. Technical Working Group meetings:

- Oct., 13, 2015, in Bern, Switzerland, hosted by AIUB (Astronomical Institute of the University of Bern)
- Feb, 29 - March, 1, 2016, in Lisbon, Portugal, hosted by IPMA (Instituto Português do Mar e Atmosfera)
- May, 23, 2016, in San Sebastian, Spain, hosted by ARANZADI (Sociedad de Ciencias Aranzadi)
- Oct., 20-21, 2016, in Vienna, Austria, hosted by BEV (Bundesamt für Eich- und Vermessungswesen)
- February, 16, 2017 in Matera, Italy, hosted by ASI/e-geos (Space Geodesy Centre)
- May, 28-29, 2018 in Amsterdam, The Netherlands, hosted by Kadaster (Nederlands Kadaster)
- Oct., 24, 2018 in Brussels, Belgium, hosted by ROB (Royal Observatory of Belgium)
- February, 12-13, 2019, in Budapest, Hungary, hosted by FÖMI (BFKH FTFF Satellite Geodetic Observatory)
- May, 20-21, 2019, in Tallinn, Estonia, hosted by MAA-AMET (Estonian Land Board)

EUREF Annual Symposia:

- May, 25-27, 2016, in San Sebastian, Spain (approx. 95 participants from 28 countries)
- May, 15-17, 2017, in Wroclaw, Poland (approx. 106 participants from 28 countries)
- May, 30-June, 01, 2018 in Amsterdam, The Netherlands (approx. 110 participants from 31 countries)
- May, 22-24, 2019 in Tallinn, Estonia
Figure 1.3a.4. Participants of EUREF annual symposium in San Sebastian (2016, top) and in Wroclaw (2017)

EUREF Analysis Workshops:
- Oct., 14-15, 2015, in Bern, Switzerland, AIUB (Astronomical Institute of the University of Bern)
- Oct., 25-26, 2017, in Brussels, Belgium, ROB (Royal Observatory of Belgium)

EUREF Tutorials:
- May, 24, 2016, “Terrestrial Reference Systems in Practice“, San Sebastian, Spain (approx. 60 participants)
- May, 16, 2017, “(Open) Real-time Infrastructure and Applications in Europe (and Beyond)“, Wroclaw, Poland (approx. 45 participants)
- May, 29, 2018, “InSAR-Geodesy and Geodetic Infrastructure“, Amsterdam, The Netherlands (approx. 50 participants)
- May, 21, 2019, “Transformations using PROJ“, Tallinn, Estonia

Publications


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

Chair: William Martinez (Colombia)
Vice-chair: Virginia Mackern (Argentina)

Introduction and structure

SIRGAS is the Geocentric Reference System for the Americas. Its definition corresponds to the International Terrestrial Reference System (ITRS) and it is realized by a regional densification of the International Terrestrial Reference Frame (ITRF). SIRGAS includes the definition and realization of a vertical reference system, based on ellipsoidal heights as geometrical component and geopotential numbers (referred to a global conventional $W_0$ value) as physical component.

SIRGAS is a member of the Sub-Commission 1.3 (Regional Reference Frames) of the Commission 1 (Reference Frames) of the IAG (International Association of Geodesy) and corresponds to a Working Group of the Cartography Commission of the PAIGH (Pan-American Institute for Geography and History). The administrative issues are managed by an Executive Committee, which depends on the Directing Council, main body of the organization. The official policies and recommendations of SIRGAS are approved and given by the Directing Council. Since this Council is composed by one representative of each member country, one of IAG and one of PAIGH, it is also in charge of communicating the SIRGAS recommendations to the national bodies responsible for the local geodetic reference systems. The scientific and technical activities are coordinated by the Working Groups in close cooperation with the Scientific Council and the representatives of IAG and PAIGH.

Figure 1.3b.1. SIRGAS structure
Members

Executive committee
William Alberto Martínez Díaz (President, Colombia)
Maria Virginia Mackern Oberti (Vicepresident, Argentina)
Víctor Cioce (SIRGAS-WI Chair, Venezuela)
Roberto Pérez Rodino (SIRGAS-WGII Chair, Uruguay)
Silvio Rogerio Correia De Freitas (SIRGAS-WGIII Chair, Brazil)

Directing council
Hermann Drewes (Representative of IAG, Germany)
Hector Carlos Rovera Di Landro (Representative of PAIGH, Uruguay)
Andres F. Zakrajsek, Juan Francisco Moirano (Argentina)
Arturo Echalar Rivera, Mario Sandoval Nava (Bolivia)
Luiz Paulo Souto Fortes; Sonia Maria Alves Costa (Brazil)
Juan Pedro Harms, Hector Parra Bravo (Chile)
Jose Ricardo Guevara Lima, Francisco Javier Mora Torres (Colombia)
Max Lobo Hernández, Álvaro Álvarez Calderón (Costa Rica)
Alejandro Jiménez Reyes, José Leandro Santos (Dominican Republic)
Ricardo Coyago Remache, Jose Luis Carrión (Ecuador)
Carlos Enrique Figueroa, Wilfredo Amaya Zelaya (El Salvador)
Óscar Cruz Ramos, Fernando Oroxan Sandoval (Guatemala)
Rene Duesbury, Hilton Cheong (Guyana)
Bruno Garayt; Alain Harmel (French Guyana)
Luis Alberto Cruz (Honduras)
Enrique Muñoz Goncen (Mexico)
Wilmer Medrano Silva, Ramón Aviles Aburto (Nicaragua)
Israel Sánchez, Javier Cornejo (Panama)
Sindulfo Miguel Colman; Joel Roque Trinidad (Paraguay)
Julio Enrique Llanos Alberca, Julio Sáenz Acuña (Peru)
Norbertino Suárez, Jose Maria Pampillón (Uruguay)
Dana J. Caccamise II, Daniel R. Roman (United State of America)
Jose Napoleón Hernández, Melvin Jesús Hoyer Romero (Venezuela)

Activities during the period 2015-2019

SIRGAS-CON GNSS network
The number of continuously operating GNSS stations included in the SIRGAS-CON network (see Figure 1.3b.2) is 395 (322 active and 73 inactive) of which 59 belong to the global International GNSS network (IGS), 339 have GPS+GLONASS capability, 79 measure on GPS+GLONASS+Galileo and 43 GPS+GLONASS+Galileo+BeiDou (see Figure 1.3b.3). For historic works, 138 removed stations may also be considered.

Nine SIRGAS Local Processing Centers compute loosely constrained weekly solutions for the SIRGAS-N national networks, which are combined with the SIRGAS-C core network to get homogeneous precision for station positions and velocities. All Analysis Centers follow unified standards for the computation of the loosely constrained solutions.

The support of the countries interested on adopting SIRGAS as official referenc frame continued. At this moment, 19 countries in the region have already adopted SIRGAS as the
official reference frame for Geodesy and Cartography. More than 50 institutions from 19 countries, including the national mapping agencies of Latin America, are committed to SIRGAS in a voluntary partnership.

SIRGAS continues its consolidation as the continental reference frame and as the basic layer of spatial data infrastructures national and regional levels.

The SIRGAS-Real Time project advances successfully: Its objectives were achieved and its support to the countries is integrated into the WGII (SIRGAS at the national level). Figure 1.3b.4 shows the SIRGAS stations that transmit data in real time in the region. These data are available from the IGS-RT caster and from national casters (Table 1.3b.1). WGI and WGII recognize the need to adjust the measurement intervals of the permanent stations to 1 second in order to provide more appropriate data for seismological and atmospheric phenomena.
Table 1.3b.1. RT Casters

<table>
<thead>
<tr>
<th>Caster</th>
<th>IP: Port</th>
<th>Web link</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIRGAS Experimental</td>
<td>200.3.123.65:2101</td>
<td><a href="http://www.fceia.unr.edu.ar/gps/mapatc/">http://www.fceia.unr.edu.ar/gps/mapatc/</a></td>
</tr>
<tr>
<td>REGNA-SGM (Ur)</td>
<td>201.217.122.178:2101</td>
<td><a href="http://www.sgm.gub.uy/">http://www.sgm.gub.uy/</a></td>
</tr>
<tr>
<td>IGS-RT</td>
<td><a href="http://www.igs-wip.net:2101">www.igs-wip.net:2101</a></td>
<td><a href="http://register.igs-ip.net/cgi-bin/registration.cgi">http://register.igs-ip.net/cgi-bin/registration.cgi</a></td>
</tr>
</tbody>
</table>

An effort has been made by the countries to increase the usage of SIRGAS products and the maintenance of its geodetic infrastructure. Work has been done in the context of the MONOLIN group (NO Lineal Movements) studying the different earthquakes that occurred in Latin America and their influence on the coordinates, thanks to the measurements at the SIRGAS_CON stations. This has allowed studying the seismic activity of the region. Particularly the work related to, or based on, the monitoring of the post-seismic deformations, lead to national frame updates and the development of the last two velocity models VEMOS2015 (Sanchez and Drewes 2016a, 2016b) and VEMOS2017 (Drewes and Sanchez 2017a, 2017b) (see Figure 1.3b.5).

SIRGAS_CON a densification of the ITRF in Latin America

To keep the SIRGAS objective of densifying the ITRF in Latin America, the weekly and multi-year solutions have been adjusted to the corresponding ITRF according to the specified standards. Therefore, the weekly SIRGAS realizations refer:

- To the IGS05 (ITRF2005) from Nov. 4, 2006 to April 16, 2011
- To the IGS08/IGb08 (ITRF2008) from April 17, 2011 to January 28, 2017
- To the IGS14 (ITRF2014) since January 29, 2017.

The artificial coordinates changes caused by the frame changes are show in Figure 1.3b.5 (ITRF2005 to ITRF2008) and Figure 1.3b.6 (ITRF2008 to ITRF2014).

Figure 1.3b.5. Jumps caused by the change of ITRF2005 to ITRF2008, in Horizontal coordinates (left) and in Vertical coordinates (right) (Sánchez, 2018), taken from www.sirgas.org.
Two SIRGAS multi-year solution, SIR15P01 and SIR17P01, have been computed.

- **SIR15P01** includes positions and velocities of 303 SIRGAS reference stations and 153 additional stations. SIR15P01 refers to the IGb08 frame, epoch 2013.0. It covered a five years period from March 14, 2010 to April 11, 2015. The normal equations between 2010-03-14 and 2011-04-17 were reprocessed using the IGS products generated during the second reprocessing of the global IGS network and applying the absolute corrections to the variations of the phase centers referred to the IGS08. The averaged RMS precision for the station positions at the reference epoch is ±0.7 mm in the north-south component, ±0.9 mm in the east-west component, and ±3.5 mm in the height. The averaged RMS precision for the station velocities is ±0.5mm/a in the north-south component, ±0.8mm/a in the east-west component, and ±1.6mm/a in the vertical component. (Sánchez and Drewes, 2016c).

- **SIR17P01** includes only weekly solutions referring to the IGS08/IGb08 and covers the time span from 2011-04-17 to 2017-01-28. SIR17P01 contains 345 stations with 504 occupations; it refers to the IGS14, epoch 2015.0 and its precision is about ±1.2 mm (horizontal) and ±2.5 mm (vertical) for the station positions and ±0.7 mm/a (horizontal) and ±1.1 mm/a (vertical) for the constant velocities. The main objective of this solution is the computation of an updated deformation model for Latin America (VEMOS). Therefore, 150 additional stations were processed and linear station motions from 2014-01-06 to 2017-01-28 were computed. This “extended” solution, called VMS17P01 (Figure 1.3b.7), was the input for VEMOS2017 (Drewes and Sánchez, 2018).
SIRGAS Vertical Reference System (SVRS)

SIRGAS continues promoting the activities related to the unified vertical datum (WGIII). Four workshops were organized to promote the development of the SIRGAS Vertical Reference System (SVRS), see section on Outreach. The coordination of these activities begun to achieve some results. Three countries adjusted their Vertical Reference Frame (VRF) in terms of geopotential numbers: Argentina, Brazil and Uruguay. Their networks represent more than 60% of first order spirit leveling points (Argentina, 18000 points; Brazil, 70000 points and Uruguay, 1500 points) in the region. However, several problems remain to be resolved. Among these: the lack of international connections among countries to form consistent loops for simultaneous adjustment; the unavailability of original leveling data in some countries; and the situation of that each VRN had been linked to a different local Vertical Datum.

Since the creation of the IAG/GGOS 0.1.2. Working Group on Strategy for the Realization of the International Height Reference System (IHRS) in 2016, SIRGAS WG III is inserted in its activities. In this context, once again, SIRGAS is involved into the most important activities of geodesy through the selection of key national stations and in the future complementary measurements for the materialization of the IHRS in the region, which has been entrusted to the National Representatives and Institutions. The main current protocols of SIRGAS regarding the SIRGAS Vertical Reference System (SVRS) are:

- It is performed by appropriate physical heights (involving gravity by geopotential numbers) \[ HP = f(\text{CP}) \];
- Connected to the geometric component of SIRGAS;
- Integration of vertical networks of member countries;
- Referred to a global reference level W0 of the IHRS / IAG;
- Associated with a specific reference period; i.e., you should consider the temporal variations of the coordinates and the network.
- Linked with a profile of GGRF stations consistent with the ITRF.
In the beginning of 2017, SIRGAS proposed a set of 22 IHRF stations distributed in the South America, Central America and Caribbean regions (Figure 1.3.b.8). Since then, SIRGAS WG III is involved in the testing of approaches for facing the realization of such stations.

Two initiatives merit emphasis: The link of Ecuadorian Vertical Datum to IHRS accomplished in 2017 linked to two experimental approaches (Carrión, 2017; Carrión et al. 2018), and the insertion of two South American research groups linked to SIRGAS in the Colorado Experiment organized by the IAG/GGOS 0.1.2. Working Group. This experiment is related to the development of the strategies for the realization of IHRS stations. The experiment considered the Molodensky approach for solving the Geodetic Boundary Value Problem (GBVP, De Freitas et al, 2018). Some provisional results related to the six Brazilian IHRF stations are now available.

**Updated velocity models in Latin America**

Two SIRGAS Velocity Models were developed:

VEMOS2015 (Sánchez and Drewes, 2016; Figure 1.3.b.9) was inferred from GNSS (GPS+GLONASS) measurements gained after the strong earthquakes occurred in 2010 in Chile and Mexico (Sánchez et al., 2013; 2016). It is based on a multi-year velocity solution for a network of 456 continuously operating GNSS stations comprising a five years period from March 14, 2010 to April 11, 2015. VEMOS2015 was computed using the least square collocation (LSC) approach with empirically determined covariance functions. It covers the region from 55°S, 110°W to 32°N, 35°W with a spatial resolution of 1°x1°. The average prediction uncertainty is ±0.6 mm/a in the north-south direction and ±1.2 mm/a in the east-west direction. The maximum is ±9 mm/a in the Maule deformation zone (Chile) while the minimum values of about ±0.1 mm/a, occur in the stable eastern part of the South American plate.
The main purpose of VEMOS2015 is to allow the translation of station positions through time. However, this model is only valid for the time period 2010-2015. For the translation of station positions before the 2010 earthquakes, the model VEMOS2009 (Drewes and Heidbach, 2012) should be used and April 11, 2015, the model VEMOS2017 (Drewes and Sánchez, 2017) should be used. Although VEMOS2015 includes GNSS observations over five years, some regions were affected by further earthquakes and their effects are not included in VEMOS2015. VEMOS2015 is available at:

https://doi.pangaea.de/10.1594/PANGAEA.863132.

Figure 1.3b.9. Surface kinematics VEMOS2015 (Sánchez and Drewes, 2016)

VEMOS2017 (Drewes and Sánchez, 2017; see Figure 1.3.b.10) was inferred from GNSS (GPS+GLONASS). It is based on a multi-year velocity solution for a network of 495 continuously operating GNSS stations comprising a five years period from April 17, 2011 to January 28, 2017. VEMOS2017 was computed using LSC. The average prediction uncertainty is ±0.7 mm/a (horizontal) and ±1.1 mm/a (vertical) (Drewes and Sánchez, 2018).
(Drewes, 2017) made an exhaustive analysis of the varying surface kinematics in Latin America: VEMOS 2009, 2015, and 2017 (Figure 1.3.b.11 and Figure 1.3.b.12) and showed that it is necessary to update this model regularly. In forthcoming activities, we shall improve the distribution of the continuously operating GNSS stations, especially along the boundaries between the different tectonic plates. In the analysis of the station position time series, we want to consider possible surface loading and local effects to improve the reliability of the estimated velocities. There are perform detailed studies about the temporal-spatial evolution of the deformation field in the SIRGAS region.
Atmospheric monitoring

The integrated water vapor (IWV) was retrieved from the ZTD in each SIRGAS-CON station. From the tropospheric zenith delays obtained in the processing of the SIRGAS-CON network, the integrated tropospheric water vapor was calculated applying the strategy described by Calori (2016) in the 400 GNSS stations of SIRGAS. The time series of this variable have been generated for the period 2014 to 2018, and IWV average (Figure 1.3.b.13), maximum and minimum values for each station have been calculated (Camisay et al, 2018, Mateo et al, 2018 and Granados et al, 2018). The process of mapping this variable is being developed. These were estimated from the Analysis Centre for the Neutral atmosphere, CIMA (Centro de Ingenieria Mendoza Argentina).
25 years of SIRGAS

In 2018, the geodetic community of Latin America has celebrated together with SIRGAS, the 25 years since that important Asunción meeting of 1993 (Figure 1.3b.14). During this session, an account was made of the main achievements of SIRGAS in these 25 years and a tribute was celebrated to the referring geodesists that have accompanied SIRGAS during its trajectory (Figure 1.3b.15).

On this context, during the meeting of the Directing Council, held on Oct. 11 2018, by Resolution, SIRGAS granted the distinction of Honorary President of SIRGAS to Prof. Dr. Hermann Drewes as public proof of admiration, respect and gratitude for being the Father Founder of SIRGAS and for his 25 years of uninterrupted support (Figure 1.3b.16)

Cooperation with other organizations and international integration

SIRGAS is a member of Sub-Commission 1.3 (Regional Reference Frames) of the Commission 1 (Reference Frames) of the IAG (International Association of Geodesy) and also corresponds to a Working Group of the Cartography Commission of the PAIGH. SIRGAS has remained active in the United Nations (UN) GGRF Sub-Committee and will continue participating in the corresponding working groups. Representatives of the executive committee of SIRGAS have participated in the UN-GGIM Americas events and have endorsed the appointment of referents of the region in the Subcommittee of the World Reference Geodetic Framework of the (GGRF - UN-GGIM). In the SIRGAS events,
particular emphasis has been placed on the implementation of the Join Action Plan signed with PAIGH, UN-GGIM: Americas and GEoSUR for the advance of the regional spatial data infrastructure.

**Outreach and capacity building**

During the period 2015-2019, SIRGAS organized the following meetings:

**SIRGAS symposiums:**

Four annual SIRGAS symposiums were organized with the support of the IAG and the PAIGH. The principal topics presented were: SIRGAS advances and new challenges; maintenance and new perspectives for the continental reference frame; detection and evaluation of geodynamic effects on the reference frame; reports of the analysis and combination centers; progress in the implementation and maintenance of national frameworks; SIRGAS in real time; aspects of the practical application of SIRGAS products; geodetic estimation of geophysical parameters; advances in SIRGAS Unified Vertical Reference System; gravimetry and geoid; geodetic analysis of the Earth's crust deformation; atmosphere studies based on the SIRGAS infrastructure; other geodetic techniques in SIRGAS and various working group reports. Presentations in: http://www.sirgas.org/en/sirgas-symposia/

- **SIRGAS2015**, Nov. 18 to 20, 2015, Santo Domingo, Dominican Republic: 148 participants (Figure 1.3.b.17) from 19 countries; 54 oral presentations and 15 posters. Prior to the Symposium (Nov. 16 and 17), a new edition of the SIRGAS School on Reference Systems was held. Both events were hosted by the Universidad Nacional Pedro Henríquez Ureña (UNPHU). They were also supported by the project “Monitoring crustal deformation and the ionosphere by GPS in the Caribbean” granted by the IUGG in agreement with the International Association of Seismology and Physics of the Earth's Interior (IASPEI) and the International Association of Geomagnetism and Aeronomy (IAGA).

  ![Figure 1.3b.17. Symposium SIRGAS2015](image)

- **SIRGAS2016**, Nov. 16-18, 2016, Quito, Ecuador: 217 participants (Figure 1.3b.18), from 14 countries; 56 oral presentations and 12 posters; hosted by the Instituto Geográfico Militar of Ecuador.
Figure 1.3b.18. Symposium SIRGAS2016

• SIRGAS2017, Nov. 27-30, 2017, Mendoza, Argentina: 128 participants (Figure 1.3b.19) from 16 countries; 51 oral presentations and 18 posters; organized by the Universidad Nacional de Cuyo and the Universidad Juan Agustín Maza.


Figure 1.3b.19. Symposium SIRGAS2017, Mendoza, Argentina, 2017

• SIRGAS2018, Oct. 9-12, 2018, Aguascalientes, Mexico: 97 participants (Figure 1.3b.20) from 21 countries; 43 oral presentations and 13 posters; organized by the Instituto Nacional de Estadística y Geografía (INEGI) of Mexico.
The symposium included a session “Tribute for the 25 years of SIRGAS” and five invited presentations: “Challenges to be faced by Geodesy in the coming years from the perspective of the IAG” (H. Drewes), “Strategy for the establishment of the IHRS” (L. Sanchez), “The development of SIRGAS over 25 years and prospective challenges of science and humanity” (H. Drewes), and “Participation and geodetic development of Latin American countries during the 25 years of the SIRGAS project and SIRGAS in future time” (M. Hoyer).

In the frame of this symposium, two additional activities were programmed: A “Conversation SIRGAS in practice” on Oct. 7 (5 presentations) and a workshop about Vertical Datum from Oct. 15 to 17, 2018.
Training events:

- The SIRGAS School 2015, Nov. 18-19, 2015, Santo Domingo, Dominican Republic: 60 participants from 19 countries.
  The subject of the school concentrated on strengthening the basic concepts needed for the appropriate generation and use of fundamental geodetic and geophysical data in the Caribbean Region, especially for studying, understanding and modelling deformations of the Earth's surface and features of the ionosphere, and its influence on navigation systems used for civil aviation.

- Four Workshops in Vertical Reference SIRGAS System focussed on the unification of the National Vertical Networks in the region of SIRGAS in order to realize a continental adjustment by means of processing and adjustment of geopotential numbers. The processing and adjustment of gravimetric and leveling data corresponding to the national vertical networks were also considered. Sílvio R.C. de Freitas (Brasil), Chair of SIRGAS WG III, coordinated the Workshops. The basis of data processing was a software package developed by H. Drewes and L. Sánchez. Preliminary analyses of the consistency of national networks was done by using a software package developed by R. Teixeira Luz (Brazil). All of them acted as instructors in some Workshops.
  - o 3rd WGIII Workshop 2015, May 18-22, 2015, Curitiba, Brazil: 29 participants (Figure 1.3.b.21) from 10 countries. The workshop included five nine-hour sessions with theoretical classes and practical exercises.
  - o 4th WGIII Workshop 2016, Nov. 21-25, 2016, Quito, Ecuador: 45 participants (Figure 1.3.b.22) from 10 countries
o 5th WGIII Workshop 2017, Nov. 6-10, 2017, Heredia, Costa Rica: 33 participants (Figure 1.3.b.23) from 5 countries

o 6th WGIII Workshop 2018, Oct. 15-17, 2018, Aguascalientes, Mexico: 33 participants (Figure 1.3.b.24) from 12 countries. On this occasion, issues related to the unification of the vertical datum for the SIRGAS member countries were developed again, such as the guidelines and actions for the materialization of the IHRS. Classes were taught with theoretical foundations and practical tasks were developed with data provided by the countries attending the workshop.

• The SIRGAS Workshop on Real Time GNSS positioning, Nov. 22-24, 2017, Mendoza, Argentina; 50 participants (Figure 1.3.b.25) from 12 countries. The main objective was to follow up on the activities developed during the SIRGAS RT Workshop held in 2012 with the aim of promoting the use of the available capacity of SIRGAS and analyzing the possibilities of offering services in this context to the Latin American and international geodesic community. It was organized as an activity of the SIRGAS Working Group II “SIRGAS at national level”. The main topics were: Real-time...
positioning systems and techniques (RTK, NetRTK, PPP), national real-time infrastructures, caster and real-time stream management, NTRIP and associated software (BNC, RTKLib, etc.), theoretical foundations of the European project AUDITOR (Improved GNSS ground-based augmentation system for precision agriculture services) with emphasis on the generation of reliable ionosphere products for the calculation of real-time corrections. Three practical exercises were developed: one for real-time measurements in the field and two for connectivity, configuration, and calculation in the cabinet.

**Figure 1.3b.25.** SIRGAS Workshop in RT positioning 2017, Mendoza, Argentina.

- The SIRGAS Workshop on SLR in Latin America, Nov. 30-Dec. 1, 2017, Mendoza, Argentina: 43 participants from 10 countries. The main objective of the workshop was to evaluate the possibility of extending the SIRGAS reference frame by means of SLR stations to improve the geocentric realization of the regional frame. Representatives of the four SLR observatories installed in South America (Arequipa, AGGO, Brasilia and San Juan) reported about the status and future improvements at the different stations. B. Sierk of the European Spatial Agency (ESA) presented the ESA plans related to new SLR developments and applications. D. Thaller (Bundesamt für Kartographie und Geodäsie, Germany) provided an overview about the SLR dataflow and analysis performed within the International Laser Ranging Service (ILRS) and outlined some recommendations to start SLR data processing experiments within SIRGAS. Following these recommendations, the next activity is to prepare and distribute an input data set to be processed by the different groups installed in Argentina, Brazil, Peru and Costa Rica. Results of this experiment will be discussed during the next SIRGAS symposium in 2019.

**Figure 1.3b.26.** SIRGAS Workshop on SLR in Latin America 2017, Mendoza, Argentina

- Two training courses in processing GNSS observations:
  - “Processing with Bernese 5.2”, July 17-20, 2018, Universidad de Santiago de Chile,
Santiago, Chile (Figure 1.3b.27)

- “Processing with Gami”, Sept. 3-8, 2018 Instituto Geográfico Nacional de Argentina, Buenos Aires, Argentina; 27 participants (Figure 1.3b.28) from 8 countries

Figure 1.3b.27. Training course, Santiago, Chile

Figure 1.3b.28. Training course, Buenos Aires, Argentina

SIRGAS participated to the following international conferences:


• Actual Continuous Kinematic Model (ACKIM) of the Earth’s Crust based on ITRF2014. H. Drewes. In: Joint Scientific Assembly of the International Association of...

• Differential coordinate changes (velocities) vs. coordinate differences (epoch coordinates) for realising the time dependency of the ITRF. H. Drewes. In: Joint Scientific Assembly of the International Association of Geodesy and the International Association of Seismology and Physics of the Earth’s Interior (IAG-IASPEI 2017). Kobe, Japan. July 31 - Aug. 4, 2017.


Publications


Sánchez, Laura; Drewes, Hermann (2016c): SIR15P01: Multiyear solution for the SIRGAS Reference Frame, https://doi.org/10.1594/PANGAEA.862536,

Sub-Commission 1.3c: North America (NAREF)

Co-Chairs: Michael Craymer (Canada), Dan Roman (USA)

Introduction and structure

The objective of this sub-commission is to provide international focus and cooperation for issues involving the horizontal, vertical, and three-dimensional geodetic control networks of North America, including Central America, the Caribbean and Greenland (Denmark).

The regional sub-commission is co-chaired by representatives from the Canadian Geodetic Survey and the U.S. National Geodetic Survey, currently Dr. Michael Craymer and Dr. Dan Roman, respectively.

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

- SC1.3c-WG1: North American Reference Frame (NAREF)
- SC1.3c-WG2: Plate-Fixed North American Reference Frame
- SC1.3c-WG3: Reference Frame Transformations

The following summarizes the activities of each working group, followed by a report of other reference frame activities in Canada and the U.S., during the period 2015-2019. For more information and publications related to the working groups, see the regional Sub-Commission web site at http://www.naref.org/.

Note: the acronyms “NAD83” (as used in Canada) and “NAD 83” (as used in the U.S.) will be used interchangeably throughout this report.

Members

The membership of SC1.3c consists primarily of representatives from the national geodetic agencies in North America with additional members from other government agencies and academia as needed for specific working groups. The following is a list of members organized by agency affiliation.

Michael Craymer (Co-Chair, Canada)
Dan Roman (Co-Chair, U.S.A.)
Remi Ferland (Canada)
Joseph Henton (Canada)
Mike Piraszewski (Canada)
Finn Bo Madsen (Denmark)
Kevin Choi (U.S.A.)
Theresa Damiani (U.S.A.)
Dru Smith (U.S.A.)
Mike Bevis (U.S.A.)
Geoff Blewitt (U.S.A.)
Jeff Freymueller (U.S.A.)
Tom Herring (U.S.A.)
Corné Kreemer (U.S.A.)
Richard Snay (U.S.A.)
Activities during the period 2015-2017

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

The objective of this working group is to densify the ITRF and IGS global networks in the North American region by organizing the computation of weekly coordinate solutions and associated accuracy information for continuously operating GPS stations that are not part of the current IGS global network.

Originally, the regional densification of the ITRF and IGS network consisted of on-going weekly combinations of several different regional weekly solutions across the entire North American continent using different GPS processing software. However, no weekly combinations have been generated since GPS week 1583 due to the large number of stations. Since that time, the Canadian Geodetic Survey (CGS) and Mexico’s Instituto Nacional de Estadística y Geografía (INEGI) have continued to generate weekly solutions in the current IGS reference frame for their own regions. The U.S. National Geodetic Survey (NGS) has continued computing and archiving weekly solutions after GPS week 1631 but they are not currently aligned to the ITRF or IGS reference frames. After NGS has completed their “repro2” reprocessing of all their CORS data, these and future weekly solutions will be aligned to ITRF2014.

CGS completed a repro2 reprocessing in 2016 of data since 2000 for nearly 200 federal and provincial public GNSS tracking stations across Canada as well as over 250 high accuracy campaign stations and nearly 600 U.S. CORS in the northern conterminous U.S., eastern Alaska and GNet stations in Greenland (Ferland et al., 2016; Craymer, 2017; Craymer et al., 2018). This reprocessing used the Bernese GNSS Software v5.2 with CODE repro2 products in the IGb08 reference frame due to the unavailability of combined IGS repro2 orbits at the time. On-going processing of current weeks are aligned to the IGS reference frame of date, currently IGS14. These solutions include many new permanent GNSS stations in strategic locations targeted to improve coverage of GIA across the northern parts of Canada and the monitoring of tectonic deformation of the west coast.

CGS has also completed the combination of all weekly solutions since 2000 into a multi-year cumulative solution that is aligned to IGS14 and updated monthly (see Figure 1.3c.1). These cumulative solutions are based on newly developed SINEX combination software that allows for the estimation of coordinates, velocities, annual and semi-annual terms for seasonal signals, exponential and logarithmic terms for post-seismic deformation, together with position and velocity discontinuities. In addition to solutions for public GNSS tracking stations, CGS has been computing weekly coordinate solutions and monthly updated multi-year cumulative solutions for nearly 900 Canadian commercial RTN base stations in support of compliance agreements between the federal government and commercial RTN service providers (see Other Activities below). CGS is presently investigating the suitability of these RTN stations to densify sparse regions of the public network for improved modelling of crustal dynamics.

NGS also began “repro2” reprocessing of their entire NOAA CORS Network (NCN) in 2017. The processing includes data spanning 1996 to 2016 (weeks 0834 to 1933), a total of 1100 weeks or 21 years, and includes about 3050 CORS, IGS and other (e.g., NGA) stations across the conterminous U.S., Alaska, Hawaii, American Samoa, Guam, the Northern Mariana Islands, Puerto Rico, the U.S. Virgin Islands, and a handful of non-U.S. locations. The reprocessing used IGS repro2 orbits and is presently available online for user testing. The final weekly solutions are set to be released for production use in the summer of 2019.
Weekly solutions up to week 1933 will be combined into a multi-year cumulative solution, a preliminary version of which is given in Figure 1.3c.2.

**Figure 1.3c.1.** Horizontal (left) and vertical (right) velocities from Canadian multiyear cumulative solution transformed to NAD83(CSRS) using weekly solutions to GPS week 1929. Vertical velocity vectors in red represent uplift while those in blue represent subsidence.

**Figure 1.3c.2.** Horizontal (left) and vertical (right) velocities in ITRF2014 from a preliminary multi-year cumulative solution of “repro2” weekly solutions to GPS week 1933. In the vertical plot, warm colors represent uplift and cool colors represent subsidence.

**SC1.3c-WG2: Plate-Fixed North American Reference Frame**

The objective of this working group is to establish a high-accuracy, geocentric reference frame, including velocity models, procedures and transformations, tied to the stable part of the North American tectonic plate which would replace the existing, non-geocentric North American Datum of 1983 (NAD 83) reference system and serve the broad scientific and geomatics communities by providing a consistent, mm-accuracy, stable reference with which scientific and geomatics results (e.g., positioning in tectonically active areas) can be produced and compared. In addition, similar plate-fixed reference frames will be established for U.S. states and territories on other tectonic plates in the Caribbean and Pacific regions.

Although NAD 83 was the best realization of a geocentric reference frame at the time it was introduced in 1986, it is now well known that it is offset from the actual geocentre (and thus ITRF) by about 2 meters. There is also a residual rotation with respect to North American tectonic plate of about 2 mm/yr at mid latitudes due to an inconsistency in the definition of the transformation from ITRF that now defines NAD 83. These problems make NAD 83 incompatible with modern geocentric reference frames used internationally and by all GNSS positioning systems. Consequently, the U.S. has been making plans to replace NAD 83 in 2022, along with its vertical datum, with a high accuracy geocentric reference frame called the North American Terrestrial Reference Frame of 2022 (NATRF2022). This high accuracy
geocentric reference frame will be based on the latest ITRF realization at a specific epoch and fixed to the North American plate. Discussions are also underway in Canada to adopt the same frame sometime after 2022. Regardless whether or not the new frame is officially adopted, the Canadian Geodetic Survey will make coordinates and velocities available in both NAD83(CSRS) and the new frame and provide a transformation between the two.

The new reference frame will be defined by aligning it exactly with the latest realization of ITRF at an adopted reference epoch of 2020.0. It will then be kept aligned to the North American tectonic plate through an estimated Euler pole rotation. Discussions are presently underway on the selection of a set of reference frame stations representing stable North America and on the method of estimating an Euler pole rotation that either best represents the motion of the North American tectonic plate or that minimizes motions of stations outside the plate boundary zone. Investigations are also being made into methods of computing the Euler pole rotation, including a novel, robust approach developed by Kreemer et al. (2017). Remaining intra-frame motions will be modelled for propagating coordinates between epochs.

In addition to defining a new regional reference frame for North America, the U.S. is also planning to define similar plate-fixed frames for the Caribbean and its territories on the Pacific and Mariana plates. The following names have been adopted for these reference frame:

- North American Terrestrial Reference Frame of 2022 (NATRF2022)
- Caribbean Terrestrial Reference Frame of 2022 (CATRF2022)
- Mariana Terrestrial Reference Frame of 2022 (MATRF2022)
- Pacific Terrestrial Reference Frame of 2022 (PATRF2022)

SC1.3c-WG3: Reference frame transformations in North America

The objective of this working group is to determine consistent relationships between international, regional and national reference frames in North America, to maintain (update) these relationships as needed, and to provide tools for implementing these relationships.

This work primarily involves maintaining the officially adopted relationship between ITRF and NAD83 in Canada and the U.S. The NAD83 reference frame was re-defined in 1998 as a 7-parameter Helmert transformation from ITRF96 at epoch 1997.0. (Craymer et al., 2000) Transformations from/to other subsequent versions of ITRF are obtained by updating the NAD83-ITRF transformation with the official incremental time-dependent transformations between ITRF versions as published by the IERS (Soler and Snay, 2004). The NAD83-ITRF transformation was most recently updated to ITRF2014 in January 2017 just prior to adoption of ITRF2014 by the IGS. The updated transformation has been implemented in transformation software at the Canadian Geodetic Survey and U.S. National Geodetic Survey.

To enable the propagation of coordinates between the various epochs adopted by different jurisdictions in Canada and the U.S., a new velocity model and transformation software was developed by Snay et al. (2016) for North America. The model integrates velocity fields from various sources to provide North American coverage. The resulting interpolation grid of velocities has been implemented in TRANS4D, an update to the HTDP software that models and predicts horizontal motion for the U.S.

More recently, Canada has developed its own national velocity model that incorporates a GIA model to better predict vertical crustal motions in the central and northern regions where GNSS stations are sparse (Robin et al, 2016, 2017a,b). The model uses the latest Canadian
cumulative solution discussed in SC1.3c-WG1 together with a blending of the ICE-6G and LAUR16 GIA models. The blended GIA model was effectively distorted to fit the GPS velocities thereby providing a more reliable velocity interpolation grid for GIA areas with sparse GNSS coverage. Figure 1.3c.3 illustrates the resulting vertical velocity grid in the NAD83(CSRS) reference frame.

Figure 1.3c.3. Canadian vertical velocity model in NAD83(CSRS) (left) obtained from an integration of GNSS velocities with a GIA model. Velocity model uncertainties (right) indicate areas for improvement

Other activities

NGS is creating a new high-level network of 36 highly stable, highly reliable GNSS tracking stations across the country at a spacing of approximately 800 km that will be contributed to the IGS and ITRF (see Figure 1.3c.4). These 36 stations include a minimum of 3 stations on each tectonic plate upon which the U.S. has significant populations (North American, Pacific, Caribbean, and Mariana) to enable computation of an Euler pole rotation (see SC1.3c-WG2). Unlike most of the other stations in the NCN, these sites will be operated by the U.S. National Geodetic Survey (either through direct ownership or MOU’s with other federal agencies) and will be built and operated to IGS standards. Referred to as the NOAA Foundation CORS Network (NFCN), this network is a subset of the larger NCN and will provide a more stable foundation for the reference frame in the U.S. Thirteen of these GNSS stations are already collocated with other techniques such as VLBI and SLR in order to create true GGOS stations. Another nine new collocated stations will be built at other GGOS sites lacking GNSS. The first of these sites was installed in Miami in late 2014 and the others will be built approximately two per fiscal year beginning the winter of 2019. When the project is completed, all NFCN stations will be fully GNSS capable, will support RINEX3, and will have local surveys ties between the different techniques performed to IERS standards about once every 5 years.

CGS has also been working towards a major enhancement of their geodetic infrastructure similar to that implemented in Australia (see Figure 1.3c.5). The primary objective of the so-called PNT initiative is to densify the existing CORS network with many more real-time stations in partnership with industry and the provincial governments, and at least one multi-technique GGOS station. The resiliency of the network would be improved through redundancy and integrity monitoring. More consideration will also be given to non-geodetic
uses of the GNSS data, such as meteorology. Although still in the proposal stage, it has received much support.

Figure 1.3c.4. Planned Foundation CORS network showing stations collocated with other techniques, densification stations, stations for Euler pole determination and other addition stations. Two additional stations on the Caribbean plate are yet to be determined.

Figure 1.3c.5. Current CORS station distribution in Canada (left) and proposed PNT densification (right).

Commercial real-time kinematic network (RTN) services and their networks of base stations have grown significantly over the years. They are effectively providing access to the NAD83 reference frame for many users independent of the public government networks in both Canada and the U.S. Because these networks are not always integrated into the same realization of NAD83, CGS began a program of validating the coordinates of these services to ensure they are properly integrated into the NAD83(CSRS) reference frame. CGS is now providing on-going, monthly-updated multi-year cumulative solutions for 6 of the largest commercial RTN services in Canada; a total of nearly 900 stations (see Figure 1.3c.6). Compliance agreements have signed with the five largest services where they have committed...
to using coordinates for their base stations that are generated in a consistent way by CGS. This ensures those RTN services are integrated into the latest realization of NAD83(CSRS). CGS is also monitoring the stability of RTN stations through time series of weekly coordinate solutions published on CGS’s public website.

NGS is also committed to developing an RTN Alignment Service (RAS) for RTN operators and users in the U.S. that will ensure RTN coordinates are consistent with the National Spatial Reference System (NSRS). This is intended to be a two-step procedure by first quantifying the alignment of base stations and then quantifying the alignment of rover positions relative to the NSRS.

![Figure 1.3c.6. Distribution of the six largest commercial RTK networks in Canada (blue dots) in relation to public federal and provincial networks of permanent GNSS stations (red dots). The commercial RTN stations significantly densify the public network in the Prairies.](image)

**Cooperation with other organizations and international integration**

There has been much international coordination between NAREF and other groups. In particular, NAREF is looking to foster closer cooperation and collaboration with the SIRGAS Sub-Commission 1.3b for South and Central America. To this end, the U.S. has become a member of SIRGAS and has participated in recent meetings.

Members of NAREF participated as members in both the UN-GGIM Americas regional committee and the SIRGAS Sub-Committee 1.3c. UN-GGIM-Americas focuses on the regional implementation of the GGRF for all of the Americas. SIRGAS was originally tasked with this implementation for the Americas. However, it is no longer clear how this governance will be handled since the creation of the UN-GGIM Sub-Committee on Geodesy, which now has the responsibility for implementing the GGRF. Regardless, SIRGAS has been briefed on NAREF activities and plans to ensure coordination in any implementation of the GGRF. At the urging of NAREF members and others, UN-GGIM-Americas is also developing a new Working Group 4 on Geodetic Reference Frames to balance the scientific input and requirements of SIRGAS countries with those of the other Member States in the
Americas. The WG4 will act as the liaison for the UN-SCoG within the UN-GGIM Americas regional committee.

Members of NAREF have also been contributing to the UN-GGIM Sub-Committee on Geodesy (SCoG) and its working groups. NGS and CGS are members of the SCoG while M. Craymer has been chairing the Working Group on Data Sharing, Standards and Conventions.

Related to the SCoG standards working group are NAREF contributions to the development of ISO standards and the ISO Geodetic Registry. The Registry is an authoritative collection of definitions of international reference frames and the transformations between them, similar to the privately run EPSG registry. Both CGS and NGS have made a significant effort to populate the Registry with all current and historical reference frame realizations used in Canada and the U.S. along with the many transformations among them. The Control Body that approves and facilitates the entry of data into the Registry is presently chaired on behalf of the IAG by M. Craymer (Canada) and L. Hothem (U.S.). Under their leadership, registry software has been developed and implemented by Ribose Group. The Registry is available at the following link: http://registry.isotc211.org

**Outreach and capacity building**

SC1.3c-WG1: North American Reference Frame:
Meetings of the working group were held on an ad hoc basis in 2015, 2016 and 2018 during the AGU Fall Meetings in San Francisco and Washington. A status report on the activities of WG activities was presented during the References Frames for Applications of Geosciences (REFAG2018) symposium held concurrently with the 2018 COSPAR Scientific Assembly.

The weekly coordinate and annual cumulative coordinate/velocity solutions are available from the NAREF website at http://www.naref.org/

SC1.3c-WG2: Plate-Fixed North American Reference Frame:
A variety of well organized outreach and capacity building efforts by NGS to support the implementation of the new North American reference frame has been underway in the U.S. since 2010. A “New Datums” website has been created to inform the public and provide supporting material to education users on the definition and use of the new NATRF2022 reference frame.

The definition, implementation and use of NATRF2022 and the accompanying new vertical datum NAPGD2022 have been published in the following three “blueprint” documents:

- Blueprint for 2022, Part 1: Geometric Coordinates
- Blueprint for 2022, Part 2: Geopotential Coordinates
- Blueprint for 2022, Part 3: Working in the Modernized NSRS

There have also been informative discussions with the public during four Federal Geospatial Summits organized by the NGS in 2010, 2015, 2017 and 2019. These well-attended meetings informed the public about the new reference systems, the status of their implementation, and solicited valuable feedback. To ensure the public kept up to date with progress on the implementation of NATRF2022 and NAPGD2022, NGS has published regular NSRS Modernization Newsletters at a rate of about 3 to 4 every year since 2015. The Blueprint documents and presentations and video recordings from the Summits are available online from the NGS website at http://www.ngs.noaa.gov/datums/newdatums/.
Scientific meetings and workshops have also been organized to address the significant scientific and practical challenges of realizing these regional reference frames, including the definition, maintenance and future evolution of plate-fixed regional reference frames for North America; the effects and modelling of crustal motions, including glacial isostatic adjustment and tectonic motions along plate boundaries on the western coast of North America and in the Caribbean; and standards needed for accurate geodetic positioning in time-dependent reference frames. The following sessions and workshops were organized to discuss these issues included:

- 2016 AGU Fall Meeting, San Francisco, Dec. 12-16; Session: Scientific and practical challenges of replacing NAD 83, NAVD 88 and IGLD 85
- 2018 Joint Meeting of CGU, CSSS, CIG, ES-SSA and CSAFM Niagara Falls, ON, June 10-14; Session: Further Evolution of North American Reference Frames
- North American Reference Frame Workshop, 2018 Joint Meeting of CGU, CSSS, CIG, ES-SSA and CSAFM Niagara Falls, ON, June 14
- 2018 AGU Fall Meeting, Washington, DC, Dec. 12-16; Session: Modernizing Regional Reference Frames and Vertical Datums for North America

For other outreach efforts, see the list of publications and presentations.

**Publications and presentations**


Additional references

Sub-Commission 1.3d: Africa

Chair: Elifuraha Saria (Tanzania)

Introduction and Structure

The African Geodetic Reference Frame (AFREF) was conceived as a unified geodetic reference frame for all 54 countries in Africa, fully consistent and homogeneous with current International Terrestrial Reference Frame (ITRF). AFREF will be the fundamental basis for the national and regional three-dimensional reference networks to make it easier to coordinate planning and development activities within the 54 countries in Africa and across national boundaries.

The major goal of Sub-Commission 1.3d is to establish a permanent GNSS network of base stations in support of an effort to unify the reference frames in Africa. The project has been under the support of the United Nations Committee for Development Information, Science and Technology (CODIST) with the following objectives:

- Define the continental reference system of Africa. Establish and maintain a unified geodetic reference network as the fundamental basis for the national 3-D reference networks fully consistent and homogeneous with the global reference frame of the ITRF;
- Establish continuous, permanent GPS stations such that each nation or each user has free access to, and is at most 500km from, such stations;
- Determine the relationship between the existing national reference frames and the ITRF to preserve legacy information based on existing frames;
- Realize a unified vertical datum;
- Provide a sustainable development environment for technology transfer, so that these activities will enhance the national networks, and numerous applications, with readily available technology and assist in establishing in-country expertise for implementation, operations, processing and analyses of modern geodetic techniques, primarily GPS;
- Sensitize African countries to the aims and objectives of AFREF.

In pursuance of these objectives, sparse continuous operating reference stations (CORS) GNSS networks have been established in Africa, and managed by some member States, IGS and other partners conducting research in Africa.

Members and Steering Committee

The organizational structure of the AFREF Steering Committee was decided during the 2nd AFREF WG meeting which was held from 20-24 Nov. 2017 in the United Nation Economic Commission for Africa (UNECA). The meeting was attended by about twenty-five experts in the geospatial field from Africa and other parts of the world. The structure is yet to be finalized and the names will be submitted once the document is approved. The structure is as shown in Fig. 1.3d.1.
**Activities and publications during the period 2015-2019**

**Data and GNSS network**

Various institutions, governmental agencies, organizations, and research projects installed permanent GNSS sites in Africa for various purposes including tectonic or volcano deformation, meteorology and ionosphere monitoring, as well as survey and mapping. A number of National Mapping Authorities has also established CORS networks in their countries. The AFREF Operational Data Centre (ODC, afrefdata.org) is archiving subsets of all these GNSS networks with an average of 40 sites each day. There are also other portals that have African data, however they have fewer data than the ODC. These include data-out.unavco.org, cddis.gsfc.nasa.gov, geoid.hartrao.ac.za, and www.station-gps.cea.com.eg. In addition, there are number of CORS whose data are not available online, but kept in individual countries. These data are shared through personnel communications.

A recent study on Africa investigated the rigidity of Nubia by dividing it in three sections and comparing the Euler pole obtained when using sites located in each section, or when using the whole set of Nubian stations (Njoroje, 2015). The results show discrepancy of at most 1 degree. However, it is too early to draw firm conclusions since almost 80% of Nubia has no GNSS data.
A second recent study investigated the optimal locations of new AFREF stations based on the criteria in the AFREF objectives (Muzondo et al., 2015). This study also documented the freely available GNSS stations as of 2015 for each country in Africa, where South Africa and Nigeria contributes the most data in the region (Figure 1.3d.3).

Although progress in increasing the number of GNSS stations in Africa has been slow, it has a positive trend, since the available GNSS stations are ranging now between 70 – 85 compared to 65 – 70 in 2016. Despite this increase, the lack of adequate funding and maintenance has affected some of the GNSS sites and reduced their capability to acquire data and provide these data to the ODC. Africa is thought to have more GNSS sites to complement the freely available GNSS sites, but, as already mentioned, some African countries do not share data, thereby making it difficult when it comes to AFREF solution computations. AFREF is expecting that through upcoming meetings, we may have representatives from those countries that may facilitate data sharing. Figure 1.3d.4 shows the current distribution of freely available GNSS stations that contribute to AFREF.
Figure 1.3d.4. GNSS CORS with freely available data operating in Africa as of 2017. Red dots show the active GNSS sites and white dots show the inactive GNSS sites (their data are still being used). The lack of freely available CORS data in the area from Angola through Central Africa, Sudan and Sahara and North African countries remains a concern.

Reference frame solution

Most of the GNSS CORS stations in Africa are used to generate AFREF solution. Some of these data were processed by 5 analysis centers to produce AFREF static solution in 2012 – 2013. The solution was expected to be published, however it is not yet. AFREF plans to produce a combined AFREF solution which will include both a static solution and velocity solution only for GNSS sites that are publicly available. AFREF expects to write to all analysis centers to ask them to produce weekly solutions since 1996 to 2019. The plan is to ask IGN France to do the combination, or do the combination in one of the analysis centers. The analysis centers will be identified after the call for participation, which will be released early 2020.

AFREF meeting and Establishment of Africa Geodetic Commission (AGC)

The United Nations Economic Commission for Africa (UNECA) prepared a workshop of the UN expert group on the GGRF between 20 – 24 Nov. 2017 at Addis Ababa, Ethiopia. The unification and modernization of the current national reference frames aiming at creating a uniform geodetic reference for Africa has been included in ECA’s annual work plan. The main aim of the workshop was to enhance regional and national expertise for implementation, operations, processing, and analyses of modern geodetic techniques, and discuss the future development of the AFREF initiative. Particularly the workshop aimed at

• Provide updates on the status and on-going activities of the AFREF Project.
• Review of the project objectives and milestones and come up with tasks for the future of AFREF
Discussions and formalization of coordination arrangements between the various partners and stakeholders.

Contribute to develop technical capacity in Africa for the successful implementation of AFREF.

The meeting agenda comprised a review of the available computations, the development of guidelines for the computation of independent solutions and the combined AFREF velocity fields, and the African Geoid Model. The meeting also discussed the Development of an Action Plan for Revamping AFREF Programme’s Coordinating Arrangement, Operational Protocol, Resources Mobilization and Global Partnership, as well as the development of the Africa Geodetic Commission (AGC). The AGC responds to the need of African geodesists and geophysicists to have an organ to manage, monitor, and disseminate their views. It has been a culture for African geodesists and geophysicists to meet in other meetings that are organized by other organs. Given the development in technology on geodetic instrumentation and software, as well as the increased geodetic activity in Africa, it is time now to establish the AGC. The commission aims at harnessing the hidden potentials that abound in the continent, and thereby will contribute to the global geodetic community. The meeting agreed on the establishment of the AGC and recommended that, to establish the ACG, a letter of intent should be sent to IAG for comment and advice. Communications were opened with IAG, through the Secretary General. It was observed that, the IAG does not have general Regional Commissions, but instead, continental Sub-commissions for geometric, reference frame, and gravity and geoid where Africa is already represented. It was therefore suggested that, ACG may find its place in GGOS which is considering a new structure allowing to include Affiliates, i.e. regional organisations within GGOS that coordinate geodetic activities. It is expected that GGOS will consider the establishment of the African Geodetic Commission or African Geodetic Association under its umbrella.

Capacity Building

There haven’t been any new workshops on GNSS processing since the 2015 workshop at Regional Centre for Mapping of Resources for Development in Nairobi, Kenya. A small workshop is planned during the AfricaArray workshop in South Africa in June 2019.

Challenges

Since its inception, AFREF progress has been slow due to the lack of funding for training and meetings amongst African geodesist, as well as computational facilities among African institutions. The AFREF goal to have a geodetic infrastructure with a spatial distribution of 500 to 1000 kilometers spacing is not yet realized and will need more attention. It is caused by many factors, some of them may be related to lack funding, ignorance or challenges depending on the political situation in individual countries, as well as some countries not willing to share their data. Encouraging is however, the fact that the number of young African geodesists is growing and attention is well nurtured to make AFREF successful.

Acknowledgements

We acknowledge and thank all organizations and individuals for their efforts towards AFREF initiatives, in particular UNECA, IAG, IGA and all governmental initiative. This includes all organizations and governmental agencies that make their data openly available to AFREF ODC particularly the Nigerian GNSS Reference Network (NIGNET), Ethiopian Mapping Agency (EMA), the Regional Centre for Mapping of Resources for Development (RCMRD),
the TRIGNET in South Africa, the Tanzania Geodetic Reference Frame (TAREF), and AfricaArray (via UNAVCO archive). Other includes individual projects particularly AMMA project in Benin, SEGMENT project in Tanzania, Malawi and Zambia as well as initiatives from SEGAL Portugal for installation in Mozambique.

In particular, AFREF thank the officer-in-charge of Geoinformation Systems Section at UNECA Mr. Andre Nonguerma for continuous support on AFREF initiative.

Publications

Sub-Commission 1.3e: Asia-Pacific

Chair: John Dawson (Australia)

Introduction and structure

The objective of sub-commission 1.3e is to improve the regional cooperation that supports the realization and densification of the International Terrestrial Reference frame (ITRF). Its work is carried out in close collaboration with the Geodetic Reference Framework for Sustainable Development Working Group of the United Nations Global Geospatial Information Management for Asia and the Pacific (UN-GGIM-AP).

The specific objectives of the Sub-commission 1.3e are:

• The densification of the ITRF and promotion of its use in the Asia Pacific region;
• To encourage the sharing of GNSS data from Continuously Operating Reference Stations (CORS) in the region;
• To develop a better understanding of crustal motion in the region;
• To promote the collocation of different measurement techniques, such as GPS, VLBI, SLR, DORIS and tide gauges, and the maintenance of precise local geodetic ties at these sites; and
• To outreach to developing countries through symposia, workshops, training courses, and technology transfer activities.

Members

John Dawson (Australia)
Yamin Dang (China)
Farokh Tavakoli (Iran)
Basara Miyahara (Japan)
Yi Sang Oh (Republic of Korea)
Azhari bin Mohamed (Malaysia)
Enkhtuya Sodnom (Mongolia)
Graeme Blick (New Zealand)

National mapping agencies of the Asia-Pacific region are listed here:

Activities during the period 2015-2019

APREF

The purpose of the Asia-Pacific Reference Frame (APREF) project is to create and maintain an accurate geodetic framework to meet the growing needs of industries, science programs and the general public using positioning applications in the Asia-Pacific region. The project specifically is:

• Encouraging the sharing of GNSS data from Continuously Operating Reference Stations (CORS) in the region;
• A source of an authoritative source of coordinates, and their respective velocities, for geodetic stations in the Asia-Pacific region;
• Establishing and maintaining a dense velocity field model in Asia and the Pacific for scientific applications and the long-term maintenance of the Asia-Pacific reference frame.

![Figure 1.3e.1. APREF GNSS stations](image)

A large number of agencies have and are participating in APREF, the following table summarises commitments and contributions by member nations/organisations.

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<td>✓ ✓ 38</td>
</tr>
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<tr>
<td>Papua New Guinea</td>
<td>National Mapping Bureau, Papua New Guinea, and Geoscience Australia</td>
<td>✓ 2</td>
</tr>
<tr>
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<td>Department of Environment and Natural Resources, National Mapping and Resource Information Authority</td>
<td>✓ ✓ 4</td>
</tr>
<tr>
<td>Samoa</td>
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<tr>
<td>Solomon Islands</td>
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<td>Tonga</td>
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<td>Tuvalu</td>
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</tr>
<tr>
<td>Vanuatu</td>
<td>Geoscience Australia</td>
<td>1</td>
</tr>
</tbody>
</table>

APREF data and products are provided with an open access data policy via the internet, following the practice of the International GNSS Service (IGS).
- APREF network and time-series plots, see http://192.104.43.25/status/solutions/analysis.html

**Asia Pacific Regional Geodetic Project**

The group has continued to support the annual Asia Pacific Regional Geodetic Project (APRGP), which is a week-long GNSS campaign throughout the region (see Fig. 1.3e.2). Campaigns were undertaken in 2015, 2016, 2017, and 2018. A campaign is planned for 2019.
Cooperation with other organizations and international integration
Sub-Commission 1.3e made a significant contribution towards the development of the UN-GGIM Global Geodetic Reference Frame Roadmap document prior to the Sixth Session of UN-GGIM at the UN Headquarters, New York.

Outreach and capacity building

Efforts to build capacity in the region have included:

- A UN-GGIM-AP, FIG, IAG, ICG and NZIS Technical Seminar on Reference Frame in Practice: Reference Frames, Datum Unification and Kinematics was held in Christchurch, New Zealand, 1-2 May 2016.

- Support for the establishment of the Pacific Geospatial and Surveying Council (PGSC) and the associated reference frame development in the South Pacific. The PGSC represents the Pacific Island Countries. More information on the PGSC can be found at their website, http://pgsc.gem.spc.int/.
A joint UN-GGIM-AP, IAG, FIG and JUPEM forum on Geospatial and GNSS CORS Infrastructure was undertaken 16 – 17 Oct. 2016, Kuala Lumpur – Malaysia. The forum compromised of 6 sessions, and 22 presentations. The forum hosted by JUPEM (Department of Survey and Mapping, Malaysia) had over 150 delegates from 21 countries. Over the 2 days, the forum attracted over 100 participants each day and these attendees actively engaged and contributed to the program. Presentations are here: http://www.fig.net/organisation/networks/capacity_development/asia_pacific/index.asp

A joint technical seminar of UN-GGIM-AP, FIG, IAG, Japan Federation of Surveyors, International Committee for GNSS (IGC), Geospatial Information Authority of Japan (GSI) was held 29-30 July 2017 before the IAG-IASPEI 2017 in Kobe, Japan. The programme focused on geodetic reference frames and crustal deformation. The programme included theory, ITRF, APREF, UN Initiatives, monitoring and modelling of crustal deformation, case studies and software dealing geodetic adjustment. Meeting presentations can be found here: http://www.fig.net/resources/proceedings/2017/2017_07_refframe_japan.asp
- Jointly with the IAG, the Geospatial Information Authority of Japan (GSI), and the FIG Asia Pacific Capacity Development Network convened a meeting for Asia Pacific member states on “Regional Challenges, Benefits and Opportunities of Exchanging Geodetic Data”. This forum was held prior to the UN-GGIM-AP Plenary Meeting on the 16 Oct. 2017 at the Kumamoto City International Centre, Kumamoto Prefecture, Japan. Forty-four delegates from 14 countries attended. The meeting program and presentations can be found here http://www.fig.net/resources/proceedings/2017/2017_10_ARN.asp.

Figure 1.3e.7. Forum on “Regional Challenges, Benefits and Opportunities of Exchanging Geodetic Data”, 2017, Japan.

- Support for the Pacific Geospatial and Surveying Council (PGSC) including helping with the development of their strategic plan. The WG1 Chair attended the PGSC meeting in Suva, Fiji, in Nov. 2017 and the PGSC meeting in Nuku’alofa, Tonga, in April 2018. The PGSC is facilitated by the Geoscience, Energy and Maritime Division of Pacific Community (SPC) and their Strategy for 2017 – 2027 was launched at special function officiated by the Prime Minister of the Kingdom of Tonga on 10 April 2018.

- The International Workshop on Legal and Policy Frameworks for Geospatial Information Management – Licensing of Geospatial Information, held in Nuku’alofa, Tonga, from 10 – 13 April 2018. This International Workshop raised awareness among the 42 participants from 12 Member States and one Pacific Island Territory on the evolving and increasingly complex legal and policy environment that will impact the availability, accessibility and application of geospatial and geodetic data.

Figure 1.3e.8. International Workshop on Legal and Policy Frameworks for Geospatial Information Management – Licensing of Geospatial Information, 2018, Tonga.
Contributed to the FIG Reference Frame in Practice series in Suva, Fiji 18-20 Sept. 2018. The theme and objectives of the seminar was to provide perspectives and case studies on technical matters relating to the “Operational Aspects of GNSS CORS” infrastructure. Presenters also delivered content on the - “what, why and how” to build a sustainable and modernised geodetic reference frame and datum; challenges faced in the Pacific in relation to geospatial information management and data sharing; legal, policy, and codes of practice (including standards); and the issues pertaining to developing the capacity of surveyors in the discipline of geodetic surveying. There were 23 presentations and 2 exploratory “question and answer” workshops over the 3 day event. The quality of all presentations was of a high standard, which often stimulated involvement and interaction amongst the seminar delegates. The registrations and attendance to the event totalled just below 100, comprising of surveyors, engineers, town planners, students and geospatial experts from 14 different countries in the region. The technical program and presentations can be found here http://www.fig.net/resources/proceedings/2018/2018_09_rfip.asp.

Figure 1.3e.9. FIG Reference Frame in Practice series, 2018, Fiji.

Publications

Sub-Commission 1.3f: Antarctica

Chair: Martin Horwath (Germany)

Introduction and Structure

SC 1.3f deals with the densification of the ITRF in Antarctica and the application of geodetic GNSS measurements for geoscientific investigations, especially in geodynamics, geophysics, and glaciology. For this, the SC 1.3f promotes and supports all activities to realize geodetic GNSS measurements on bedrock sites in Antarctica. Therefore, a close linkage is maintained to the Scientific Committee on Antarctic Research (SCAR), especially to the SCAR Expert Group (EG) “Geodetic Infrastructure in Antarctica” (GIANT).

In terms of geodetic infrastructure Antarctica is a special case because it is not subject to sovereignty of any state. Instead, the Antarctic Treaty ensures freedom of research. Thus, geodetic markers and GNSS installations have been set up and are being maintained by a large number of different national Antarctic programs.

Members

The membership is mostly identical with that of SCAR EG GIANT. In that way, cooperation and coordination can best be pursued since all nations are represented who are involved in geodetic GNSS activities in Antarctica.

Martin Horwath (Germany, Chair of SC 1.3f)
Alessandro Capra (Italy, Co-chair of SCAR EG GIANT)
Mirko Scheinert (Germany, Co-Chair of SCAR EG GIANT)
Manuel Berrocoso (Spain)
Graeme Blick (New Zealand)
Jan Cisak (Poland)
Beata Csatho, Brendan Hodge, Larry Hothem, Erik Ivins, Terry Wilson (U.S.A.)
John Dawson, Matt King (Australia)
Giorgianna De Franceschi, Angelo Galeandro, Monia Negusini (Italy)
Koishiro Doi, Kazuo Shibuya (Japan)
Rene Forsberg (Denmark)
Thomas James (Canada)
Aspurah Kamburov (Bulgaria)
Christoph Knöfel (Germany)
Jeronimo Lopez-Martinez (Spain)
Jaakko Mäkinen, M. Poutanen (Finland)
Kenichi Matsuoka (Norway)
Alexey Matveev (Russia)
Gennadi Milinevsky (Ukraine)
Elizabeth Petrie (United Kingdom)
Goncalo Prates (Portugal)
Yves Rogister (France)
Lars Sjoberg (Sweden)
Norbertino Suarez (Uruguay)
Andres Zakrajsek (Argentina)
Activities during the period 2015-2019

SCAR GNSS Database
In close linkage with SCAR EG GIANT a database on geodetic GNSS in Antarctica (SCAR GNSS Database) is being maintained at TU Dresden. This is an ongoing activity (see data1.geo.tu-dresden.de/scar) and provides an important background support for the GIANT-REGAIN project (see below).

Reprocessing of GNSS data in Antarctica (GIANT-REGAIN)
At the SCAR Meeting 2016 in Kuala Lumpur, an initiative was launched by M. Scheinert (Germany) and M. King (Australia) entitled “Geodynamics in Antarctica based on Reprocessing GNSS Data Initiative” (GIANT-REGAIN). This project aims to provide a consistent solution of coordinates and coordinate changes for the most complete set of GNSS bedrock stations in Antarctica for further applications in geodesy, geophysics and geodynamics (especially studies on glacial-isostatic adjustment). Collection of data and metadata was just finalized in early 2019. It was a huge task especially to collect and homogenize the necessary metadata. The project comprises now about data from about 250 bedrock sites in Antarctica over a time span from 1995 to the end of 2017. The progress and first results of GIANT-REGAIN will be reported at the 27th IUGG General Assembly in Montreal, 2019.

Cooperation with other organizations and international integration

Endorsement of UN Resolution:
The group supported the endorsement of the UN resolution on A Global Geodetic Reference Frame for Sustainable Development that was finally approved on 18 February 2015 (see also unggrf.org).
Outreach and capacity building

2nd SCAR Summer School on Polar Geodesy:
Mirko Scheinert (co-chair of SCAR EG GIANT) and Martin Horwath (chair of SC 1.3f) organized a 2nd SCAR Summer School on Polar Geodesy that was held at AARI Ladoga Base, Ladozhskoe Ozero, Russia, 10–19 May 2018. This summer school was locally organized by colleagues from the Arctic-Antarctic Research Institute (AARI), St. Petersburg (especially A. Klepikov, Head of the Russian Antarctic Expedition, and A. Ekaykin, AARI Glaciology). It was supported by IAG, SCAR, Germany Society of Polar Research (DGP), AARI, Aerogeodesya (St. Petersburg) and TU Dresden. 12 young scientists (Master and PhD students) from 7 different countries took part in this summer school. A focus was given to the application of geodetic GNSS techniques in polar research, both in lectures and practical exercises.

Group meetings:
Related to SC 1.3f business meetings of SCAR EG GIANT were organized at the SCAR Meetings in Kuala Lumpur (2016) and Davos (2018).

Participation in related meetings, conferences and workshops:
Group members took part in relevant meetings, conferences and workshops. Besides the annual EGU General Assemblies and AGU Fall Meetings, the following meetings are most relevant.
- International Symposium on Antarctic Earth Sciences, Goa (India), 2015
- XXXIV SCAR Meeting and Open Science Conference, Kuala Lumpur (Malaysia), 2016
- Workshop “Glacial Isostatic Adjustment and Elastic Deformation”, Reykjavik (Iceland), 2017
- XXXV SCAR Meeting and SCAR/IASC Open Science Conference, Davos (Switzerland), 2018

Publications


**WG 1.3.1: Time-Dependent Transformations Between Reference Frames**

*Chair: Richard Stanaway (Australia)*

**Introduction and structure**

The main aim of the WG has been to focus research in deformation modelling into the rapidly emerging field of regional and local reference frames used in applied geodesy, particularly positioning and GIS. Deformation models and time-dependent transformation schema provide linkages between global reference frames such as ITRF, regional reference frames and local reference frames commonly used for land surveying and mapping.

A rapidly emerging issue that the WG research has addressed is the misalignment of precise GNSS positions and derived spatial data over time. GNSS positions are intrinsically defined in a kinematic reference frame (RF) such as ITRF or closely aligned RF. Spatial data on the other hand, is intrinsically static in nature being essentially a snapshot of a RF at the epoch of data acquisition or capture. The volume of spatial data being created is increasing almost exponentially as laser scanning technologies and high-resolution imagery acquired by UAV/drone become mainstream. These massive datasets are fixed epoch representations of a positioning RF used to acquire the data. Consequently, the data are effectively "stale" in the context of later data acquired using a kinematic RF used in GNSS positioning for example.

Precise time-dependent transformation models are required to enable spatial data acquired at different epochs to be aligned at a common epoch for visualization and analysis. Furthermore, GNSS positions requires a time-dependent transformation to be applied in order to be used in the context of spatial data defined in a static or fixed epoch RF, or vice versa. Addressing these practical issues is an urgent requirement as precise GNSS positioning becomes more accessible to a wider spectrum of users of RF, many of whom have limited or no geodetic expertise.

The WG has developed a time-dependent transformation model concept that can be used for kinematic and semi-kinematic RF transformations, even in tectonically complex plate boundary regions subject to frequent earthquakes. The approach also supports realization of regional and local reference frames from ITRF to support GIS and positioning technologies through integration of positioning with spatial data. The concept can form a basis for implementation of complex time-dependent RF transformations by international registries of geodetic parameters such as those hosted by ISO/TC 211 and EPSG (European Petroleum Survey Group).

WG 1.3.1 has worked closely with FIG Commission 5 (Positioning and Measurement), specifically FIG Working Group 5.2 (Reference Frames). WG members have comprised a wide spectrum of researchers from different fields of geophysics, geodesy, land surveying and GIS.

**Members**

*Richard Stanaway (Chair, Australia)*  
*Hasanuddin Abidin (Indonesia)*  
*Sonia Alves, (Brazil)*
Activities and publications during the period 2015-2019

There has been a major impetus for national and regional RF modernization since 2015 with many countries implementing or considering time-dependent reference frames. The impetus has been driven by increasing adoption of precise GNSS positioning, especially at the mass market level, precision GIS and the United Nations 2015 resolution in support of a Global Geodetic Reference Frame (GGRF).

One of the main aims of WG 1.3.1 has been to develop a framework for time-dependent reference frame transformations, especially in plate boundary regions with complex tectonic settings. At present, the 14-parameter model is widely used (e.g. for transformations between different realizations of ITRF, ETRF, GDA and NAD83). Plate motion models (PMM) can also be used to describe the kinematics of the stable portion (rigid) of a tectonic plate or microplate. The rotation rate parameters of the 14-parameter transformation model can be adapted from a PMM (rotation rates of the Cartesian axes). The 14-parameter and PMM approach, however, does not adequately accommodate intraplate, plate boundary, co-seismic and post-seismic deformation. Models of these forms of deformation are essential for higher precision transformations and there is a rapidly growing requirement to develop international standards for deformation model formats and application (e.g. IOGP/EPSG and ISO/TC 211). Presently, different jurisdictions in tectonically active regions have different approaches to handle these types of deformation. The lack of a standardized approach for time-dependent transformations is leading to a potentially unmanageable scenario where every jurisdiction adopts a different model format or schema. This is an undesirable situation for developers of positioning and GIS software and it is an impediment for the GGRF to be applied in practice. Many developing countries have limited budgets and technical capacity to modernize their geodetic datum to a GGRF template and require standardized approaches and schema.

WG 1.3.1 has reviewed the different approaches currently in use globally as basis for development of a conceptual model for time-dependent transformations in deforming zones.

The current consensus amongst geodetic agencies participating in this study is the adoption of a semi-kinematic RF or dual frame (kinematic + static or kinematic + semi-kinematic) until full time-dependence transformation capabilities are developed, tested and built into GIS, surveying software and spatial data management tools. The status quo of a static RF is increasingly incompatible with the current precisions achievable with GNSS-PPP for example.
An updated crustal motion model has been developed (Snay et al., 2016) to support applied geodesy in the USA and Canada with the development of TRANS4D software, which will supersede the HTDP software currently being used for time-dependent transformations. The new model now includes uncertainties of estimated velocities and vertical velocities. The USA is in the process of modernizing its RF from the current NAD83 datum with the realization of four stable plate RF for the major regions and territories of the USA. The main RF will be the North American Terrestrial Reference Frame (NATRF2022) which will be time-dependent with site velocities defined in a stable North American plate RF.

**South America**

The present SIRGAS Velocity Model (VEMOS2017; Sánchez and Drewes, 2017) was inferred from GNSS (GPS+GLONASS) measurements gained after recent earthquakes in Chile and Mexico (Sánchez et al., 2013; 2017). It is based on a multi-year velocity solution for a network of 515 continuously operating GNSS stations between 2015 and 2017. VEMOS2015 was computed using the least square collocation approach with empirically determined covariance functions. It covers the region from 55°S, 120°W to 32°N, 35°W with a spatial resolution of 1° x 1°. The average prediction uncertainty is ±1.0 mm/a in the north-south direction and ±1.7 mm/a in the east-west direction. The maximum is ±9 mm/a in the Maule deformation zone (Chile) while the minimum values of about ±0.1 mm/a occur in the stable eastern part of the South American plate.

The main purpose of VEMOS2017 is to allow the translation of station positions through time. However, this model is only valid for the time period 2015-2017. For the translation of station positions before the 2010 earthquakes, the model VEMOS2009 (Drewes and Heidbach, 2012) should be used. The earlier VEMOS2015 model includes GNSS observations over five years, some regions were affected by further earthquakes and their effects are not included in VEMOS2015 yet. Consequently, it is necessary to continue updating this model regularly. In forthcoming activities, we shall improve the distribution of the continuously operating GNSS stations, especially along the boundaries between the different tectonic features. In the
analysis of the station position time series, we want to consider possible surface loading and local effects to improve the reliability of the estimated velocities. Finally, we plan also to perform detailed studies about the temporal-spatial evolution of the deformation field.

Figure 1.3.1.2. VEMOS2017 velocities in a stable South American plate reference frame (Sánchez et al., 2019), taken from www.sirgas.org.

Europe

A European deformation model grid is being developed within the EUREF WG on “Deformation models”. The modelling is done using the least squares collocation (LSC) approach and are based on recent GNSS station velocity results from the EUREF WGs on “EPN Densification” and “European Dense Velocities” with about 2000 and 4500 station velocities respectively (Rebekka Steffen et al., 2019). The GNSS time series are up to about 20 years, and a minimum of 3 years are used for velocity estimation.
Fig. 1.3.1.3. Preliminary horizontal velocity model computed using the least square collocation (LSC) approach with empirically determined covariance functions (Steffen et al 2019). In the Fennoscandia area a background GIA-model have been considered in a “remove-compute-restore” methodology. Plate boundary information are considered by reducing the correlation between locations on different sides of a plate boundary zone.

The model will benefit from work already completed on regional dense velocity fields (former IAG WG 1.3.1, 2007-2015 - Juliette Legrand and Carine Bruyninx) and plate boundary deformation models developed by geodetic agencies and universities in Greece, Turkey and Italy. Miltiadis Chatzinikos, Stylianos Bitharis, Aristeidis Fotiou, Christopher Kotsakis and Christos Pikridas have completed extensive studies to support velocity modelling and semi-kinematic RF development in Greece. The Fennoscandian land uplift model NKG2016LU has been developed by the NKG (Nordic Geodetic Commission) to model the (Glacial Isostatic Adjustment) GIA kinematics impacting the Nordic nations of Europe. Olav Vestøl, Jonas Ågren, Holger Steffen, Halfdan Kierulf, Martin Lidberg, Pasi Häkli have been lead researchers in this effort. The use of land uplift models enables precise transformations between national realizations of ETRS89 and different realizations of ITRF at the few mm level. An important aspect to note is the smaller but significant horizontal velocities associated with GIA. A time-dependent RF is being developed for Iceland, which straddles the active plate boundary between the North American and Eurasian tectonic plates. The complexity in Iceland is exacerbated by volcanic and GIA deformation.

Figure 1.3.1.4. The NKG_RF03vel velocity model. Reference for the horizontal velocity field (left) is “stable Eurasia” as defined by the ITRF2000 Euler pole for Eurasia. The vertical uplift rates are “absolute” values relative the earth centre of mass. Units: mm/year (from Lidberg et al., 2017).
**Indonesia**

The Geospatial Agency of Indonesia has launched a new geocentric datum named the Indonesian Geospatial Reference System 2013 (IGRS 2013) (Susilo et al., 2016). This new datum is a semi-dynamic datum in nature realized by ITRF2008, with a reference epoch of 1 January 2012 (2012.0). A deformation (velocity) model is used to transform coordinates from an observation epoch to or from this reference epoch. For its initial implementation, the model considers an initial deformation model setting based on 4 tectonic plates, 7 tectonic blocks, and 126 earthquakes. At present, the velocity model of IGRS 2013 is mainly realized using repeat GPS observations on the passive geodetic control network and CORS, covering the period from 1993 to 2014. These GPS data are managed by the Geospatial Agency of Indonesia (BIG), Land Agency of Indonesia (BPN), and the Sumatran GPS Array (SUGAR). The GPS data has been reprocessed and analyzed using the GAMIT/GLOBK 10.5 processing software suite. The derived velocities field shows the spatial variation of velocity direction and magnitude, which represents various plates or blocks tectonic motion in Indonesia region. This analysis has been used for the development of the IGRS 2013 deformation model.

![Figure 1.3.1.5.](image)

**Figure 1.3.1.5.** Velocity model of IGRS2013 with respect to ITRF2008 (Susilo et al., 2016). Red line is blocks boundaries from MORVEL 56 (Argus et al. 2011). Faults lineation downloaded from the East and Southeast Asia (CCOP) 1:2000000 geological map.

**New Zealand**

The New Zealand Geodetic Datum 2000 (NZGD2000) Deformation Model has been updated based on improved site velocities estimated from GPS observations made on both the passive geodetic network and active CORS network between 1996 and 2011 (Crook et al., 2016). Earthquake patch models of coseismic displacement have also been incorporated for a number of significant earthquakes that have occurred in New Zealand (Fig. 1.3.1.6). These displacement patches are distributed for each significant earthquake with different resolutions.

The NZGD2000 deformation model velocity field is published on a rectilinear 0.1° grid of ellipsoidal coordinates in comma separated variable (csv) format. Coseismic displacement grids (patches) have been defined with different resolutions and extents. The current model can be downloaded at:

The current Japanese Geodetic Datum 2000 (JGD2000) defined at epoch 1997.0 has been updated for the Eastern part of Japan to epoch 2011.39 to account for the very significant coseismic and postseismic deformation arising from the 2011 Tohoku earthquake sequence (Fig. 1.3.1.6). Coseismic and postseismic corrections are updated and applied annually to the JGD2000 coordinates at the reference epoch for each part of the country. From 2014, JGD2000 has been re-realized by the 1318 station GEONET CORS network. The ongoing issues with large vertical coseismic and postseismic displacements arising from large earthquakes together with the large cost of geometrical leveling are motivating the implementation of a geoid based vertical frame in 2024.
References


Figure 1.3.1.7. JGD2000 horizontal coordinate changes arising from the 2011 Tohoku earthquake sequence

Nepal

Following the April 25, 2015 Mw7.8 Gorkha earthquake, a new semi-dynamic datum is being developed for Nepal incorporating a secular site velocity model based on ITRF2014 (Fig. 1.3.1.7) and co-seismic deformation model to enable pre earthquake spatial data to be transformed and visualized in ITRF2014 (Pearson et al., 2016).

Figure 1.3.1.8. Velocity grid for Nepal and surrounding parts of India and China.

Australia
Australia implemented a modernized geodetic datum, GDA2020 in late 2018 to supersede GDA94. GDA2020 is a realization of ITRF2014 projected to epoch 2020.0 using a stable plate motion model for Australia, implemented as rotation rates in a 14-parameter transformation with zeros for other parameters. A fully kinematic RF, the Australian Terrestrial Reference Frame (ATRF) is in development; however it is anticipated that GDA2020 and ATRF will operate as a dual-frame system for some time into the future until robust time-dependent transformations within GIS and management of spatial data are developed, tested and adopted.

Other countries

Malaysia, Taiwan, The Philippines, Turkey, Israel, Vietnam, Papua New Guinea and Egypt are in the process of development of time-dependent reference frames with extensive research undertaken by researchers in these respective countries.

Complex time-dependent transformation schema

A complex time-dependent transformation schema has been developed by Richard Stanaway, UNSW, Australia. The schema includes sub-model formats for interseismic (secular) velocities, coseismic displacement, postseismic parameter grids and localized deformation. The schema includes estimation of uncertainty arising from interpolation of the different models used. The work also includes an appraisal of the effect of deformation on RF considering different requirements for end users of RF. The schema will be published later in 2019.

Outreach and capacity building

WG meetings and workshops have been held in conjunction with the technical seminars on Reference Frames in Practice (RFIP) series jointly run by the FIG, IAG, International Committee on GNSS (ICG) and the United Nations Initiative for Global Geospatial Information Management for Asia-Pacific (UN-GGIM-AP). The RFIP seminars have been very successful with great synergy between the different participating organizations, particularly Commission 5 (Positioning and Measurement) of FIG. The meetings and technical seminars have been run annually as follows:

- Christchurch, New Zealand, 1-2 May 2016.
- Kobe, Japan, 29-30 July, 2017
- Istanbul, Turkey, 4-5 May, 2018
- Hanoi, Vietnam, 20-21 April, 2019

Twelve members of WG 1.3.1 have attended and made presentations at these seminars.
Figure 1.3.1.9. RFIP, Christchurch, New Zealand, 1-2 May 2016.

Figure 1.3.1.10. RFIP, Kobe, Japan, 29-30 July 2017.

Figure 1.3.1.11. RFIP, Istanbul, Turkey, 4-5 May 2018
Publications


Reference System 2013, Proceedings from FIG Working Week, Christchurch, New Zealand

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

Chair: Zinovy Malkin (Russia)

Structure
Working Group 1.4.1: Consistent realization of ITRF, ICRF, and EOP
Working Group 1.4.2: Impact of geophysical and astronomical modeling on reference frames and their consistency
Working Group 1.4.3: Improving VLBI-based ICRF and link to the Gaia-based CRF (GCRF)

Overview
International terrestrial and celestial reference frames, ITRF and ICRF, respectively, as well as the tie between them expressed by the Earth Orientation parameters (EOP) are key products of geodesy and astrometry. The requirements to all the components of this triad grow steadily and the mm/μas level of accuracy is the current goal of the astronomic and geodetic community.

The current computation procedures for ITRF and ICRF are based on multi-stage processing of observations made with several space geodetic techniques: VLBI, SLR, GNSS, and DORIS. Not all of them provide equal contributions to the final products. The latest ITRF realizations have been derived from combination of normal equations obtained from all four techniques, whereas the ICRF is a result of a single global VLBI solution. The latter is tied to the ITRF using an arbitrary set of reference stations. However, VLBI relies on the ITRF origin provided by satellite techniques and shares responsibility with SLR for the ITRF scale. Finally, all the techniques contribute to positions and velocities of the ITRF stations.

This situation causes complicated mutual impact of ITRF and ICRF, which should be carefully investigated in order to improve the accuracy of both reference systems and the consistency between each other and EOP. The subject becomes more and more complicated when moving to millimeter accuracy in all components of this fundamental triad. Consequently, we face systematic errors involving the connection between the ICRF and ITRF realizations, which cannot be fixed by datum correction during the current solution.

There are several issues currently preventing the consistent realization of the terrestrial and celestial reference systems (TRF and CRF, respectively) at the mm/μas level of accuracy:

- Insufficient number and non-optimal distribution of active and stable stations (VLBI and SLR in the first place) and radio sources.
- Technological (precision) limitations of existing techniques.
- Incompleteness of the theory and models.
- Not fully consistent models applied during data analysis.
- Not fully understood and agreed-upon details of the processing strategy.
- Not fully understood and accounted for the systematic errors of different techniques.

These issues are subject of research activity of the IAG SC 1.4.
All the three IAG SC 1.4 working groups are working in close cooperation with each other, in particular, because there is clear interaction among their topics. To provide this, it was decided that each WG chair becomes a member of two other working groups, and the SC chair if a member of all the three groups.

**SC 1.4 Meetings:**

IAG SC 1.4 Meeting on 25 April 2017 in Vienna during the EGU 2017 week

IAG SC 1.4 Meeting on 11 April 2019 in Vienna during the EGU 2019 week

At both meetings, IAG SC 1.4 Working Groups chairs prepared presentations on the current activities of their WGs. Several accompanying presentation of WG members were also given. Details of these studies and obtained results are described below in WG reports.

**Other related meetings:**

Several other meetings, except IUGG, IAG, IAU, AGU, and EGU General Assemblies, with active participation of the SC 1.4 members were held in 2015–2019 where the scientific problems related to the IAG SC 1.4 topics were discussed:

- 9th IVS General Meeting, March 2016, Johannesburg, South Africa;
- GAGER Meeting, May 2016, Wuhan, China;
- ROTANUT Meeting, September 2016, Brussels, Belgium;
- ICRF-3 IAU Working Group Meeting, October 2016, Haystack, USA;
- IAU Symposium 330, Nice, France
- 23rd EVGA Working Meeting, May 2017, Gothenburg, Sweden;
- Journees 2017, September 2017, Alicante, Spain;
- 10th IVS General Meeting, June 2018, Longyearbyen, Spitsbergen, Norway;
- 24rd EVGA Working Meeting, March 2019, Las Palmas (Gran Canaria), Spain.
WG 1.4.1: Consistent Realization of ITRF, ICRF, and EOP

Chair: Manuela Seitz (Germany)

Members
- Claudio Abbondanza (US)
- Sabine Bachmann (Germany)
- Richard Gross (US)
- Robert Heinkelmann (Germany)
- Chris Jacobs (US)
- Hana Krasna (Austria)
- Sebastien Lambert (France)
- Karine Le Bail (US)
- Dan MacMillan (US)
- Zinovy Malkin (Russia)
- David Mayer (Austria)
- Benedikt Soja (US)

Activities and publications during the period 2015-2019

General aspects

Many applications in the geosciences, astrometry and navigation require consistency of the terrestrial and the celestial reference frame and the Earth Orientation Parameters. But ITRS, ICRS and EOP are not realized fully consistently today. In addition, the realizations of the reference systems do not take full advantage of the high precision of the space geodetic techniques due to (i) modeling deficiencies in single technique analysis and (ii) inhomogeneity w.r.t. modeling and parameterization between the techniques.

The WG 1.4.1 aims to develop and investigate the methods to generate consistent TRF-CRF-EOP solutions based on optimal modeling, analysis and combination strategies and to assess the quality of the results. The focal points of the WG are:

1. Investigation of the impact of different analysis options and combination strategies on the consistency of TRF, CRF, and EOP derived from a joint analysis of space geodesy observations.
2. Investigation of the consistency of the current ICRF and ITRF versions and IERS EOP C04 series.
3. Investigation of the consistency of VLBI-only (IVS) CRF, TRF, and EOP series with the ITRF, ICRF, and C04 EOP series.
4. Study of effects of geodetic datum realization on VLBI-derived CRF.
5. Study of optimal use of the space-collocated techniques for the improvement of the consistency of TRF, CRF, and EOP.

Consistency of current ITRF solutions and EOP

A general scheme of the computation of the ICRS and ITRS realization is shown in Fig. 1.4.1. In 2015/2016 three new realizations of the ITRS are computed and released by the ITRS Combination Centers DGFI-TUM, IGN and JPL. The IGN solution, the ITRF2014, is computed from a combination of the VLBI, SLR, GNSS and DORIS solutions. In the ITRF2014 solution non-linear station motions are approximated by estimating annual and semi-annual signals. The realization performed by DGFI-TUM, the DTRF2014, is based on the combination of normal equations of the space-geodetic techniques.
In DTRF2014 computation non-linear station motions caused by hydrologic and atmospheric loading are reduced. The loading signals are considered by model values based on the hydrology model GLDAS and the atmospheric model NCEP, respectively. The time series of model values are derived and provided by Tonie van Dam. JPL computes an ITRS realization, the JTRF2014, by applying a Kalman filter approach. The resulting station position time series approximate the non-linear station motions very well.

In order to investigate the consistency of the current ITRS realizations, the GFZ group computes EOP series and global CRF solutions by fixing the station coordinates to the previous ITRS realization ITRF2008 and the new realizations ITRF2014, DTRF2014 and JTRF2014. The individual EOP series obtained from a session-wise analysis are compared using the series based on the ITRF2014 coordinates as a reference. The EOP series obtained by fixing the station coordinates to DTRF2014 show the smallest differences. The difference series of the terrestrial pole coordinate series show small drifts in the very early years of VLBI observation and a slightly increased scatter in 2013/2014. The WRMS values are 0.004 mas and 0.002 mas for x- and y-pole, respectively. For UT1 and nutation no systematic occur. The WRMS values are 0.10 μs for UT1 and 0.09 and 0.11 mas for X- and Y-pole, respectively. The EOP series computed by fixing ITRF2008 coordinates show a larger scatter compared to the ITRF2014 based series than the DTRF2014 based series. This can be related to the fact that ITRF20014 and DTRF2014 are computed from the same input data. The scatter of the ITRF2008 based series increases strongly after 2008 when coordinates are extrapolated. For the JTRF2014 based EOP series a larger scatter than for DTRF2014 series was obtained which might be a result of the different approximation of station motions. But also, systematic effects are identified which can be related to the handling of seismic events. In a second step global CRF solutions are computed by again fixing the station positions and velocities to the three reference frames and by fixing also the EOP. The CRF solutions obtained from fixing ITRF2014 and DTRF2014, respectively, agree very well. The WRMS values are 2.06 μas and 9.67 μas for RA*cos(DE) and DE, respectively. Only small
systematics in declination and declination rate are found. For JTRF2014 the differences are larger, in particular for sources in the high southern declinations. For ITRF2008 also larger differences are obtained which can be explained by the 6 more years of data used for the 2014 realizations.

**Realization of ITRS and ICRS from VLBI data**

VLBI is the only space-geodetic technique which observes extra galactic objects and thus allows for a consistent realization of TRF, CRF and the EOP. Therefore, it is very important to investigate the impact of different VLBI analysis options on the resulting TRF and CRF. In the period 2015-2019, three analysis options were investigated: the reduction of non-linear station motions, an improved modelling of tropospheric a priori parameters and the effect of combining different VLBI solutions on the stability of source positions.

In the ITRS realizations ITRF2014, DTRF2014 and JTRF2014 for the first time non-linear station motions are considered. TU Vienna investigated the impact of non-linear station motions in VLBI-based TRF-CRF-EOP solutions on source positions and EOP. The results indicate that the seasonal signals do not propagate into the orientation of celestial reference frame but they can cause significant position changes for radio sources observed non-evenly over the year. On the other hand, it was found that the harmonic signals in station horizontal coordinates propagate directly into the ERP by several tens of microarcseconds.

VLBI solutions depend on the quality of the a priori values of tropospheric parameters as these parameters are slightly constrained in the VLBI solutions. Therefore, TU Vienna tested different types of a priori modelling (see report of WG 1.4.2). It was found, that the different modelling options lead to significant differences in the declination biases which occurs around 30°S.

BKG performs the combination of different VLBI solutions routinely in its function as IVS Combination Centre. Up to now, station positions and EOP were combined on a routine basis. In order to investigate the benefit of a combination of source positions for the CRF, BKG includes source positions in the combination process. The results look very promising. The WRMS of session-wise estimated source positions were improved by the combination as shown in Fig. 1.4.2. Figure 1.4.3 displays the homogeneity of position residuals of all contribution solutions w.r.t. ICRF-2 exemplarily for one R1 session. The impact of the combination of sources on the TRF was found to be not significant.

![Fig.1.4.2. WRMS over all sources for individual and combined solutions. Only sources with ten sessions and a time span of more than 2 years were considered. The number of sources is given below the name of the analysis center (AC).](image)
Two further VLBI analysis options are investigated by WG 1.4.2: the spline parameterization for special handling sources that allows to include these sources in the NNR conditions and the minimization of source structure effects on the CRF.

**Consistent realization of ITRS and ICRS**

Two groups are working on the consistent realization of ITRS and ICRS, namely JPL and DGFI-TUM.

In the recent years JPL developed a Kalman filter approach (KALREF) for the realization of the ITRS and became an ITRS Combination Centre. JPL provided the solution JTRF2014 in the framework of the ITRS realization. For this purpose, JPL improved their TRF solution by using GRACE data and loading models to include statistics of regional ground deformation in the Kalman filter's stochastic model of process. In a second step, the Kalman filter approach was extended to compute also CRF solutions. Therefore, radio source coordinates were modeled as random walk processes and a source-based process noise model was developed. The special handling of sources featuring measurable motions, benefit most from this time series approach. Physical properties of radio sources, such as the direction of the jet, have been obtained from radio source images and incorporated in the process noise models.

A new software, SREF, has been developed at JPL. It is based on KALREF, but more flexible in terms of parameterization and stochastic treatment. SREF adopts a sequential time series approach to parameter estimation, but uses a square-root information filter (SRIF) instead of a Kalman filter. The SRIF algorithm performs the state updates – and hence the combination – at the normal equation level. Furthermore, it is more robust numerically. In addition to the capability of determining TRF solutions, SREF includes the possibility to estimate radio source position and nutation parameters.

SREF has been successfully used to compute consistent TRF/EOP/CRF solutions. The input data for GNSS, SLR, and DORIS was based on the input for JTRF2014. Instead of the IVS VLBI contribution to ITRF2014, the GSFC VLBI operational solution (gsf2016a) was used since it contains radio source positions. Compared to JTRF2014, the number of stations was reduced to 510 in order to efficiently compute and experiment with different solution set-ups. For the same reason, a rather small number of 298 radio sources was selected. The origin was defined by SLR and the scale by SLR and VLBI. Comparisons of the station and source coordinates to frames like ITRF2014 and ICRF3 revealed a reasonable agreement. EOP from the SREF solutions were compared to IERS C04 14 and the EOP series from ITRF2014,

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**Fig.1.4.3.** Source position residuals w.r.t. ICRF2 for individual and combined solution for session 14MAY27XA (R1637).
DTRF2014, and JTRF2014. The next steps will be to compute solutions with larger terrestrial networks and a greater number of radio sources.

At DGFI-TUM, consistent realizations of ITRS and ICRS were performed by combining the space geodetic techniques on normal equation level. For the most recent solution, VLBI and SLR normal equations from DGFI-TUM and the routinely provided normal equations of the IGS Analysis Centre CODE were combined, covering the time span from January 2005 – December 2016. The parameters that were included in the combination are shown in Table 1.

**Table 1.4.1.** Parameters estimated in the consistent realization of ICRS and ITRS at DGFI-TUM.

<table>
<thead>
<tr>
<th>TRF</th>
<th>VLBI</th>
<th>SLR</th>
<th>GNSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station coordinates</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Station velocities</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Origin</td>
<td>NNT</td>
<td>intrinsic</td>
<td>NNT</td>
</tr>
<tr>
<td>Scale</td>
<td>intrinsic</td>
<td>intrinsic</td>
<td>NNS</td>
</tr>
<tr>
<td>Orientation</td>
<td>NNR</td>
<td>NNR</td>
<td>NNR</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CRF</th>
<th></th>
<th></th>
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<tbody>
<tr>
<td>Source coordinates</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orientation</td>
<td>NNR</td>
<td></td>
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</tbody>
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<table>
<thead>
<tr>
<th>EOP</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrestrial x/y-pole</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Celestial X/Y-pole</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ΔUT1*</td>
<td>X</td>
<td>(X)</td>
<td>(X)</td>
</tr>
</tbody>
</table>

(*) for the satellite techniques, one ΔUT1 value per solution is fixed to a priori

The parameters common to all techniques are station coordinates and EOP. Detailed studies are performed to investigate the impact of the combination of these parameters on the CRF. While the combination of the station coordinates has only a small effect on the CRF (see Kwak et al., 2018), the combination of EOP leads to significant changes in two different ways. Figure 1.4.4 shows the change of source position standard deviations by the combination of EOP. The mean effect (more than 90%) is by the combination of x- and y-component of the terrestrial pole. In particular, the VCS sources and the newly added sources (not included in ICRF-2) benefit from the combination of the EOP.
Also, the WRMS values of the EOP series w.r.t. IERS 08 C04 are improved by the combination. Figure 1.4.5 shows the WRMS values for two test scenarios weighting the VLBI normal equation in the combination with the factor 1.0 and 0.1 (down weighting), as well as for the VLBI-only solution. It can be seen very clearly, that for x- and y-component of the terrestrial pole the WRMS but also the weighted mean offset (wmean) decrease significantly in the combination. The combination of LOD, however, leads to an expected increase of the ΔUT1 WRMS value compared to the VLBI-only solution, due to the interpolation to a continuous series (daily values). The down weighting of the VLBI contribution further enhances this effect.

In order to further validate the CRF part of the combined CRF/TRF solution transformation parameters w.r.t. the VLBI-only solution are estimated. Figure 1.4.6 shows the parameters for four different combination setups. It becomes evident that the combination of LOD (in fact we use a piece-wise linear representation of ΔUT1) lead to a systematic rotation of the frame, in particular around the third axis ($A_3$). On the other hand, it is beneficial that the combination of
LOD lead to a continuous ΔUT1 series. It is a task for the future to study how the rotational effect can be reduced.

Fig. 1.4.6. CRF transformation parameters and their standard deviations (error bars) of different EOP combination setups w.r.t. VLBI-only solution.

Summarizing the results from the consistent realization of ICRS and ITRS we can state the following:

- The combination of the techniques lead to a reduction of standard deviation of the estimated parameters due to the larger number of observations
- The impact of the local ties on the CRF and the EOP is small
- The CRF benefits from the combination of the terrestrial pole coordinates, which reduces the standard deviations of a large number of sources significantly.
- The combination of LOD leads to a z-rotation of CRF. However, it is beneficial that the ΔUT1 series become continuous. It is a task for the future to better study and reduce the rotational effect.

The consistent realization of ICRS and ITRS performed at DGFI-TUM is presented in detail in Kwak et al, 2018.

References


Mayer, D., J. Böhm, and H. Krásná, Application of Ray-traced Delays for the ICRF (2017), In: Proceedings of the 22nd EVGA Meeting in Gothenburg (Sweden), to be published.


IAG WG 1.4.2: Impact of Geophysical and Astronomical Modeling on Reference Frames and Their Consistency

*Chair:* Dan MacMillan (USA)

**Members**

- Robert Heinkelmann (Germany)
- Hana Krásná (Austria, Czech Republic)
- David Mayer (Austria)
- Sébastien Lambert (France)
- Lucia McCallum (Plank) (Australia)
- Tobias Nilsson (Sweden)
- Stanislav Shabala (Australia)
- Zinovy Malkin (Russia)

**Introduction**

Working Group 2 is concerned with the modeling of geophysical and astronomical effects and how they affect the consistent determination of the terrestrial and celestial reference frames. The work of the group generally falls into the following categories: 1) analysis and solution parametrization, 2) external models, and 3) internal inconsistencies within the VLBI technique. There clearly are overlaps between work done by the three Working Groups of IAG 1.4. Over the last four years there have been several published papers and presentations on topics including source position time series stability, radio source structure, galactic aberration, ICRF3, accuracy of radio source catalogs, correlations between VLBI observations due to troposphere noise, and VLBI+GNSS combination solutions. Several of the group members (D. MacMillan, S. Lambert, H. Krásná, and Z. Malkin) are also in the IVS Aberration Working Group, which worked on a recommendation for a galactic aberration model for VLBI analysis and for use in the ICRF3 solution.

**Modeling Source Structure Variation**

Karbon et al. (2016) addressed the issue of systematic variation of radio source positions, which is likely due to source structure, and its effect on the TRF and EOP in VLBI solutions. They employed an efficient automated recursive spline fitting procedure to determine spline parameters for each source. The spline parametrizations are then applied as a priori models for each source (see Fig. 1.4.7). This allows sources with significant systematic variation, e.g., the ICRF2 “special handling” sources, to be included in the CRF NNR condition. In the ICRF2 solution, these sources were excluded from global estimation and were estimated as local session parameters, thereby weakening their contribution to estimated CRF. Depending on the distribution of sources in the NNR condition, this spline procedure expands the number of datum sources by 114-146% for 1980-1990 and 27-46% for 1990-2013. Benefits of this parametrization are an improvement in nutation precision with respect to the IAU 2006/2000 precession model of 10-12% and a reduction in position series precision of up to 2.5-4 mm for high latitude sites (likely due to sources at high declination), e.g., NyAlesund, but less than 0.05 mm for other sites.
Fig. 1.4.7. Session-wise estimates of the radio source 4C39.25 position right ascension and declination (red points, semi-annual means (black curve), and the spline fits (blue curve) to the estimates (Karbon et al. 2016).

Plank et al. (2016) investigated the effect of source structure on the CRF. In simulations, they applied 2-component source models and determined the resulting shift in source position estimates. For sources with structure index of 2 or 3, these shifts tend to be aligned with the source jet direction. Based on this result, they investigated a method of source position estimation that tries to minimize the effect of source structure by estimating the component in the direction of the jet for each 24-hr observing session and the component perpendicular to the jet as a global parameter. In simulations using observing schedules for the operational R1/R4 sessions, the median effect of structure is reduced for sources with structure indices 2-3. It remains to try the method with observed data.

For perspective, there has been considerable recent work done on the effect not modeling source structure in VLBI analysis. Anderson and Xu (2018) analyzed the VLBI CONT14 continuous 2-week observing campaign data and concluded that source structure error amounts to half the VLBI error budget. Work is continuing on how best to correct via imaging techniques the source structure error in the historical S/X data set (1980-present) as well as into the future and for next generation VGOS broadband observing.

**ICRF3 and Other ICRF Accuracy/Precision Investigations**

Krásná and Titov (2017) have investigated an alternative method of estimating galactic acceleration (secular aberration drift). They estimate for each source a global scale parameter relative to the a priori terrestrial reference frame. Considering the RA and DEC dependencies of the scale parameter, it turns out that the galactic acceleration vector (GA) can be derived from the scale parameter estimates for each source. Krásná and Titov then investigate the dependence of GA on the minimum number of observations required for a source to be included in the estimation. They obtained the same results with VieVS and with OCCAM software. Several estimates of the galactic aberration amplitude were then compared: 1) All VLBI data 1979-2016, standard estimation, $6.1 \pm 0.2 \ \mu$as/year; 2) VLBI R1/R4/NEOS/CONT sessions 1993-2016, standard estimation, $5.4 \pm 0.4 \ \mu$as/year; and 3) All VLBI data 1979.7 to 2016.5, scale parameter method, number of observations/source > 50, $5.2 \pm 0.2 \ \mu$as/year.

The IVS Aberration Working Group completed its investigation and recommended a galactic aberration constant of $5.8 \ \mu$as/yr for the ICRF3 solution. The aberration constant is the galactocentric acceleration scaled by the velocity of light. This constant was derived from a
Calc/Solve solution using all of the data (1979 to 2018) that was to be used for the ICRF3 solution. Galactic aberration with this constant and with a reference epoch of 2015.0 was applied as an a priori model in the final ICRF3 solution. The epoch 2015.0 is close to the Gaia DR2 reference epoch of 2015.5. Applying the model has the effect of removing the decades long effect of aberration on VLBI source positions thus allowing better comparisons between VLBI and Gaia positions. The work of the IVS WG is summarized in MacMillan et al. (2019) (submitted).

Ma C. et al. (2016) discussed different issues that needed to be addressed in the development of ICRF3. The site observation data distribution has improved significantly so that southern hemisphere sites contribute 40% of all observations compared with 10-20% from 1995 to 2009. The average source position noise (uncertainty computed by decimation test) have improved since ICRF2 (2009) from (52 µas, 62 uas) to (32 µas, 43 µas). One of the significant systematic effects that has been found in recent global CRF solutions is that there is a systematic bias in declination that peaks at about 0.1 mas at 30ºS between current solutions using all data through 2016 and ICRF2 positions that were based on data from 1980 to 2009. This bias disappears if the Australian AUSCOPE network data observed during the period since ICRF2 is removed from analysis solutions. It is not clear whether the addition of the southern hemisphere stations has improved the observing geometry for southern declination sources relative to the source geometry available for ICRF2 or whether some AUSCOPE station errors cause the bias. Tests indicated that troposphere delay modeling does not cause the systematic. There was some evidence that application of phase calibration correction at two of the AUSCOPE stations had the effect of causing the declination systematic. The group delay calculated from the phasecal correction appeared to indicate cable stretching that increased with the antenna azimuth difference (and thereby the delay error) from the cable zero (neutral) point. There has not been time to derive a reasonable method of correcting this error in all of the AUSCOPE data.

Mayer et al. (2017) studied the relationship between the VLBI tropospheric delay modelling and source positions. In particular, the effect of a priori ray-traced slant delays on source declination was investigated. Global source coordinates of 5830 geodetic VLBI sessions incorporating about 10 million group delay measurements were estimated. This data set was used for the International Celestial Reference Frame 3 (ICRF3) prototype solutions as of December 2016. They found a significant bias in source declination of about 50 µas; which can be found between a normal solution and a solution where a priori ray-traced slant delays are used. More traditional tropospheric delay modelling techniques, such as a priori gradients, were tested as well. Significant differences of about 30 µas in declination can only be found when absolute constraints are used for a priori gradient models.

Figure 1.4.8 shows the effect of different troposphere modeling options on the CRF declination bias of current solutions relative to ICRF2 that was based on data until 2009 (smoothed over declination). The options tested were 1) standard wet zenith and gradient parameter estimation, 2) troposphere ray-traced delays applied without gradient estimation, 3) ray-traced delays applied with gradient estimation, 4) standard solution with elevation weighting, 5) standard solution using DAO gradient as a priori but with constraints, and 6) standard solution with DAO gradients with gradient constraints. The difference in declination bias between the standard solution (1) and the solutions (2 and 3) that used ray-traced delays yields a declination bias that peaks at about 60 µas at about 30ºS. The rms variability of this difference is significantly greater if gradients are not estimated in the ray-traced delay solution. The conclusion from Fig. 1.4.8 is that none of the models make any significant
reduction in the declination bias implying that the declination bias is not due to tropospheric delay modeling errors.

Fig. 1.4.8. Difference between declinations from each solution and ICRF2 declinations (Mayer et al., 2017).

Liu et al. (2018) estimated the accuracy of radio source catalogs by analysis of decimation VLBI solutions. This involved a computation of the ‘precision’ of a catalog using two methods of analysis. The derived noise floor was 20-25 μas for sources observed in at least 10 24-hour observing sessions. The paper expanded on the analysis done for the ICRF3.

Gattano et al. (2018) investigated radio source stability and the VLBI celestial reference frame by using Allan standard deviation analysis of source position time series. They found that the concept of a ‘stable source’ is not realistic and that very few source coordinate series are white noise. Most series are exhibit flicker/red noise indicating that accumulating observations will not necessarily improve the astrometric position. Figure 1.4.9 provides an example of source position (right ascension and declination) time series and the corresponding Allan standard deviation (ASD) as a function of time scale. As the time scale increases, the ASD increases and essentially becomes unstable meaning that increasing the number of observations does not improve precision. In terms of the VLBI geodetic observing program, we should try to minimize the effects of instability by modifying the VLBI geodetic observing source list by removing sources that are currently exhibiting instability. For the next ICRF, the Allan variance should be used rather than assuming that noise in source position time series is Gaussian.
Fig. 1.4.9. The four-quadrant plot shows (left panels) coordinate time series with their standard deviation given by the blue area and (right panels) the Allan standard deviation as a function of the averaging timescale (black solid line), where the colored background indicates the behavior of the dominating noise (stable in gray, unstable in red, intermediate in pink), the black dotted lines represent the interval of confidence (at 90%) on the estimated Allan standard deviation at each timescale, and the gray lines represent the boundaries of deciles as computed from the Monte Carlo test. The percentage in the top right corner gives the probability that the source is AV0 (stable and not dominated by unstable noise). (Gattano et al., 2018)

Effect of A Priori High Frequency EOP models on Nutation Estimation

Panafidina et al. (2017) and Panafidina et al. (2019) investigated the propagation of polar motion and UT1 models into nutation offsets estimated by VLBI. Earth orientation parameters connect the terrestrial and celestial reference frame. Within the analysis of space geodetic observations, errors of the applied subdaily Earth rotation model can induce systematic effects in different estimated parameters. They focused on the error propagation from the subdaily model for Polar Motion and Universal Time in the estimated Celestial Pole Offsets in the processing of VLBI observations. It was found that, even though the subdaily model for polar motion does not contain any retrograde daily terms, a part of the signal from the subdaily model is numerically mistaken for a retrograde daily signal, which contributes to the estimated nutation offsets. They showed that the variations in UT1 with daily periods and the estimated nutation offsets influence each other. The presented model of error propagation from the subdaily UT1 into the daily CPO allows one to predict and explain the behaviour of
CPO estimates of VLBI solutions computed with different subdaily Earth rotation models, which can be used to test the accuracy of different subdaily tidal models.

**Modeling Troposphere Noise in VLBI Analysis**

Krasna and Gipson (2017) investigated the effect of correlated noise between observations involving the same antenna. The standard assumption in the routine VLBI analysis is that the observations are station and time independent which manifests itself in a diagonal observation covariance matrix. But this simplification causes a mis-characterisation of the measured group delays leading to incorrect estimation of parameters and too optimistic formal errors. In the first step they compared the estimated baseline length scatter from CONTinuous VLBI campaigns using two way of reweighting observations, i.e. adding baseline dependent and elevation dependent noise. In the second step they introduced correlations into the observation covariance matrix focusing on mis-modeling of the atmosphere and taking into account correlations between observations at a common time. They demonstrated that this reduces the baseline length scatter, indicating that the results are more consistent day-to-day. They also showed that introducing the correlations improves the agreement between VLBI and GPS measured polar motion.

**VLBI + GNSS combination**

Lambert et al. (2018) (conference presentation) investigated the rigorous combination at the normal equation level of GNSS and VLBI to improve Earth orientation and reference frames. Comparison of polar motion and LOD with atmospheric angular momentum showed a slight increase in the correlation after the combination of GNSS and VLBI. The addition of GNSS to VLBI appeared to improve the determination of nutation for weak sessions. It is expected that this work will be published in 2019.

**References**

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IAG WG 1.4.3: Improving VLBI-based ICRF for Geodesy

Chair: Sébastien Lambert (France)

Members
- François Mignard (France)
- Jacques Roland (France)
- Maria Karbon (Germany, now France)
- Stanislav Shabala (Australia)
- Zinovy Malkin (Russia)
- Daniel MacMillan (USA)
- Manuela Seitz (Germany)

Introduction and context

The IAG working group (WG) 1.4.3 was formed mid-2016 with the title "Improving VLBI-based ICRF for Geodesy" and membership including

The IAG WG 1.4.3 was not mandated for building any final product but rather designed for discussing the recent evolution of the VLBI celestial reference frames and raise some questions for the future. The studies that are mentioned below were not realized in the framework of IAG WG 1.4.3 but either in the frame of other WGs and consortia or independently from any formal structure.

In fact, some of the IAG WG 1.4.3 members were involved in critical actions related to the establishment of the new global reference frames via the IAU Division A WG on the Third Realization of the International Celestial Reference Frame¹ (S. Lambert, Z. Malkin) and the Data Processing and Analysis Consortium of the ESA Gaia mission² (F. Mignard, S. Lambert). These two structures gave birth to the ICRF3, the latest and the currently most accurate celestial reference frame, adopted by the IAU as fundamental reference frame in August 2018, and to the second data release (DR2) of Gaia, published in April 2018. Besides these two major products, several works were achieved to improve the accuracy of the VLBI-based CRF or understand the sources of error. We present here a summary of these achievements.

Progress in sub-milliarcsecond realizations of the ICRS by VLBI

The ICRF3 was released mid-2018 by an international team formalized by an IAU working group (IAU Division A WG on the Third Realization of the International Celestial Reference Frame) chaired by P. Charlot. The ICRF3 catalog was produced by a direct fit of the radio source coordinates to VLBI delays over 1979-2018 along with all the geodetic parameters traditionally estimated in a standard solution (Earth rotation parameters and rates, station coordinates and velocities, sub-daily troposphere wet delays and gradients, sub-daily clock drifts). The astronomical and geophysical modeling used the state-of-the-art models and was compliant with the IERS Conventions 2010. Two novelties make the ICRF3 different from earlier releases: (i) the Galactic aberration was included in the astrometric modeling based on a value recommended by a dedicated IVS working group (MacMillan et al. 2019), and (ii) it is provided at three wavelengths (8 GHz, 22 GHz, and 32 GHz). Another important point is the release of the Gaia-CRF2 catalog (Mignard et al. 2018; see also Prusti et al. 2016, Brown et

¹ https://www.iau.org/science/scientific_bodies/working_groups/192/
² https://www.cosmos.esa.int/web/gaia
al. 2018, Lindegren et al. 2018) that is an independent realization of the ICRS in the optical with an accuracy comparable with VLBI. The comparison between VLBI and Gaia (studied independently by the ICRF3 WG and the Gaia DPAC) provided important insights into the large-scale systematics and helped considerably in the validation of the VLBI solutions. Details about the ICRF3 realization are reported in Charlot et al. (2019).

**Methodologies that could improve the ICRF**

**Accuracy versus standard error**

One important question that the geodetic community must constantly raise is the accuracy of the products. *Accuracy* means here the closeness to the true value. This quantity has to be looked versus the *standard error*. The standard error on a parameter (e.g., source coordinate) reflects the number of observations rather than the closeness to the ‘truth’. In absence of measurements from an independent technique, one cannot generally get any evidence on whether the parameter is correctly determined. There exists, generally, systematics (e.g., network effect) that push the parameter away from the ‘true’ value by more than the standard error. To remedy this problem, one can rescale errors by adding quadratically a noise floor and a scale factor: this is a method that was applied in several studies related to ICRF (see, e.g., Fey et al. 2015) or other VLBI products (e.g., Herring et al. 2002). Once this is done, the modified standard errors generally explain the difference to the mean value and the data is more relevant for scientific exploitation.

Gattano et al. (2016) studied the nutation data as provided by the various IVS analysis centers and showed that nutation series differed significantly in comparison of their standard errors. They provide scale factors and noise floor for each series. Interestingly, the differences between series (that are supposedly obtained from the same VLBI observations!) could arise from subtle variations in the analysis configuration including CRF *a priori* and constraints. Though Gattano et al. showed that these differences impacted marginally the determination of the resonance frequency of the free core nutation, the influence was much more dramatic on the free inner core nutation, hampering its detection!

Liu et al. (2018) studied the accuracy of the VLBI catalogs versus their standard error by two methods: (i) the one used in Fey et al. (2015) and Charlot et al. (2019) for rescaling the ICRF2 and ICRF3 errors and based on difference between - somehow - independent solutions, and (ii) the one used by Lambert (2014) and Gattano et al. (2016) based on a comparison between scatter and formal errors. Both methods gave comparable results. The noise floor was estimated to be 20-25 μas for sources observed in at least ten sessions, which is consistent with the conservative noise floor of 30 μas chosen for the ICRF3, and it could be reduced down to ~10 μas for sources which have been observed in more than 1000 sessions.

**Handling the source structure and evolution**

The position of the radio source is not fixed: VLBI actually measures the position of the brightest part of the jet that is moving by - for some sources - several tenths of mas per year within a structure that can be extended over a comparable angular size. Such apparent ‘motion’ of the radio center is caused by the ejection or flux changes of VLBI components. It turns out that considering that the ICRF is made up of fixed reference points, this can lead to an unexpectedly rotating (or distorting) frame. Such a pollution would leak into other parameters including nutation and UT1. Several works addressed the problem of handling the extended, moving radio sources.
Plank et al. (2015) simulated source structures with a two-component model to investigate the potential effect on the frame determination. They found that systematics could rise up at the level of 10-80 μas and proposed an alternative handling of source positions based on a parameterization along and perpendicular to the jet.

Many sources are variable, and flux density monitoring provides an opportunity to study source structure. Using high-cadence (many observations over a few days) flux density monitoring, Schaap et al. (2013) showed that sources which show scintillation have lower structure indices and better astrometric stability. Studying longer-term (months to years) variability, Shabala et al. (2017) showed that sources near the peak of their light curve are more compact. These investigations open up a possibility of weighting the contribution of sources to the frame by their expected structure, even if detailed structure information (i.e., VLBI images) is not available.

Karbon et al. (2016) proposed an interesting parameterization of the source positions similar to what is done for the ITRF and based on multivariate adaptive regression splines. Such a method appears particularly relevant for some very active sources. Also, this method is a good compromise, in terms of number of parameters, between the fully global solution and intermediate approaches in which one estimates (some) source coordinates as session parameters. Moreover, once the source model is known, the minimal constraint can still be applied to the full sample of sources. Karbon et al. (2016) reported that the rms of nutation offsets was improved by 10%. An optimization and a generalization of such a modeling in all VLBI analysis chains could be promising.

Although the trajectory of VLBI components is regularly monitored and model-fitted with a nice accuracy thanks to VLBI in imaging mode (e.g., Lister et al. 2019) there is no consensus on the true nature of the ‘core’ that could contain single or multiple black hole systems. Based on a celestial mechanics approach, Roland et al. (2015, 2019) suggested that several black holes may coexist within few hundreds of μas (see, e.g., Fig. 1.4.10 for radio source 1928+738, Roland et al. 2015). The presence of several active black holes within 1 mas has strong implications on the frame realization: the position of the radio center as measured by geodetic VLBI will move accordingly to the ratio of the fluxes of the various bright (eventually ejected) components, resulting in jumps in the apparent trajectories. This could be at the origin of the various noise types detected by Gattano et al. (2018) using advanced spectral methods. Such results can lead to interesting alternative modeling and/or parameterization of source positions in VLBI analysis, complementary to those of the studies cited earlier.
The objection that ICRF is produced through a single technique – while the ITRF is obtained from four independent techniques – is regularly raised within the geodetic community. Though efforts are made in the direction of obtaining a CRF from the combination of VLBI, GNSS, SLR, and DORIS at the normal equation or the observation level, so-called ‘Combined CRF’ - assimilating data from techniques that are not sensitive to radio source positions but that can constrain other common parameters - still have to be assessed in terms of accuracy. There is no doubt that the next few years will be devoted to such tasks.

Kwak et al. (2018) and Soja et al. (2019) produced such consistent realization of terrestrial and celestial reference frames with associated Earth orientation parameters by processing data from the four techniques over 2006-2015 in a single software package. They demonstrated the feasibility of such a combination with a satisfactory consistency with the VLBI-only solutions at the level of tens of μas. Some sources of errors (e.g., local ties) still have to be addressed.

Other teams are working on this exciting topic such the French GEODESIE project (Coulot et al. 2017) that proposes a geodetic/geophysical data assimilation within a single analysis chain to produce new references and geodetic/geophysical series (e.g., Earth orientation parameters, sea level) freed from terrestrial/celestial reference frame effects.

One must keep in mind that, if the combination of several techniques returns, in general, lower standard errors, reduced noise level and lowered correlations between parameters, this does not mean that the obtained parameters are more accurate. Systematics could still arise and lead to misinterpret the results. The accuracy of the combination products should be assessed by comparison with independent measurements or physical phenomenon measured or modeled independently (e.g., Ray et al. 2005, Lambert et al. 2017). For instance; global reference frames can be compared with realizations from independent techniques (e.g., upcoming releases of Gaia). The rigorous homogeneity of the geophysical and astronomical modeling between all the techniques is also mandatory, although sometimes hard to realize in
practice. Setting up an operational multitechnique combination at the observation or normal equation level that meets the objectives of accuracy of one millimeter in position and one millimeter per year in stability will therefore constitute one of the challenges of the next decade for the geodetic and astrometry communities and the international services.

References


Commission 1 Joint Working Group 1.1: Site Survey and Co-Location

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Vice Chair: John Dawson (Australia)

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- Jim Long, NASA SGP (USA)
- Ralf Schmid, IGS (Germany)
- Rüdiger Haas, IVS (Sweden)
- Xavier Collilieux, IGN Surveying entity (France)

Members

Activities and publications during the period 2015-2019

The activities have been directed towards a common terminology in space geodesy in order to facilitate exchange of data between services. This has improved surveying practices for DORIS with a local tie uncertainty between observation and topocentric measurements now estimated to be of order 3 mm. Specially adapted programs have been developed to monitor the geometric reference points of VLBI telescopes with terrestrial total stations during observation schemes. Internal VLBI telescope deformations have also been shown to contribute significantly to position uncertainties, and further development in this field is expected. The Onsala-Metsähovi baseline was observed between the IGS and IVS stations at the sites, simultaneously with terrestrial and GNSS measurements of the local ties; processing has been delayed. Different GNSS antenna calibration methods exhibit results that prohibit the determination of local ties to the desired level; an issue which touches the scope of the WG but requires a broader approach.

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Commission 1 Joint Working Group 1.2: Modelling Environmental Loading Effects for Reference Frame Realizations


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Activities and publications during the period 2015-2019

Description of the activities including graphics, tables, literature (references to the activities)

The activity of the working group has been focused on the impact of loading deformation in GNSS time series. Several loading models have been used and compared. Loading corrections have been applied a posteriori and at the observation level. Results have been presented during a splinter meeting organized on Wednesday 26th April, 2017 at the EGU (see report in Appendix). The meeting came to the following recommendations for 2017 – 2019:

- Extend investigation of loading effects to other geodetic techniques (VLBI, SLR) and perform an homogeneous analysis with all the techniques
- Check and clearly display the strategy regarding loading effects adopted by each analysis center
- An up to date list of references should be displayed on the working group website
- This working group should be continued
- A workshop is suggested for 2018 to discuss points that have not been discuss during the splinter meeting (loading and geocenter motion, current and future approaches in modeling loading effects, recommendations to IERS)
Commission 1 Joint Working Group 1.3: Troposphere ties (joint with Sub-Commission 4.3)

Chair: Robert Heinkelmann (Germany)
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Activities and publications during the period 2015-2019

The new working group was established in 2015. The terms of reference and objectives were drafted, discussed and approved. The working group chair gave the first presentation about the working group objectives at the IAG Commission 4 Meeting at the Wroclaw University of Environmental and Life Sciences, Wroclaw, Poland, on 5th of September 2016, see http://www.igig.up.wroc.pl/IAG2016/?page=2. The first regular Working Group Meeting was held on the 26th of April 2017 aside the EGU General Assembly at Vienna University of Technology, Vienna, Austria.

During past years, Geodetic Observatory Pecny (GOP) has developed a powerful database, GOP-TropDB (Gyori and Douša, 2017), for the intra-/inter-technique comparisons for tropospheric parameters stemming from data analyses of space geodetic techniques. The database was completed with a web-gui service for interactive exploration of site/pair metadata and comparison statistics.

It is under construction within the IGS Tropospheric WG (Hackman et al, 2016). The current database is ready to accommodate tropospheric path delays in zenith and horizontal gradients estimated using data of GNSS, VLBI and DORIS, Numerical Weather Model (NWM) re-analysis and radiosondes at least. For inter-technique comparisons of nearby stations, tropospheric parameters usually refer to different locations and thus require vertical, time-dependent correction between site reference altitudes. We developed and assessed several models for calculating tropospheric ties/corrections and vertical scaling with
support of different parametrization, vertical approximations and different meteorological data.

The tropospheric ties are optimally separated into two components - zenith dry and wet delays - and we thus focused on developing new models particularly for the wet scaling (Dousa and Elias, 2014). Different strategies for both wet and dry scaling were evaluated in the scenario using numerical weather data fields only, i.e. by approximating NWM differences in vertical profile by using new models for parameter scaling. Additionally, the impact of tropospheric ties was assessed in a comparison of GNSS and radiosonde tropospheric parameters and it will be finally evaluated by applying tropospheric ties specifically for GNSS and VLBI intra/inter-technique site collocations.

The online service has been developed for calculating tropospheric parameters from NWM reanalysis which can be directly used for several scenarios of calculating tropospheric ties. The web is currently available at http://www.pecny.cz/Joomla25/index.php/gop-tropdb/tropomodel-service and it is under preparation to become a part of the IGS Tropospheric WG webpages (http://www.igs.org).

Swisstopo is since years active in generating information which allow to extract tie information. With the enhancement from GPS to GPS/GLO in 2008, 9 from 30 site antennas and receivers were not switched to the new technology: parallel to the continued GPS-only station double stations were build. Furthermore, local tie measurement linked these double stations on a precision of a millimeter (baselines of some 10 meters).

In May 2015, all permanent stations (with the exception of the old GPS-only stations) were enhanced to GPS/GLO/GAL/BDS and a data flow based on RINEX3 was established in summer 2015. Since summer 2016 the complete processing chain is switched to Multi-GNSS using a special development version of the Bernese Software and using CODES MGEX orbit products. The tie information is extremely helpful, because the antennas were "only" calibrated on GPS/GLO.

Routine inter system transformation parameters are calculated on a daily basis, showing the differences of coordinates and troposphere parameters between GPS and the satellite systems GLO/GAL/BDS. Troposphere biases are extremely sensitive to analysis models (especially the antenna PCVs for receiver and satellite antennas). These parameters are made available online. Example ZIM2:
http://pnac.swisstopo.admin.ch/pages/en/qsumzim2.html#TRA_LONG

Local refraction effects in space geodetic techniques are normally investigated by small scale GNSS networks. However, with the new pair of radio telescopes at the Geodetic Observatory Wettzell in Germany, the Institute of Geodesy and Geoinformation, University of Bonn, is now able to carry out similar investigations with geodetic VLBI observations, which are affected by the same refraction phenomena. The main objective is to analyse systematic effects between the tropospheric parameters in space and time. In a further step, this scenario is augmented by a local GNSS network set up on the Wettzell area in order to investigate the systematics between different measurement techniques.

The Vienna University of Technology contribution to JWG 1.3 aims at improving the understanding of systematic effects in tropospheric delay modelling between various satellite techniques. First action is related to the modelling of hydrostatic effects.
Comparisons between in-situ measurements of pressure and global HRES weather model data (as provided by ECMWF) reveal in general high accuracy in pressure within 0.5 +/- 1 hPa. Slightly worse agreement was found between in-situ data and regional weather model data (60% larger standard deviation). However, independent from the pressure sources high consistency can only be guaranteed if comparable data processing methods are applied. In particular, vertical interpolation methods and distance dependent pressure variations are further investigated and compared at co-located sites.

Further activity is related to the modelling of wet delays. The GNSS tomography technique allows for estimation of accurate wet refractivity fields in the lower atmosphere. By vertical integration or ray-tracing through these fields, accurate tropospheric wet delays can be derived. Introduced into the parameter estimation process of various space-geodetic techniques their impact on the station coordinates is analysed. Therefore, the wet delays are either treated as a priori information or as replacement of the tropospheric parameters.

ASI/CGS is going to contribute to objective 1 through VLBI and GNSS inter-technique comparison of atmospheric parameters at the eight European co-located sites. These sites are associated with the European Reference Frame (EUREF) and the European part of the International VLBI Service for Geodesy and Astrometry (IVS), called European VLBI group for Geodesy and Astrometry (EVGA). We plan to compute long-term time series of the differences between the EPN-Repro2 (Pacione et al. 2017) for the period 1996–2014 completed with the EPN operational products afterwards and the EVGA combined solutions.

The German Space Operations Center (GSOC) of the German Aerospace Center (DLR) performs precise orbit and clock determination for satellites of the global and regional navigation systems GPS, GLONASS, Galileo, BeiDou, and QZSS on a routine basis. A global network of about 150 stations is processed with the NAPPOS software to solve for station coordinates, troposphere and Earth rotation parameters, receiver and satellite clocks as well as satellite orbit parameters. DLR/GSOC provides normal equations obtained from the multi-GNSS analysis in SINEX format including station coordinates, troposphere, and Earth rotation parameters for analysis and combination studies of the joint working group.

In last year Shanghai Astronomical Observatory, Chinese Academy of Sciences, studied the possibility of common tropospheric parameters as another ‘local ties’ of TRF. The work mainly includes the following:

1) We compared the tropospheric parameters obtained by different techniques at co-located sites and found the VLBI tropospheric zenith delay is approximately consistent with that of GNSS. But there exists a big constant term and a long period (about 1 year) term in the tropospheric zenith delay difference between SLR and GNSS.

2) We compared the mapping function used in SLR (FCULa mapping function) and GNSS (GMF) at all co-located sites, we found the difference is very small.

3) Compared with the strategy used in GNSS, our SLR orbit determination didn’t consider estimating the ZTD parameters. So, we change our software to estimate the ZTD parameters in SLR. The results show that there are big differences between the dry zenith delay models of SLR and GNSS. We analyzed the difference and found that it is almost approximately a scaling factor between the two kinds of dry zenith delays. The factor is equal 1.061392746364195.

4) Then we compare the wet delays obtain by SLR and GNSS. And there was still a big offset exiting in SLR and GNSS zenith wet delay because the radio wavelength technique is more sensitive to water vapor in troposphere than optical wavelength technique. The SLR zenith wet delay is very small.
5) Next step, we decide to consider the effect of the horizontal gradients of atmosphere on tropospheric delay in SLR, which is described by G. C. Hulley (2007). We will adopt the parameterization used in GNSS to our SLR data processing, then estimate the horizontal gradient parameters $G_N$ and $G_E$, finally compare them with GNSS. We will continue to find the rules of the ZTD offsets between SLR and GNSS which is of great help to apply tropospheric ties for a combination of the space geodetic techniques.

At GFZ Potsdam we installed a service which provides Numerical Weather Model (NWM) based tropospheric parameters valid for radio frequencies. The station specific values (zenith delays, mapping function coefficients and gradient components) are available for ~800 GNSS stations. Recently we updated our ray-trace algorithm (Zus et. al 2014) in order to derive tropospheric parameters valid for optical frequencies. Therefore, station specific values (zenith delays, mapping function coefficients and gradient components) are available for ~100 SLR stations as well. The tropospheric parameters are derived from short range forecasts and are available with no latency. The underlying NWM is the NCEP Global Forecast System (0.5 deg resolution, 31 pressure levels). The epochs 0, 6, 12 and 18 UTC are based on 6h forecasts whereas the epochs 3, 9, 15, 21 UTC are based on 9h forecasts. The data and a short description (how to use) are available at ftp://ftp.gfz-potsdam.de/pub/home/kg/zusflo/TRO/.

Currently we do not fully exploit the information from NWMs. For example, we use model level (or pressure level) fields but we do not take into account the near surface fields. Within this working group we will update our algorithms to extract the near surface pressure, temperature and humidity. We will derive the corresponding lapse rates which can then be used as tropospheric ties.

References

