Commission 1 – Reference Frames

http://iag.uni.lu

President: Tonie van Dam (Luxemburg)
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Overview

This commission deals with the theoretical aspects of 1) defining reference systems for geodetic and scientific applications; 2) the practical applications of reference frame realizations; and 2) applied research in reference frame development.

The main objectives of Commission 1 are:

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

The main activities of Commission 1 during the period 2011-2015 include the following:

• A dedicated web site was established immediately after the IUGG General Assembly in Melbourne, where the new Commission members were approved by the IAG Executive Committee. The Web site (http://iag.uni.lu) contains all the information related to the activities and objectives of the commission, its sub-commissions, projects and Working Groups. The Web site is regularly updated directly by the president; Sub-commissions and sub-components prefer to have control over their own websites; links to those websites can be found at the Commission 1 website.

• The terms of reference for the new Commission 1 were compiled and submitted

• Mid-term report compiled and submitted

• Commission 1 Symposium, REFAG, 13-17 October, 2014

• Organization of the IUGG Commission 1 sessions

Main highlights of the activities of Commission 1 Sub-components

Sub-commission 1.1: Coordination of Space Techniques

The activities of SC-1.1 where significant progress has been made since 2011 are the following:

• Establishment of a non-exhaustive list of existing formats at the IAG services and GPS time series providers

• The development of innovative combination aspects such as, e.g., GPS and VLBI measurements based on the same high-accuracy clock, VLBI observations to GNSS satellites, and the combination of atmospheric information (troposphere and ionosphere) of more than one technique.

• Validation of the GGFC fluid models

• An analysis of combining Synthetic Aperture Radar (InSAR), LIDAR and optical image analysis methods.

Sub-commission 1.2: Global Reference Frames

Highlights of the activities of SC-1.2 include the following:

• The estimation of a plate motion model consistent with ITRF2008

• Workshop on Site Surveys and Co-location, Paris, May 2013

• ITRF2014 under development but will be released in 2015

• Comparison of DTRF2008 and ITRF2008 in order to assess the accuracy of the reference frames; The agreement is between 7 and 10 mm and between 0.2 and 2.0 mm/a for the station positions and velocities, respectively, depending on the technique and if only core stations are considered (Seitz et al. 2013)

• A Kalman filter and smoother algorithm has been developed and coupled to the CATREF software, KALREF (JPL)

• GRASP is a proposed satellite mission that will carry very precise sensor systems for all the key geodetic techniques used to define and monitor the TRF. It would allow us to achieve the requirements established by the Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020
• The publication of IGS08 a new IGS reference frame based on ITRF2008 (Rebischung et al., 2012)
• Collilieux et al. (2014) established that the accuracy of the ITRF2008 in terms of origin rate is likely to be less than 0.5 mm/yr on the three components while the scale rate error is smaller than 0.3 mm/yr
• The UN Committee of Experts on Global Geospatial Information Management (UN-GGIM) decided in July 2013 to formulate and facilitate a draft resolution for a Global Geodetic Reference Frame

Sub-commission 1.3: Regional Reference Frames

The main activities of SC-1.3 are the following:
• Increase of the number of GNSS permanent stations within the 6 regional sub-commissions;
• The preparation for the future Galileo system and the development of the EPN towards a multi-system GNSS network started;
• The number of continuously operating GNSS stations that support the SIRGAS Reference Frame is still growing. It is composed by about 300 stations, 140 of which with GLONASS capability, and 60 with real time data transfer;
• The densification of the ITRF and IGS network is made by weekly combinations of 5 regional weekly solutions using different GPS processing software;
• The increase of the number of stations of the CORS network (approximately 480 stations from 28 countries), whose data are processed by three Analysis Centres (ACs). The increase of the number of institutions contributing to APREF in several domains (analysis, archive and stations). The availability of a weekly combined regional solution, in SINEX format and a cumulative solution, which includes velocity estimates;
• The realization of SCAR GPS Campaigns in 2012 and 2013. The data of 40 Antarctic sites are collected in the SCAR GPS database since 1995.

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

• Together with the Working Group Chairs, Johannes Böhm, summarized the main challenges to be addressed in determining the terrestrial and celestial references in the proceedings paper for the IVS General Meeting 2012 in Madrid, Spain (Böhm et al., 2012).
• Böhm et al. (2011) compared the influence of two different a priori gradient models on the terrestrial reference frame as determined from VLBI observations
• Heinkelmann and Tesmer (2013) assess systematic effects between VLBI terrestrial and celestial reference frame solutions caused by different analysis options
• Malkin (2013) outlines several problems related to the realization of the international celestial and terrestrial reference frames at the millimetre level
• Krásná et al. (2013) reaffirm results firstly shown by MacMillan and Ma (1997) that if tropospheric gradients are neglected, the TRF will experience a scale change of 0.65 ppb compared to a TRF with estimated gradients
• Liu et al. (2012) show that the effect of the Galactic aberration strongly depends on the distribution of the sources that are used to realize the ICRS
• Malkin (2011) as well as Krásná and Böhm (2014) investigate the impact of seasonal station motions on EOP and reference frames
• Seitz et al. (2011) show the first results of a consistent computation of CRF, TRF, and the EOP series linking both frames
• Seitz et al. (2012) deal with the consistent realization of ITRF and ICRF by combining normal equations from VLBI, SLR, and GNSS
• Plank et al. (2013) discuss and simulate VLBI observations to satellites at different altitudes

Joint Working Group 1.1: Tie vectors and local ties to support integration of techniques

JWG 1.1 organized a workshop on site surveys and co-location sites, May 2013 in Paris. One of the most important outcomes of the workshop is a list of recommendations that were identified in an open discussion with all the participants. The document sets out tasks with deadlines and assigns an individual to lead each task. The main tasks were outlined as follows:
• Define a clear nomenclature and terminology to be adopted for local tie discussions;
• Define the models to be adopted in the local tie survey data reduction;
• Propose a survey priority list for the next ITRF2013 computation;
• Recommend a surveying frequency;
• Create a local survey data archive; and
• Prepare of a draft document containing the site survey guidelines and specifications.

Joint Working Group 1.2: Modelling environmental loading effects for reference frame realizations

The activity of the working group has been dominated by the IERS campaign “for space geodetic solutions corrected for non-tidal atmospheric loading”, an action item defined at the Unified Analysis Workshop 2011. A call for participation was sent to the analysis technique coordinators of every service in the beginning of 2012. A 6-year loading data set has been generated at The Global Geophysical Fluid Center (GFC) to be used a priori in the data processing of the space geodetic technique observations. Analysis Centers from the four technique services have submitted 12 individual solutions from GNSS, Satellite Laser Ranging (SLR, Very Long Baseline Interferometry (VLBI) and Doppler Orbitography Integrated by satellite (DORIS). These solutions have been analyzed to determine:
• The effect of non-tidal atmospheric loading on the TRF datum and the Earth Orientation Parameters (EOPs);
• The effect of non-tidal atmospheric loading on individual averaged coordinates and velocities; and
• The level of agreement between a priori corrections and a posteriori corrections.

Preliminary results were presented at the EGU in 2013. They are of particular importance for ITRF2014. This effort goes beyond just addressing the bullets above. The main success of this exercise is that it has catalyzed an open dialogue between modeling experts and technique ACs. A splinter meeting has been organized on Wednesday 10th of April 2013 at the EGU and another is planned in 2014.

Joint Working Group 1.3: Understanding the relationship of terrestrial reference frames for GIA and sea-level studies

• Studies concentrated on the evaluation of static- and time variable effects in orbit determination (e.g., Rudenko et al., 2014) and in effects of reference frame (ex)changes (e.g., Couhert et al., 2014)
• Important contributions for the understanding of reference frame issues in sea level research are summarized in Collilieux and Altamimi (2013) and in the External Evaluation of the Terrestrial Reference Frame: Report of the Task Force of the IAG Sub-commission 1.2 (Collilieux et al., 2014).
Joint Working Group 1.4: Strategies for epoch reference frames

The following research results of this JWG include

- Datum realization for epoch reference frames can be improved by using an SLR solution which includes at least LARES in addition to LAGEOS1 and 2,
- The time series of weekly epoch reference frames approximate the complete station motion (linear and non-linear part) very well,
- The neglect of non-linear station motions in long-term reference frames affects the consistently estimated EOP-series by annual and semi-annual signals (Bloßfeld et al. 2014),
- Epoch reference frames do not provide such a high long-term stability as long-term reference frames. With regard to the geodetic datum four-weeks solutions show the highest stability. But non-linear station motions are characterized by short-term effects, which can be approximated better with a weekly or even shorter resolution,
- The integration of 10 spherical SLR satellites in the SLR solution and the combination of the techniques allow for a simultaneous estimation of TRF, EOP and gravity field coefficients in epoch reference frame solutions with high accuracy,
- The weekly combination at the observation level of GNSS and SLR (via satellite co-location) leads to very promising results, which allow the transfer of the SLR-derived centre-of-mass of the Earth to GNSS station network with very high accuracy and for a validation of the local ties at ground sites.
Sub-Commission 1.1: Coordination of Space Techniques

Chair: Tom Herring (USA)

The space geodetic observation techniques, including Very Long Baseline Interferometry (VLBI), Satellite and Lunar Laser Ranging (SLR/LLR), Global Navigation Satellite Systems (GNSS) such as GPS, GLONASS, GALILEO, and COMPASS, and the DORIS system, as well as altimetry, InSAR, LIDAR, and the gravity missions, contribute significantly to the knowledge about and the understanding of the three major pillars of geodesy: the Earth's geometry (point coordinates and deformation), Earth orientation and rotation, and the gravity field as well as its time variations. These three fields interact in various ways and they all contribute to the description of processes in the Earth System. Each of the space geodetic techniques contributes in a different and unique way to these three pillars and, therefore, their contributions are critical to the Global Geodetic Observing System (GGOS).

Sub-Commission 1.1 coordinates efforts that are common to more than one space geodetic technique, such as models, standards and formats. It shall study combination methods and approaches concerning links between techniques co-located at fundamental sites, links between techniques co-located onboard satellites, common modeling and parameterization standards, and perform analyses from the combination of a single parameter type up to a rigorous combination on the normal equation (or variance-covariance matrices) as well as at the observation level. The list of interesting parameters includes site coordinates (e.g. time series of combined solutions), Earth orientation parameters, satellite orbits (combined orbits from SLR, GPS, DORIS, altimetry), atmospheric refraction (troposphere and ionosphere), gravity field coefficients, geocenter coordinates, and others. One important goal of SC1.1 will be the development of a much better understanding of the interactions between the parameters describing geometry, Earth rotation, and the gravity field as well as developing methods to validate combination results, e.g., by comparing them with independent geophysical information.

To the extent possible SC1.1 should also encourage research groups to develop new observation techniques connecting or complementing the existing set of measurements.

Sub-Commission 1.1 has the task to coordinate the activities in the field of the space geodetic techniques in close cooperation with GGOS, all of the IAG Services, and with COSPAR.

Objectives

The principal objectives of the scientific work of Sub-Commission 1.1 in collaboration with GGOS are the following:

• Study systematic effects of and between space geodetic techniques.
• Develop common modeling standards and processing strategies.
• Comparison and combination of orbits derived from different space geodetic techniques.
• Explore and develop innovative combination aspects such as, e.g., GPS and VLBI measurements based on the same high-accuracy clock, VLBI observations to GNSS satellites, and the combination of atmospheric information (troposphere and ionosphere) of more than one technique.
• Establish methods to validate the combination results (e.g., with global geophysical fluids data).
• Explore, theoretically and practically, the interactions between the gravity field parameters, EOPs, and reference frames (site coordinates and velocities plus extended models),
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improve the consistency between these parameter groups, and assess, how a correct combination could be performed.

- Study combination aspects of new geodetic methods such as Synthetic Aperture Radar (InSAR), LIDAR and optical image analysis methods.
- Additional objectives of Sub-Commission 1.1 are:
- Promotion of international scientific cooperation.
- Coordination of common efforts of the space geodetic techniques concerning standards and formats (together with the IERS and GGOS).
- Organization of workshops and sessions at meetings to promote research. - Establish bridges and common activities between SC1.1 and the IAG Services.

Links to Services

Sub-Commission 1.1 will establish close links to the relevant services for reference frames, namely Global Geodetic Observing System (GGOS), International Earth Rotation and Reference Systems Service (IERS), International GPS Service (IGS), International Laser Ranging Service (ILRS), International VLBI Service for Geodesy and Astrometry (IVS), and International DORIS Service (IDS) and the International gravity services.

Working Groups:

WG 1.1.1: Creation of common geodetic coordinate time series

Chair: Laurant Soudarin (Laurent.Soudarin@cls.fr)
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Members
- Bernd Richter (BKG) GGOS portal manager
- Thomas Herring (MIT) IERS Analysis Coordinator
- Xavier Collilieux (IGN) ITRS Combination Center
- Manuela Seitz (DGFI) ITRS Combination Center
- Laurent Soudarin (CLS) IDS representative
- Paul Rebischung (IGN) IGS representative
- Erricos Pavlis (Univ. of Maryland, Baltimore County) ILRS representative
- Alexis Nothnagel (Uni. Bonn) IVS representative
- Médéric Gravelle (Uni. La Rochelle) user (SONEL)
- Yehuda Bock (Scripps Institution of Oceanography) user (SOPAC GPS webservice)
- Simon Williams (Proudman Oceanographic Laboratory) user (CATS software)
- Xiaoping Wu (JPL) user

Summary of the activity of the WG since its creation

The first meeting of the WG was organized in San Francisco at AGU, on 6-Dec, 2012. Despite the very short time of meeting, we had rich discussions on some important issues concerning the data: time scale, reference system, coordinate system… The metadata are of
prime importance in the format because they will give the necessary information to identify the time series and to make them easily used. They were briefly discussed. S. Bachman, representing GGOS informed us of the existence of ISO standards for Geospatial metadata, and of the metadata search engine included in the GGOS portal.

The second meeting of the WG was held in Vienna at EGU, on 10-April, 2012 with a few participants because of travel restrictions for our NASA colleagues and the meeting of GGOS Bureau of Networks and Communications at TUW at the same time. A list of existing formats at IAG services and GPS time series providers were presented. Several issues concerning the time series were discussed (epoch, time tag, accuracy, correlations,…).

The activity of the WG was presented in the session “Unification of product formats” at the IERS retreat held in Paris in May 2013. The purpose of the session was to discuss the benefits of common formats for the IERS data products, especially for EOP estimates and position time series. It was expressed that there is a clear need to have a standardized format to allow easy comparison. There were not any particular recommendation concerning position time series, just that the WG must continue developing a common format and investigate methods for web access to these files (including graphical presentations). Meeting summary and presentations are online at: http://www.iers.org/nn_128276/IERS/EN/Organization/ Workshops/Retreat2013.html

A third meeting took place in Vienna, on 15-April, 2015, at EGU. Based on a non-exhaustive list of existing formats at IAG services and GPS time series provider, metadata and data have been examined. The next step is to define the necessary elements for the time series exchange format (metadata content, data table, mandatory and optional inputs) as well as the units, the coordinate system, the date and time system.

Analysis of time series formats from IDS (STCD), PBO/UNAVCO, NGL, ULR, SOPAC

The WG has established a non-exhaustive list of existing formats at IAG services and GPS time series provider. I examined the time series formats developed by the (a) IDS (STCD format), (b) PBO/UNAVCO, (c) NGL, (d) ULR, (e) SOPAC (see the references in Appendix). These formats have been developed for the own needs of each of these institutions. Examples

There are (at least) three different formats at NGL:
- txyz2 for xyz time series,
- tenv for east, north, up time series,
- tenv3 an upgraded version of tenv using a decomposition of the north, east and vertical coordinates in integer and fractional parts to, if I understand correctly, (1) keep the values in the format in case of important drifts (e.g. AMU2 moving 10 meters per year) or jumps more than 10 meters, (2) make plotting easier (simply plot the fractional parts), (3) detect problems from integer parts.

Note that PBO/UNAVCO has developed formats for various products: GPS station position (POS file), GPS velocity (VEL file), GPS phase RMS (RMS file), ...

The format developed by SOPAC is the most complete.
Type of format:

The first four (IDS, PBO, NGL, ULR) are text format while the latter (SOPAC) is a XML format (XML for Geodesy project).

- **IDS STCD format**: metadata are given in the header divided in blocks derived from the SINEX format; data are in formatted columns separated by blanks; metadata block and data block are easily identifiable.
- **PBO**: metadata are given in the first part of the file; data are in formatted columns separated by blanks; metadata block and data block are not clearly separated.
- **NGL**: this format does not include metadata; data are in formatted columns separated by blanks.
- **ULR**: metadata lines start with an “#”; data are in formatted columns separated by blanks.

**SOPAC**: metadata and data are encoded in XML language.

**Content:**

**Data**

Main characteristics of the fields:

- **IDS**: position differences XYZ and NEU; one date system; no correlation.
- **PBO**: positions XYZ and position differences XYZ and NEU; 2 date systems; correlations.
- **NGL**: positions differences NEU; 4 date systems; correlations.
- **ULR**: position differences NEU; one date system; no correlation.
- **SOPAC**: positions XYZ and NEU + delta position NEU; 2 date systems; correlations; quality index.

<table>
<thead>
<tr>
<th>Station name</th>
<th>IDS</th>
<th>PBO/UNAVCO</th>
<th>NGL tenv</th>
<th>ULR</th>
<th>SOPAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>time</td>
<td></td>
<td>Date &quot;yyyyymmdd&quot; and time &quot;hmmss&quot; + decimal MJD (f10.4)</td>
<td>Date (a) + decimal year (f9.4)+ MJD (i5) + GPS week and day</td>
<td>Decimal year (f9.4)</td>
<td>Date &quot;yyyyymmdd&quot; and time &quot;hmmss&quot; + decimal MJD (f11.4)</td>
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<td>X</td>
<td>-</td>
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<td>-</td>
<td>-</td>
<td>m (f15.5)</td>
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<tr>
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<td>mm (f6.1)</td>
<td>-</td>
<td>-</td>
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<tr>
<td>dY</td>
<td>mm (f6.1)</td>
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<tr>
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<tr>
<td>sX</td>
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<td>m (f7.5)</td>
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<tr>
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<td>-</td>
<td>(f6.3)</td>
<td>-</td>
<td>-</td>
<td>(f7.3)</td>
</tr>
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</table>
North - decimal deg (f14.10) (b) - decimal deg (f19.10)
East - decimal deg (f14.10) (b) - decimal deg (f16.10)
Up - m (f10.5) (b) - m (f11.5)
dN mm (f6.1) m (f8.5) m (f9.6) m (f7.4) m (f12.5)
dE mm (f6.1) m (f8.5) m (f8.6) m (f7.4) m (f10.5)
dU mm (f6.1) m (f8.5) m (f8.6) m (f7.4) m (f11.5)
sN mm (f5.1) m (f7.5) m (f8.6) m (f6.4) m (f9.5)
sE mm (f5.1) m (f7.5) m (f8.6) m (f6.4) m (f9.5)
sU mm (f5.1) m (f7.5) m (f8.6) m (f6.4) m (f9.5)
cNE - (f6.3) (f9.6) - (f11.3)
cNU - (f6.3) (f9.6) - (f9.3)
cEU - (f6.3) (f9.6) - (f9.3)
Antenna height - - m (f6.4) - -
Other (c) - Solution type - - quality

(a) YYMMdd ex: 10JUL28
(b) for tenv3, in addition to fractional portions, integer portions of the coordinates are used: longitude (degrees) of reference meridian and integer portion of eastings (m) (from ref. Meridian), integer portion of northings (m) (from equator), integer portion of vertical (m).
(c) in PBO format, this extra column indicates the type of orbit product used to generate the time series (rapid, final, ...). It seems to be the same usage by SOPAC.

Common fields: time, dN, dE, dU, sN, sE, sU.

Positions
• X,Y,Z is probably better than dX, dY, dZ.
• X, Y, Z is unambiguous. dX, dY, dZ depend on the XYZ reference position. Bias between two dX, dY, dZ time series may be introduced when XYZ reference positions differ.
• 7-parameters transformation can easily be applied on X, Y, Z series.
• From X,Y,Z + sigmas and correlations, one can obtained NEU + sigmas and correlations on different ellipsoids.
• XYZ: for a precision of 0.01 mm (+/-6400000.12345) f14.5 (f15.5 too large)
• XYZ: for a precision of 0.01 mm (+/-6400000.12345) f14.5 (f15.5 too large)

Date system:
• IDS and ULR use only one date system, decimal MJD and decimal year respectively, which are “easy-to-plot” system.
• PBO and SOPAC use two date systems: date and time for humans, decimal MJD for plotting tools.
• NGL uses four date systems: date YYMMdd (ex: 96JAN02) + decimal year (ex: 1996.0027) + integer MJD (ex: 50084) + GPS week and day (ex: 834 3).

Comments:
- There is no date system that can be easily understood by human beings and easily used to plot time series. One or several date systems are applied according to the intended use.
Use of several date systems can introduce errors as the correspondence between the systems must be ensured. Moreover, information redundancy increases the size of files.

We previously note that decimal years are not recommended at they can cause problems because of leap years (/365.00, /365.25, or /366.00 ?)

In my opinion, events in a time series such as discontinuities are detectable only when plotted (except in case of large discontinuities and spurious values). This means that a plot tool is used that can often convert date systems to each other. If so, a human readable date system is not absolutely required for the data.

Propositions:
- in metada, start and end epoch expressed in human readable system (e.g. yyyymmdd hhmmss) AND corresponding easy-to-plot system; in data, only easy-to-plot system
- an alternative to MJD date system is the POSIX timestamp (or Unix time http://en.wikipedia.org/wiki/Unix_time) defined as the number of seconds that have elapsed since 00:00:00 UTC, Thursday, 1 January 1970. For instance, 1405555272 corresponds to 2014-07-17T00:01:12Z.

Advantages:
- integer value (no problem of rounding)
- a unique 10-digit format (no 11th digit before year 2287) for time series up to one-second precision. (11 digits are necessary to develop MJD up to the second)
- widely used in Unix system (command: date +%s)

Drawbacks:
- it is neither a linear representation of time nor a true representation of UTC due to its handling of leap seconds. When a leap second occurs, a discontinuity occurs in the Unix time number. At the time the leap second is added, the Unix number is doubled.
  23:59:59 \rightarrow \text{posix time} = S
  23:59:60 \rightarrow \text{posix time} = S+1

representation of time prior to 1970.
- an alternate way to represent date "yyymmdd" and time "hhmmss" is the ISO 8601 standard yyyy-MM-ddTHH:mm:ss.sss (see Annex). SOPAC uses it in the metadata block.

Field format:
- IDS: data content, data format and units defined in header
- PBO: data content and units defined in header, data format not described.
- NGL: no header
- ULR: data content and units defined in header, data format not described.
- SOPAC: data, content, data format and units defined in header

Fixed format or not?
A fixed format is easy to read but is not flexible.
Different possibilities:
- to have different versions of the field format according to the characteristics of the time series as NGL did (tevn and tenv3).
- to define field formats so that a maximum of cases is taken into account; ex: same number of digits for positions and deltas.
- the field format is free and given in the header

**Metadata**

In addition to the time series, a header section is included to give information about the station or site, the source, the content..., except for NGL formats which contain only columns of the time series.

<table>
<thead>
<tr>
<th></th>
<th>IDS</th>
<th>PBO/UNAVCO</th>
<th>NGL tenv</th>
<th>ULR</th>
<th>SOPAC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>File information</strong></td>
<td></td>
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<td>1 format name</td>
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<td></td>
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<td>(name of hosting agency) (f)</td>
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<td>-</td>
<td>X (g)</td>
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<td>25 solution code</td>
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<td>28 processing reference</td>
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<td>-</td>
<td>X (link)</td>
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</table>


| 29 | software | X | - | - | - | X (e) |
| 30 | hardware | X | - | - | - | - |
| 31 | start epoch | - | X | - | - | X (c) |
| 32 | end epoch | - | X | - | - | X (c) |
| 33 | sampling frequency | - | - | - | - | - |
| 34 | number of points | - | - | - | - | X |
| 35 | reference system | X | X | - | X | X |
| 36 | Earth ellipsoid | X | X | - | X | X |
| 37 | reference position X | X | X | - | X +sigmas | X |
| 38 | reference position Y | X | X | - | X +sigmas | X |
| 39 | reference position Z | X | X | - | X +sigmas | X |
| 40 | reference epoch | X | - | - | - | X |
| 41 | reference position N | - | X | - | X | X |
| 42 | reference position E | - | X | - | X | X |
| 43 | reference position U | - | X | - | X | X |
| 44 | VX | - | - | - | X +sigmas | X +sigmas + correlations |
| 45 | VY | - | - | - | X +sigmas | X +sigmas + correlations |
| 46 | VZ | - | - | - | X +sigmas | X +sigmas + correlations |
| 47 | VN | - | - | - | X +sigmas | - |
| 48 | VE | - | - | - | X +sigmas | - |
| 49 | VU | - | - | - | X +sigmas | - |
| 50 | Processing description | - | - | - | - | X |
| 51 | Models | - | - | - | X (b) | X (d) |

(a) Release date
(b) Given as notes
(c) Given in file info and time series info
(d) Largely detailed in a block motion model terms
(e) Given in the processing phase blocks of the processing description
(f) + Nearest city + county + state code + country + tectonic plate
(g) Height + ellipsoid height + geoid height
(h) + foundation type and depth + inscription + installation date + geological characteristics + status

**Propositions for the exchange format**

**FILE FORMAT**

A priori, text formats are the most readable for humans.
- XML language was defined to be both human readable and machine readable.
- YAML is a human-readable data serialization format. It could be a trade-off.

The format should be easily generated so to minimize resistance to using it (initially maybe there could be lots of optional blocks and descriptors) and there needs to be an ease of use of the format (e.g., ideally someone should be able easily plot files in Matlab/Octave/Excel). There should be documentation in the format of loading models that have used and the nature
of the frame for the time-series (centre of mass versus centre of figure). The plate reference system should also be specified. Any scale changes applied should also be specified.

**METADATA**

I identify three types of metadata:
1. file information
2. site information
3. product information

**1. File information**

This block gives information about its type, its date of creation, its provider, and a general description of its content.

Propositions for the content of this block

1. format name (file type)
2. format version (file type)
3. creation date (date of creation of the file) (a) (b)
4. provider name (file provider)
5. provider code (file provider)
6. contact name (file provider)
7. contact email (file provider) (c) (d)
8. type of product (content) (e)
9. Citation information (text containing how to cite use of data)

Comments:
(a) Date of creation and/or date of release? is it useful to distinguish between both cases?
(b) All calendar dates should be given with the same date and time system (see data)
(c) Is it useful to give a complete postal address too?
(d) A web site may be given too
(e) Human readable description. This point is not trivial to standardize. It could be optional if we consider there is only one type of product for this format. However, we may want to distinguish time series of station coordinates, time series of position residuals, etc.

One possibility could be to include the field description of the data tin this block. It would be necessary if some fields are optional. Field descriptors is a good approach with some recommendations for default values if they are not given in the file. Advantage is adding new descriptors would not break old code provided it is originally written so that unknown descriptors are ignored. Disadvantage is reading of software needs to decode each descriptor, straightforward but tedious.
2. Site information

This block gives information about the identification of the site and its location.

Propositions for the content of this block

9  code  (identification)  (f)
10 DOMES  (identification)  (g)
11 station name  (identification)
12 type  (identification)  (h)
13 latitude  (location)  (i) (j)
14 longitude  (location)  (i) (j)
15 height  (location)  (i) (j)
16 Reference date+time  (date/time at which the position is given)

Comments:

(f) the code is the 4-character ID; capital or small letters?
(g) if any
(h) it gives the type of instruments (GPS receiver, DORIS antenna, ...) Possible combined option as well i.e., when VLBI+SLR+GNSS are combined for an averaged position—this could also depend on time in the time series i.e., not all days would have all systems.
(i) in my opinion, only an approximate position should be given here. A precise reference geodetic position would require to define the reference frame and the reference epoch. I think the latter is worth considering.
(j) units need to be defined; decimal degrees and meters?

Additional descriptors to identify the monument location may be considered (cf SOPAC): Nearest city, County, State code, Country, Tectonic plate. To be discussed. Monumentation type is also important. Maybe a standard set of terms for monument types.

3. Product information

This block gives information about the time series.

It gives information about the product: its name (solution code given by the provider), what data are used to generate this product (input data), where to find more information (reference about the processing).

It gives the necessary elements to describe the time series itself: epoch range, sampling frequency, number of points, reference system, reference position.

SOPAC includes a block “Processing” including indications about motion models (slope, annual, semi-annual, co-seismic offset, co-seismic decay removed or not). To be discussed.

16  solution code  (product)
17  input data  (product)
18  processing reference  (product)  (k)
19  start epoch  (time series; epoch range)  (l)
20  end epoch  (time series; epoch range)  (l)
<table>
<thead>
<tr>
<th></th>
<th>Description</th>
<th>Notes</th>
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<tr>
<td>21</td>
<td>sampling frequency <em>(time series)</em></td>
<td><em>(m)</em></td>
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<tr>
<td>22</td>
<td>number of points <em>(time series)</em></td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>reference system <em>(time series)</em></td>
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<td>reference position X <em>(time series)</em></td>
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<td>26</td>
<td>reference position Z <em>(time series)</em></td>
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<td>27</td>
<td>reference epoch <em>(time series)</em></td>
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</tr>
<tr>
<td>28</td>
<td>ellipsoid <em>(time series)</em></td>
<td><em>(n)</em></td>
</tr>
<tr>
<td>29</td>
<td>Averaging duration <em>(length of time used to estimate position, 1-Hz, daily, weekly?)</em></td>
<td></td>
</tr>
</tbody>
</table>

Comments:

(k) the reference could be a publication, a web link, a DOI, ...
(l) All calendar dates should be given with the same date and time system (see data)
(m) See how to represent the sampling. For VLBI this is problematic.
(n) datum or flattening + equatorial radius?

Users have requested offset values in time series so that they can just use these values (removed from the time series) when analyzing the series for say hydrological signals.

**DATA**

The time series must contain at least: time, dN, dE, dU, sN, sE, sU

- XYZ coordinates are necessary to express positions in a different reference frame or to obtain NEU and then deltas NEU on a different ellipsoid.
- XYZ sigmas and correlations are necessary to get NEU sigmas and correlations

An additional column could be useful to give a quality index.

**References**

(a) IDS


(b) PBO/UNAVCO

http://www.unavco.org/projects/major-projects/pbo/lib/docs/NOTICE%20TO%20UNAVCO%20DATA%20PRODUCT%20USERS%2020130315.pdf

http://pbo.unavco.org/doc/NOTICE%20TO%20UNAVCO%20DATA%20PRODUCT%20USERS%2020130315.pdf

(c) NGL

http://geodesy.unr.edu/gps_timeseries/README_txyz2.txt

http://geodesy.unr.edu/gps_timeseries/README_txyz3.txt

http://geodesy.unr.edu/gps_timeseries/README_txyz4.txt
(d) ULR
   None
(e) SOPAC
   http://sopac.ucsd.edu/projects/xml/measures/geodeticMLTest_pos.xml
   http://sopac.ucsd.edu/projects/xml/measures/geodeticMLTest.xml

**Others formats:**

**Files**
- One file per component of site: XXXX.lat , XXXX.lon ; XXXX.rad

**Fields**
- Time in years
- Value in cm
- Formal error in cm
- Site name
- Component
- Date

**Example**

1994.0014  -4.715238240429318e+00 7.453062599186759e-02 ALGO LAT 94JAN01
1994.0041  -4.890997156680867e+00 7.092009642598809e-02 ALGO LAT 94JAN02

**IVOA time series**
- http://dotastro.org/simpletimeseries/
- http://www.ivoa.net/documents/latest/UCDlist.html

**Another XML format**
WG 1.1.2: Investigate methods for merging geodetic imaging systems (InSAR, LIDAR and optical methods) into a geodetic reference system.

With the development of new methods for studying surface deformations, such as InSAR, LIDAR and optical methods, this working group will explore the methods that should be used to ensure that these deformation measurements are made in a well-defined geodetic reference frame. Issues to be addressed include how to establish the reference frame for these classes of measurements, how to ensure the long-term stability of the reference frame, and to make recommendations for changes in future systems that would allow more robust reference frame realization.

WG 1.1.2: Investigate methods for merging geodetic imaging systems (InSAR, LIDAR and optical methods) into a geodetic reference system

- Chair Lead: Sebastien Leprince, California Institute of Technology
- Members: Francois Ayoub, California Institute of Technology
- Jean-Philippe Avouac, California Institute of Technology
- Bruno Conejo, California Institute of Technology
- Jiao Lin, California Institute of Technology
- Sang-Ho Yun, NASA/JPL
- Piyush Shanker Agram, NASA/JPL
- Mark Simons, California Institute of Technology

The chair of this working group changed position to one that was not related to this working group and the working stopped activities with no new chair being appointed.

Possible new chairs if this working group is to be reconstituted are:
- Remi Michel, remi.michel@upmc.fr, Pierre et Marie Curie University, Paris
- Ian Joughin, ian@apl.washington.edu, University of Washington
- Sang-Ho Yun, Sang-Ho.Yun@jpl.nasa.gov, JPL
- Piyush Shanker Agram, piyush@gps.caltech.edu, JPL
- Mike Oskin, meoskin@ucdavis.edu, UC Davis
- Ramon Arrowsmith, ramon.arrowsmith@asu.edu, Arizona State University
- Craig Glennie, clglennie@uh.edu, University of Houston
- Peter Reinartz, Peter.Reinartz@dlr.de, DLR

The latest report of the working group is given below.

Activities of this geodesy group have focused around five main activities dedicated to producing dense and precise observations of ground deformation and changes using remote sensing systems. Group members have been meeting regularly and have been working in close collaboration on these topics:
3D estimation of ground motion using multi-temporal optical satellite acquisitions

Participants: Sebastien Leprince, Francois Ayoub, Jean-Philippe Avouac

This topic aims at taking advantage of the newly available high-resolution stereoscopic acquisitions from optical push broom satellites such as Worldview, Quickbird, or Pleiades. Using multi-temporal stereoscopic acquisitions, ground motion can be observed in three-dimension, with accuracy within tens of centimetres, and measurement density of one observation distributed every couple meters or so. This group aims at improving this technique to make it reliable and current study areas involve the 2010 El-Mayor Cucapah earthquake in Baja California, Mexico, and the observation of fast flowing alpine glaciers in New-Zealand, in particular the Franz Josef and the Fox Glaciers.

3D matching of 3D point clouds

Participants: Bruno Conejo, Sebastien Leprince, Francois Ayoub, Jean-Philippe Avouac

This topic aims at providing a new framework to extract three-dimensional measurement of deformation from point cloud data of surfaces. Point cloud data of surfaces can be generated from stereoscopic acquisition of optical imagery, or directly from LiDAR imaging technology. It has appeared to us that the computer vision community is indeed lacking such expertise providing precise measurements of surface deformation. The work currently involves formulating a regularized matching function of 3D point clouds, assuming a continuous deformation field, with potentially high deformation gradients. Test cases are currently being investigated using airborne LiDAR time series of the migrating White Sand Dunes in New Mexico.

Development of InSAR time-series analysis tools

Participants: Piyush Shanker Agram, Mark Simons

The project involves the development of a multi-scale wavelet-based InSAR time-series technique to extend the current MInTS processor, based on Short Baseline and Persistent Scatterer techniques.

A new simple covariance model has been developed for time-series techniques. Simple analytical models for decorrelation and atmospheric inhomogeneities in individual interferograms have been around for the last decade, but no work has been undertaken to model the covariance structure of interferometric phase - both in space and in time. Understanding the structure of the covariance matrix is key to designing optimal interferogram networks and to quantify the errors in the estimated time-series.

Damage detection of buildings combining multi-temporal stereo imagery and SAR decorrelation maps

Participants: Sebastien Leprince, Jiao Lin, Sang-Ho Yun, Mark Simons

This topic aims at merging information from optical satellite and SAR satellite sensors to provide rapid estimate of damages following large disasters around urban areas. Our approach relies on producing accurate maps of building heights using optical stereoscopic acquisitions. The challenge is to provide an automatic and reliable technique to produce 3D maps of
buildings from space. Comparing building heights before and after an event provides good estimate of potential building collapse. In addition, the study of the phase decorrelation of SAR images acquired before and after an event has been found to be a reliable proxy to estimate zones affected by large disasters. This group is currently working on merging both techniques (stereo optical and SAR decorrelation) to produce more accurate damage maps estimation. On-going studies are currently focused on data that were collected during the 2010 earthquake near the city of Christchurch, New Zealand.

**Datum inconsistencies in the processing of satellite imagery on Mars**

Participants: Francois Ayoub, Sebastien Leprince, Jean-Philippe Avouac

Planetary bodies such as Mars have very few reference surfaces and projections available compared to Earth. This should be an advantage to limit the confusion surrounding the projections and datum conversions. On Mars, the traditional map projections used by the imagery community are the equirectangular and polar stereographic. However, the equirectangular projection is defined for a spheroid and not an ellipsoid reference surface. The spheroid radius is chosen arbitrarily by the user to best match the local radius of the area of interest. With the multiplication of imagery available and the increasing needs to put in a common projection system various source of imagery, this poses the immediate problem of potential different radius for the same area. For instance, the MOLA geoid reference is defined with respect to a spheroid of radius 3396 km, and the USGS is delivering DEMs and orthophotos of MRO imagery with respect to a spheroid whose radius is defined locally (unique radius per 5 degrees latitude increment). To avoid much of the confusion it would be convenient to define a cartographic projection that relies on an ellipsoidal reference surface, for instance the one defined by IAU 2000, in order to remove the arbitrarily-chosen spheroid radius issue and have a unique projection system, which would allow faster and easier merging and comparison of all the data now being collected on Mars.

The studies of this group have been supported by the Keck Institute of Space Studies, The Gordon and Betty Moore Foundation through Grant GBM 2808 to the Advanced Earth Observation Project at Caltech, by the NASA MDAP# 11-MDAP11-0013 grant, and by the NASA/JPL R&TD grant to the ARIA project.
Sub-Commission 1.2: Global Reference Frames

Chair: Claude Boucher (France)

The IAG Sub-Commission 1.2 was created in 2003 as a part of the new structure of the International Association of Geodesy (IAG). It is engaged in scientific research and practical aspects of the global reference frames. It investigates the requirements for the definition and realization of the terrestrial reference systems and frames, addresses fundamental issues, such as global geodetic observatories or methods for the combined processing of heterogeneous observation data.

Numerous activities are actually realized in other IAG-related structures, mainly:
• Sub-commission 1. 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 to refer to their individual reports.

Beyond IAG, cooperation with other relevant international organizations such as IAU, FIG or ISO are also developed.

Contributors to this report:
Zuheir Altamimi (France) IERS
Detlef Angermann (Germany)
Claude Boucher (France) President
Xavier Collilieux (France) C1
David Coulot (France)
Pacome Delva (France)
Sakis Dermanis (Greece) ICCT
Bruno Garayt (France)
Richard Gross (USA)
Gary Johnston (Australia) C1
Paul Rebishung (France) IGS
Pierguido Sarti (Italy) C1
Michael Soffel (Germany)
Tonie van Dam (Belgium) C1
Pascal Willis (France) IDS

Relativistic modeling

This topic is of great interest and was identified as one of the goals of the sub-commission. Two specific points were identified:
• extension of the IAU model to geodesy
• investigations on the use of emission coordinate systems
Detailed report on IAU model will be published in the final report.

**Emission coordinates and relativistic reference frames**

The development of the concept of emission coordinates (Coll and Morales 1991, Rovelli 2002, Blagojević, Garecki, Hehl, & Obukhov 2002, Lachieze-Rey 2006) led to new ideas about the realization of global reference frames. Clocks combined with time transfer techniques are powerful tools for positioning in the 4-dimensional space-time, and it has been suggested to use a constellation of clocks linked one to another with a time transfer technology, so-called Inter-Satellite Links (ISLs), in order to build a satellite-based dynamical reference frame (Coll 2002). Such constellations are already a reality with GNSS (GPS, Galileo, GLONASS, Beidou), and the last generation of GPS implemented such links (NAVSTAR). It is planned to be implemented on the second generation of Galileo satellites (2020).

Inter-satellite links (ISLs) allow to directly synchronize the satellite clocks in space, and determine orbits using ISLs pseudo-ranges. This realizes an autonomous, four-dimensional, dynamical and relativistic reference frame, so-called the ABC (Autonomous Basis of Coordinate) frame (Delva et al 2011 bis, Gombac et al 2013). The benefit of such a reference system compare to the actual GNSS process is to separate the realization of the frame from the determination of Earth-specific parameters, such as the ground station coordinates, Earth rotation parameters and atmospheric parameters. Indeed the realization of the frame relies only on ISLs observables. Such a frame would be decoupled from an Earth fixed frame and even from a celestial frame. It would shine a new light on the space-time geometry around the Earth. Indeed, the space ensemble of clocks can be used to monitor Earth based clocks and determine their trajectories and the Earth gravity field (thanks to the red shift effect), and therefore link the ABC dynamical frame to an Earth fixed frame. Clock accuracies regarding the gravitational potential determination and height determinations begin to be competitive with classical techniques, e.g. in the sub-decimetre range for the determination of the geoid.

Several teams are developing concepts around relativistic positioning systems, and a workshop has been organized to exchange and foster new ideas: "Relativistic Positioning Systems and their Scientific Applications". It took place in Brdo near Kranj, Slovenia 19-21 September 2012. Proceedings have been published in Acta Futura in 2013 (http://dx.doi.org/10.2420/ACT-BOK-AF07).

**ITRF**

More details can be found in the report from the IERS ITRS Product Center. In general research activities related to ITRF are developed by three groups in the frame of IERS: DGFI, IGN and JPL.

**ITRF2008 results**

The ITRF2008 solution was released in May 2010. A dedicated website has been established (http://itrf.ign.fr/ITRF_solutions/2008/) providing full description of ITRF2008 solution, together with all associated products: station positions and velocities of the 920 stations (located at 580 sites) in SINEX as well as in simple table formats; Earth Orientation Parameters in different formats; plots of technique origin and scale time variations and station position residuals. The website also provides synthesized summary descriptions of the IERS Technique Centres (TC) solutions used in the ITRF2008 elaboration. All the submitted solutions were combined solutions by the Combination Center of each TC and based on repro-
cessed individual solution generated by the Analysis Centers of each one of the four techniques (VLBI, SLR, GNSS/GPS and DORIS). The submitted solutions cover the full history of observations, except for the GNSS/GPS series which start in 1997. These solutions are archived by the ITRS Center and the Central Bureau and were analysed by the two IERS Combination Centers (IGN and DGFI). Interaction and communication between the IERS Center and the TCs were operated as necessary and as a function of the ITRF2008 analysis conducted by the IERS CCs. The following table summarizes the final time series of station positions and EOPs submitted by the TCs.

<table>
<thead>
<tr>
<th>TC</th>
<th>Span</th>
<th>Solution type</th>
<th>EOPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>IVS</td>
<td>1980.0–2009.0</td>
<td>Normal Equation</td>
<td>Full set</td>
</tr>
<tr>
<td>ILRS</td>
<td>1983.0–2009.0</td>
<td>Variance-Covariance</td>
<td>Polar Motion, LOD</td>
</tr>
<tr>
<td>IGS</td>
<td>1997.0–2009.5</td>
<td>Variance-Covariance</td>
<td>Polar motion, rate, LOD</td>
</tr>
<tr>
<td>IDS</td>
<td>1993.0–2009.0</td>
<td>Variance-Covariance</td>
<td>Polar motion, rate, LOD</td>
</tr>
</tbody>
</table>

A detailed article on ITRF2008 results was prepared and published in 2011 in Journal of Geodesy with the “open access” option so that the ITRF2008 users have full and free access to the details of the ITRF2008 analysis and results.( Altamimi Z., Collilieux X., and Métivier L. (2011).)

**ITRF2008 Plate Motion Model**

Detailed analyses of the ITRF2008 velocity field were undertaken in order to estimate a plate motion model consistent with ITRF2008. Indeed, for various geodetic and geophysical applications of ITRF2008, the aim of this study is to provide users with the most precise plate motion model derived from and consistent with the ITRF2008. The analysis consisted in simultaneously estimating angular velocities for 14 plates, together with an origin rate bias of the selected velocity field of 206 sites. The obtained results provide a model for 14 plates, with a global WRMS of 0.3 mm/yr. (Altamimi Z., Métivier L. and Collilieux X. (2012), )

![Figure 1. Velocity differences between ITRF2008 and (left) NNR-NUVEL-1A and (right) NNR-MORVEL56, after rotation rate transformation. In mm/yr, Green: less than 2 mm/a. Blue: between 2–3 mm/a. Orange: between 3–4 mm/a. Red: between 4–5 mm/a. Black: larger than 5 mm/a, and rates of velocity differences are shown only in this case.](image-url)

The article details also the comparisons between ITRF2008 PMM and the geophysical models NN-NUVEL-1A and NNR-MORVEL56. Results show in particular a large angular velocity...
residual of about 4 mm/yr for the Australian plate between ITRF2008 PMM and NNR-MORVEL56, as illustrated by Figure 1. This bias is not observed in the comparison with NNR-NUVEL-1A and suggests that the Australian plate is probably mis-modelled in NNR-MORVEL56.

**ITRF2014**

At the time of writing, the ITRF2014 is under development and expected to be released by fall 2015. The full history of data of all four techniques, up to the end of the year 2014 will be used in the generation of the ITRF2014. Daily and session-wise solutions are provided by IGS and IVS, while weekly solutions are provided by IDS and ILRS. The main novelties of ITRF2014 compared with ITRF2008 are the estimation of periodic signals (e.g. annual and semi-annual) in the station position time series and the modelling of post-seismic deformation for sites which are impacted with large Earthquakes. The estimation of periodic signals is expected to improve the determination of station linear velocities and it actually helps identifying discontinuities in the time series. The modelling of post-seismic deformation will be operated by using logarithmic or/exponential functions, as a function of the nature of the deformation per station. This modelling is expected to enhance the estimation of the linear part (velocity) of the station and therefore reinforce the connection between techniques at co-location Earthquake sites using the same parametric model.

**Research and development activities**

**IGN**

The IGN group, 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. Scientific results of specific data analysis and combination are published in peer-reviewed journals, as listed in the references’ section, but also presented at international scientific meetings.

**DGFI**

In the report period, the DGFI group published the general paper about the computation of the DTRF2008 solution (Seitz et al. 2012). In a second publication DGFI compared the two reference frames DTRF2008 and ITRF2008 in order to assess the accuracy of the reference frames (Seitz et al. 2013). The agreement is between 7 and 10 mm and between 0.2 and 2.0 mm/a for the station positions and velocities, respectively, depending on the technique and if only core stations are considered.

In addition, DGFI performed various research and development activities in the field of global geodetic reference frames. This includes basic research related to the definition and realization of global terrestrial reference system and to the datum definition (Drewes 2012; Drewes et al. 2013). Other research topics were the common adjustment of the celestial and terrestrial reference frame together with the Earth Orientation Parameters (Seitz et al. in press) and the development of strategies for the computation of epoch reference frames (Bloßfeld et al. 2011; Bloßfeld et al. 2013).
CATREF, the software package used at IGN France to produce the well-known ITRFs, has been installed at JPL and has been used to reproduce ITRF2005. A Kalman filter and smoother algorithm has been developed and coupled to the CATREF software. This Kalman filter-based software package, KALREF, has been used to produce ITRF2005-like and ITRF2008-like reference frames that compare favourably with ITRF2005 and ITRF2008, respectively (Wu et al., 2015). It has also been used to solve for time-variable weekly coordinates, as well as a model of secular, periodical and stochastic motion components. In addition, KALREF has been used to define a nearly instantaneous reference frame by specifying constant frame parameters and combining different technique data weekly. It is currently being used to determine a solution for the IERS using the input SINEX files that were produced by the Services for ITRF2014.

A simulation tool to study the effect of network geometry on reference frame determination is being developed. The tool is based on synthetic station position and reference frame parameter (geocenter, scale) data. It has been used to study the effect of station distribution, number of stations, availability of site tie measurements, etc. on the reference frame. Preliminary conclusions indicate that reasonable TRFs can be determined from a network of about 30-40 well-distributed, co-located stations as long as accurate site ties are available at each site.

The Three Corner Hat (TCH) technique has been used to determine the uncertainties of estimates of positions of stations at co-located sites. For 16 co-located sites used in ITRF2008, the median (north, east, up) uncertainties are found to be (1.1, 1.2, 2.8) mm for the GPS stations, (2.2, 2.0, 6.2) mm for the VLBI stations, (8.5, 7.6, 9.0) mm for the SLR stations, and (9.2, 11.7, 10.6) mm for the DORIS stations (Abbondanza et al., 2015).

The GRASP mission

GRASP is a satellite mission which will carry very precise sensor systems for all the key geodetic techniques used to define and monitor the TRF: a Global Navigation Satellite Systems (GNSS) receiver, a Satellite Laser Ranging (SLR) retro-reflector, a Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS) receiver, and a novel Very Large Baseline Interferometry (VLBI) beacon. It would allow to achieve the requirements established by the Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020: “Maintaining a terrestrial reference frame at the level that allows, for example, the determination of global sea level changes at the sub-millimetre per year level, pre-, co- and post-seismic displacement fields associated with large earthquakes at the sub-centimetre level, timely early warnings for earthquakes, tsunamis, landslides, and volcanic eruptions, as well as the monitoring of mass transport in the Earth system at the few Gig tons level requires an comprehensive Earth system approach.”

GRASP was proposed in response to the NASA’s Earth Venture-Mission (EV-M) call of opportunity in 2011 and was graded 2nd after the CYGNSS mission. A new NASA’s EV-M proposal opportunity is currently prepared for a release in Summer 2015. A new GRASP proposal is thus under study.

To reach mission goals, the first step is to determine the optimal orbit of this satellite. The GRGS studies an original approach, based on evolutionary algorithms, for determining such orbits. This method permits to optimize orbits according to specific criteria, such as the
visibility of the satellite from ground stations and GNSS satellites, some orbital constraints, etc. Once the orbit chosen, GRGS will carry out, in collaboration with JPL, numerical simulations with the GINS software. These simulations aim to determine the boundary of the calibration of the on-board instruments required to reach the objectives of the mission.

**TRF activities in IAG services**

**IGS**

Since February 2010, IGN France has replaced Natural Resources Canada (NRCan) as coordinator of the IGS Reference Frame Working Group. On the operational side, this coordination consists in combining the SINEX solutions provided by the IGS final Analysis Centers (ACs) and updating a long-term cumulative solution each week. The switch from NRCan to IGN was the opportunity to bring some changes to the SINEX combination strategy (Rebischung and Garayt, 2013). But the formats and contents of all products were kept unchanged so as to ensure a smooth transition. Besides a continuous monitoring of the SINEX combination results, the main achievements of the Reference Frame Working Group since 2010 were:

* the publication of IGS08 (Rebischung et al., 2012), a new IGS reference frame based on ITRF2008;
* the generation of a homogeneous set of weekly solutions based on the IGN combination strategy back to 1994 and of a new, modernized IGS cumulative solution;
* the switch from weekly to daily terrestrial frame combinations in August 2012.

More details on the recent IGS Reference Frame Working Group activities can be found in the 2011 and 2012 IGS Technical reports available at ftp://igs.org/pub/resource/pubs/

**IDS**

Several TRF related activities can be found in references below, in particular Altamimi and Collilieux 2010, Angermann, Seitz and Drewes 2010, Govind et al 2010

**External evaluation of TRF**

This topic is mainly studied within the group

**External Evaluation of Terrestrial Reference Frames**

Chair: Xavier Collilieux (France).

An accurate Terrestrial Reference Frame (TRF) is fundamental for Earth science applications. To constrain the error budget of some geoscience products such as the determination of sea level variations from space, the uncertainty of tracking geodetic station coordinates should be known reliably. The scope of the this task force is to enumerate and assess all the methods that provide an evaluation of the Terrestrial Reference Frame accuracy, especially in terms of origin and scale.

This activity has started in 2011. First results have been discussed in Collilieux and Altamimi (2013). During the previous term of the IAG commission 1, the task force has written a report that has been finalized during this term (Collilieux et al., 2014). It establishes that the accuracy of the ITRF2008 in terms of origin rate is likely to be less than 0.5 mm/yr on the three
components while the scale rate error is smaller than 0.3 mm/yr. In the meantime, Argus (2013) revisited the TRF origin and scale accuracy by relying on the assessment of space geodetic data. Post-glacial rebound models have been further investigated for evaluation purpose by several authors. King et al. (2011, 2012) have shown that models and observed station vertical velocities cannot be reconciled by shifting the origin of the TRF. However, their accuracy is sufficient to discriminate different modeling of the rotational feedback (Mactvier et al., 2012). Finally, we mention that Earthquake co-seismic models have been used globally to assess discontinuities and effect on station velocities on a global set of station. Such an approach in the future is likely to improve the accuracy of the TRF.

Too few activity of this working group has been reported during these first two years. For this reason, it is more reasonable not to continue this effort for the next two years.

**Global Geodetic Observatories**

Works on concepts and practical implementation are under progress. Detailed results with references will be provided in the final report.

We must mention the specific activities of the working group **Site Survey and Co-location** (jointly with IERS) chaired by Pierguido Sarti (Italy) (also Joint Study Group 1.2.2: Global Geodetic Observatories)

The Joint Working Group has focussed on the provision of accurate tie vectors for ITRF computation and the assessment of their accuracy. It is a rather complex process as it must rely on the extent of (dis)agreement with the space geodetic solutions and the analysis of any possible cause, either on the local survey or the space geodetic observation side. The ITRF combination residuals do not often agree with the magnitude of the tie vector formal precisions, these latter usually being at the mm or sub-mm level. In addition, the WG has focussed on the definition and validation of new methodologies for the surveying and computation of the tie vectors and the definition of standards and guidelines. Finally, the creation of a central repository for local surveys data has been discussed and evaluated during a meeting held in Paris on May 21-22, 2013. This two days meeting was organized as an official IERS workshop and brought together more than 40 experts that had the opportunity to discuss different issues related to surveying methods and approach, tie vector estimation strategies, nomenclature, guidelines, documentation, data archiving and more. The workshop was a success in terms of participation and results. 25 oral contributions were presented during the meeting. All relevant information can be found at the workshop web page: http://iersworkshop2013.ign.fr/?page=scope

A recent review paper was also published on this subject in Advance Space Research (Boucher, Pearlman, Sarti, 2015)

**Workshops, meetings, invited talks (2010-2013)**

Convening activity:


Invited/solicited talks:

2011: 37th course of the International School of Geophysics; Interdisciplinary Workshop on Earth expansion evidence: a challenge for geology, geophysics and astronomy, Erice, Italy

The consistency between local and space geodetic observations – Accuracy of the global terrestrial reference frame.

2010: IAG Commission 1 Symposium 2010, Reference Frames for Applications in Geosciences (REFAG2010); Theory and realization of global terrestrial reference systems, Marne-La-Vallée, France

A review on local ties and co-location issues

**Global Geodetic Reference Frame**

The United Nation initiative on Global Geospatial Information Management aims at playing a leading role in developing the global use and data sharing of geospatial information to address key global scientific, societal and economic challenges, and consequently to emphasize the need for a sustainable Global Geodetic Reference Frame (GGRF).

The UN Committee of Experts on Global Geospatial Information Management (UN-GGIM) decided in July 2013 to formulate and facilitate a draft resolution for a Global Geodetic Reference Frame. In order to achieve this they created a Working Group on the Global Geodetic Reference Frame (WG on GGRF) co-chaired by Australia and Norway.

At its 4th session held in New York in August 2014, the UN-GGIM Committee of Experts approved a draft text of a resolution prepared by the WG on GGRF to be submitted to (ECOSOC: Economic and Social Council of the UN) for further referral to the UN General Assembly for adoption. The said resolution is entitled “A Global Geodetic Reference Frame for Sustainable Development”.

In February 2015 the UN General Assembly adopted the resolution *A Global Geodetic Reference Frame for Sustainable Development* – the first UN resolution recognizing the importance of a globally-coordinated approach to geodesy was declared.

It is available, together with a descriptive Concept Note and other materials, at the UN-GGIM Website: http://ggim.un.org/UN_GGIM_wg1.html

The WG on GGRF was further tasked with developing a Road Map for the Maintenance and Enhancement of the GGRF. A draft of the Roadmap is due for delivery to the Committee of Experts at the 6th Session of the UN GGIM, August 2016.
ISO standardization

A project has been established within the International Standardization Organization (ISO) Technical Committee ISO TC 211 (geographical information) dealing with geodetic references. This project 19161 was chaired by Claude Boucher (France). Its objectives were to write a report showing the importance of geodetic references for geo-information and to propose some specific items relevant to an ISO standard. The ITRS has been proposed as one of them. IAG, which is a liaison organization with ISO TC211 was represented by Zuheir Altamimi. The final report was submitted to ISO TC211 on Feb 2015. For major recommendations were included, three on possible topics of standardization, and one on terminology issues.

It is planned to submit a so-called New Work Item Proposal (NWIP) on ITRS. In order to collect a comprehensive set of opinions within IAG and its services, GGOS has reactivated the WG chaired by Claude Boucher on this subject, linked to the GGOS Bureau of Products and Standards.

References


King et al. (2011), presentation at the Global Sea Level Observing System meeting, November, Paris


Sub-Commission 1.3: Regional Reference Frames

Chair: João Torres (Portugal)

Introduction

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

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

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

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

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

Furthermore, two Working Groups (WG) are active within SC 1.3:

• WG 1.3.1: Integration of Dense Velocity Fields into the ITRF
  o The main task of this WG is to study and promote consistent specifications for the generation of GNSS-based velocity field solutions and their combination in order to derive a unified dense velocity field in a common global reference frame.
• WG 1.3.2: Deformation Models for Reference Frames
  o The primary aim of the WG is to develop tectonic deformation models that will enable transformation of locations within a defined reference frame between different epochs. Such deformation models are essential to support precise point positioning applications and CORS/NRTK operations within deforming zones
Overview

The activities of each of the regional Sub-Commissions and Working Groups “Integration of Dense Velocity Fields into the ITRF” and “Deformation Models for Reference Frames” are reported hereafter. A summary of those activities and the main results achieved is given below.

Sub-Commission 1.3 a: Europe

- The number of permanent GNSS tracking sites in Europe is still growing, with more than 260 EPN stations operating by mid-2015. The number of site, switch record GLONASS data simultaneously to GPS data is steadily increasing (70%).
- Currently the EPN working group on Reprocessing conducts a second reprocessing campaign, EPN-Repro2 realized in the IGb08. The analysis is being carried out on the EPN data from 1996 till 2013 by five analysis centres.
- The preparation for the future Galileo system and the development of the EPN towards a multi-system GNSS network started.
- EUREF continued the validation of national GNSS campaigns. The following projects were accepted by the plenary as EUREF densification campaign between 2011 and 2015: “EUREF Serbia 2010” (Serbia), “EUREF-MAKPOS 2010” (Macedonia), “EUREF Faroe Islands 2007” (Faroe Islands), “EUREF BE 2011” (Belgium), “EUREF Poland 2015” and “Central European Geodynamic Research Network (CERGN)”.
- The EPN Project on “Real-time Analysis” is still developing. Based on orbit and clock corrections broadcasted in ETRS89 (realization ETRF2000), users can directly derive real-time coordinates referred to ETRS89 at few dm-level.
- The EUREF TWG set up three new Working Groups. One is on “Multi GNSS” to prepare recommendations on the use of the new signals within the EPN. The second one is on “Deformation Models”, to improve the knowledge of surface deformations in Eurasia and adjacent areas. The third one is on EPN Densification to realize a continental-scale, homogeneous, high quality position and velocity product in an homogeneous reference frame, for a very dense network of GNSS stations.
- The UELN was enhanced by additional or updated leveling data. These data make possible to close the loop around the Baltic Sea. Some countries announced to provide their levelling data and join the UELN.
- The promotion of the ETRS89 (European Terrestrial Reference System) and the EVRS (European Vertical Reference System) continued, following the adoption by INSPIRE of these systems as the basis for georeferencing in Europe.
- The latest EUREF symposia took place in Saint-Mandé, France (2012), in Budapest, Hungary (2013), Vilnius, Lithuania (2014), Leipzig, Germany (2015). Meetings of the EUREF Technical Working Group have been held three times a year. In addition a EUREF retreat was held in Nov. 2012 with the goal to review EUREF key themes and organizational structures and derive a plan to achieve the EUREF objectives for the next 4-8 years.
Sub-Commission 1.3 b: South and Central America

- The number of continuously operating GNSS stations that support the SIRGAS Reference Frame is still growing. It is composed by about 400 stations, 235 of which with GLONASS capability, 16 Galileo and 2 BEIDOU. The SIRGAS Reference Frame includes 58 formal IGS stations.

- The IGS Global Analysis Centres process 40 SIRGAS stations since January 2012 in order to improve the distribution of the ITRF sites in this region. These stations are included in the IGS Reprocessing 2.

- The SIRGAS-N national networks are computed by 9 SIRGAS Local Processing Centres. These processing centres deliver 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 Centres follow unified standards for the computation of the loosely constrained solutions.

- The computation (update) of the cumulative solution is performed every year, providing epoch positions and constant velocities for stations operating longer than two years. For the moment, the computation of multi-year solutions is stopped until it fills the criteria of getting weekly normal equations referenced to the IGS08/IGb08 and covering a time span of at least three years.

- The support of the countries interested on adopting SIRGAS as official reference frame continued. At this moment, 14 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.

- The installation of the service "Experimental SIRGAS Caster" with the goal to promote the availability of the SIRGAS Reference Frame in real time showed major advances, reported by several countries.

- The efforts needed towards the definition and realisation of a gravity field-related vertical reference system in Latin America and the Caribbean have been identified. The work has started in collecting and validating the existing databases, performing levelling field works to connect the fundamental points of the vertical networks with the SIRGAS reference station and with the main national tide gauges and levelling connections between neighbouring countries.

- The signature of the "2013-2015 Action Plan to Expedite the Development of Spatial Data Infrastructure of the Americas" constitutes a strategy for the adoption of SIRGAS as the official reference frame for Geodesy and Cartography, according to the recommendation issued in 2001 by the "United Nations Cartographic Conference for the Americas".

- The development of actions for capacity building and the promotion of SIRGAS in the member countries, in particular the 2 Workshops on Vertical Datum, 4 SIRGAS Schools, training courses on precise GNSS data processing, under the sponsorship of several international organizations and national institutions.

Sub-Commission 1.3 c: North America

- Dr. Neil D. Weston replaced Dr. Jake Griffiths as the U.S. co-chair in 2013.
- The densification of the ITRF and IGS network from weekly combinations of 5 regional weekly solutions using different GPS processing software has been on hold since GPS week 1583.
- The enhanced version of the software to enable the weekly combinations of the large number of stations was released in 2014.
- The reprocessing of the regional networks is planned immediately following the release of IGS repro2 orbits, with the exception of INEGI, who has just completed their own reprocessing with repro1 orbits.
- The discussion of the implementation of a new geocentric, ITRF-based regional reference frame for North America in 2022 continued with the second Federal Geospatial Summit in April 2015.
- CGS and NGS have begun the process of updating the International Great Lakes Datum for the management of water levels in the Great Lakes Basin. Continued repeated GPS survey campaigns of the water level gauge network are planned for 2015 and 2020.
- A program of validating commercial RTK services and their base station coordinates, to ensure correct and consistent integration of RTK services in NAD83, has begun at CGS. NGS is also planning a similar validation program in the very near future.
- No activities related to the definition and maintenance of the relationships between international and North American reference frames/datums due to delays in the release of ITRF2013 (now ITRF2014). Transformations from/to subsequent versions of ITRF96 are obtained by updating the NAD83-ITRF transformation with the official incremental fourteen parameter transformations between ITRF versions as published by the IERS.
- The working groups dedicated to the different tasks met when appropriate.

Sub-Commission 1.3 d: Africa

- Prior to March 2013 the project fell within United Nations Committee for Development Information, Science and Technology (Geo-information) (CODIST-Geo). Since March 2013, the oversight and supervisory functions of CODIST-Geo (including AFREF) were transferred to the United Nations Global Geospatial Information Management: Africa (UNG-GGIM: Africa).
- Approximately 90 stations have been installed and are registered on the AFREF Operational Data Centre which was installed to download and archive data from these stations. Of these 90 stations, however, only 60 have provided data to the ODC in 2015.
- The data of 50 AFREF stations together with 50 global stations was processed by 4 processing centres and combined to provide a set of static co-ordinates based on ITRF2008 to be used for everyday surveying and mapping operations.
- Workshops on the establishment and processing of permanent GNSS stations and networks are held annually at the Regional Centre for Mapping of Resources for Development in Nairobi, Kenya.
Sub-Commission 1.3 e: Asia-Pacific

- The increase of the number of stations of the CORS network (approximately 480 stations from 28 countries), whose data are processed by four Analysis Centres (ACs).
- The increase of the number of institutions contributing to APREF in several domains (analysis, archive and stations).
- The availability of a weekly combined regional solution, in SINEX format and a cumulative solution which includes velocity estimates.
- The publications of the weekly ITRF coordinate estimates in SINEX format, coordinates time series and velocity solutions for the APREF stations on the APREF website.
- The coordination of annual geodetic observation campaigns in order to densify the ITRF in the Asia-Pacific Region in countries without Continuously Operating Reference Stations (CORS). Four annual GNSS campaigns have been carried out since 2011.

Sub-Commission 1.3 f: Antarctica

- Dr. Mirko Scheinert replaced Dr. Reinhard Dietrich as chair of SC 1.3f in 2013.
- The realization of SCAR GPS Campaigns in every austral summer from 2011 until 2015. The data of 50 Antarctic sites are collected in the SCAR GPS database since 1995.
- The continuation of data analyses and presentation of the results at the XXXII SCAR Meetings (2012 and 2014).
- The establishment of the working plan of the SCAR Group of Experts on Geodetic Infrastructure in Antarctica (GIANT) for the years 2012-2014, where the goals of SC 1.3f are well reflected.

Working Group 1.3.1: Integration of Dense Velocity Fields into the ITRF

- The decision to start with the combination of weekly position solutions allowing the mitigation of biases, as a result of tests concluding that the level of agreement between the several multi-year solutions submitted before was not satisfactory.
- The submission of regional and global solutions containing more than 4000 stations.
- The realization of preliminary combinations of 2679 selected stations with more than 3 years observations, present in at least 104 weekly SINEX and present in at least 50% of the weekly SINEXs within the data span.
- The first solution obtained from the stacking of the weekly combined solutions is finalized. The multi-year positions and velocities are expressed in the IGS08 frame. The combination on a weekly level allows increasing the reliability of the velocity field.

Working Group 1.3.2: Deformation Models for Reference Frames

- The realization of considerable research on deformation modelling completed by WG members in Japan, South America, Australia, New Zealand and the USA, including the possibility to use remote sensing techniques such as InSar and LiDar to estimate local deformation models.
- The improvement of crustal deformation models (post-seismic deformation), the release of deformation patches which model the co-seismic and post-seismic deformation in Japan (Tōhoku earthquakes) and New Zealand (Canterbury earthquake sequence).
- The development of localised deformation models to support land surveying activities in zones where significant earthquakes occurred.
The development of next-generation geodetic datums using deformation models.

The activity of the WG members is being developed in the majority of the areas covered by the regional Sub-commissions. Also, the WG 1.3.2 has been working closely with FIG Commission 5 (Positioning and Measurement).

Conclusion

The activities developed by each of the regional Sub-Commissions and Working Groups (Integration of Dense Velocity Fields into the ITRF and Deformation Models for Reference Frames) make evident that all the components of the structure are working according to the main objectives of the SC 1.3.

Some general aspects deserve to be mentioned:

- The activities are contributing to the scientific and technical development in several topics such as GNSS analysis and processing, precise reference frame establishment, use of new GNSS signals, among others.
- The stronger involvement of the regional components in the global scientific goals of the IAG, especially their contribution to the ITRF solutions.
- The emphasis that all the regional Sub-commissions and both Working Groups are giving to the modelling of non-linear changes in the coordinates due mainly to geophysical phenomena.
- The recognition of the role of the WG on “Integration of Dense Velocity Fields into the ITRF” and the WG on “Deformation Models for Reference Frames” in the identification of problems and solutions when going from regional to global analysis, that is encouraged.
- The effort to bring together different types of institutions (R&D structures, National Mapping Agencies, political and economic agencies, etc.) to support and contribute to the activities related to the geospatial reference frames.
- The organizational and outreach aspects play a more and more important role and are crucial for the efficient achievement of results and their use by the geospatial community.
- The concern to develop education and training events, especially in less developed regions and countries. In this context, it’s worth to mention the combined IAG, FIG and ICG workshop "Reference Frames in Practice" held in Rome prior to the FIG Working Week in May 2012. This effort must be continued and supported by the IAG.

The reports presented here reinforce the strategic decision to keep and develop this kind of regional organization within the IAG, since each region of the world has its own way to proceed, considering all the variables involved in this kind of work.
Sub-Commission 1.3a: Regional Reference Frame for Europe (EUREF)

Chair: Johannes Ihde (Germany)

Introduction

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

The results and recommendations 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 are focused 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 International GNSS Service (IGS);
• Improvement of the European Vertical Reference System (EVRS);
• 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) and annual EUREF Symposia, an event that occurs every year since 1990, with an attendance of about 100-150 participants coming from more than 30 European countries and other continents, representing Universities, Research Centres and NMCA (National Mapping and Cadastre Agencies). The organization of the EUREF Symposia is supported by EuroGeographics, the consortium of the European National Mapping and Cadastral Agencies, reflecting the importance of EUREF for practical purposes.

The latest EUREF symposia took place in Saint-Mandé, France (2012) and in Budapest, Hungary (2013), Vilnius, Lithuania (2014), Leipzig, Germany (2015). Meetings of the EUREF Technical Working Group have been held three times a year. In addition a EUREF retreat was held in Nov. 2012 with the goal to review EUREF key themes and organizational structures and derive a plan to achieve the EUREF objectives for the next 4-8 years.

Members:


In addition to the already existing partnerships with EUMETNET and EuroGeographics, EUREF and CERGOP (Central European GPS Geodynamic Network Consortium) signed a Memorandum of Understanding (MoU) at EUREF symposium at Chisinau, Moldova in 2011. The general goal of the MoU is to create the conditions to facilitate data exchange and
promote the co-operation between EUREF and CERGOP in order to improve the densification of the European GNSS network for reference frame definition and geodynamical applications, and support the ECGN (European Combined Geodetic Network) project.

EUREF and EUPOS, a cooperation DGNSS service providers of RTK networks which densify the continental network EPN, agreed in 2014 a Memorandum of Understanding. Both parties, EUREF and EUPOS agreed that this general undertaking is related among other to:

- design of an interface between the European reference network EPN and the positioning services/networks of EUPOS members,
- realize a European Velocity Model for practical and scientific applications,
- working towards common standards and guidelines.

In 2014 a Knowledge Exchange Network (PosKEN) was installed. Partners are:

- EuroGeographics – representing national policy makers, namely NMCA’s,
- CLGE – representing users of permanent GNSS networks for precise positioning, especially surveyors, a large group of users of GNSS precision applications,
- EUPOS and
- EUREF.

From the objectives and roles of all four organizations within the KEN, the following goals were identified for its initial operations:

- provide the European platform for networking and sharing best practice and expertise in the field of GNSS positioning
- aim at creating the uniform GNSS services for Europe, under the working name of European Positioning System
- develop common standards, policies and guidelines that require active contribution of experts in different fields
- show the commitment to working with other organizations where the members of each organization can benefit.

EUREF is an associated member of the International Committee on Global Navigation Satellite Systems (ICG) since 2009. The main ICG objective is to promote greater compatibility and interoperability among current and future providers of the Global Navigation Satellite Systems (GNSS). The annual ICG meetings review and discuss progress towards the realization of its main objective, as well as developments in GNSS where contributions from ICG members, associate members and GNSS user community are considered.

**EUREF Permanent GNSS Network (EPN)**

The EPN is the permanent GNSS network created by EUREF (Fig 1.3a.1). Its primary objective is to maintain and provide access to the ETRS89. The EUREF TWG is responsible for the general management of the EPN. The EPN Coordination Group and the EPN Central Bureau implement the operational policies of the EUREF TWG.

The EPN is based on a well-determined structure including GNSS tracking stations, operational centres, local and regional data centres, local analysis centres, combination centres and a Central Bureau (Bruyninx et al, 2011). These different EPN components (all based on voluntary contributions) follow specific guidelines set up by the EUREF TWG.
The EPN is the European densification of the International GNSS Service (IGS) network. Therefore, the EPN uses the same standards and exchange formats as the IGS.

More than 260 EPN stations are operated today by NMCA and other scientific and technical institutions. The number of sites that record GLONASS data simultaneously with GPS data is steadily increasing (70%).

Figure 1.3a.1: EUREF Permanent GNSS Network (EPN), status May 2015

EPN reprocessing activities

Since the start of the EPN operations, its data are routinely analyzed by the EPN Local Analysis Centres in order to derive precise station coordinates and tropospheric zenith path delays. Throughout the years, the EPN has become more precise and reliable thanks to historical improvements of modeling parameters affecting the satellites (orbits, reference frame, and antenna calibration model), the propagation media (troposphere and ionosphere), the receiver units (e.g., elevation cut-off, antenna calibration model), geophysical phenomena (e.g., tidal forces, loading related to ocean, ground water and atmospheric pressure variations) and the reference frames. The EUREF TWG has therefore decided to reprocess all historical EPN data using present-day state-of-the-art models and to obtain improved and consistent coordinates, position time series and tropospheric parameters for each EPN site.

This first reprocessing (known as EPN-REPRO1) was done in 2011 for EPN observations gathered between Jan. 1996 and Jan. 2007. Different software packages, namely BERNERE,
GIPSY/OASIS and GAMIT were used for the analysis (Habrich, 2011 and Völksen, 2011). The reprocessing was done using the epn_05.atx antenna calibration model, which is derived from the igs05.atx model. The reprocessed EPN results were used for weekly combined positions (in SINEX format) and tropospheric delays generated by the EPN Analysis Coordinator and EPN Troposphere Coordinator, respectively. At its fall meeting in Oct. 2011, the EUREF TWG endorsed the EPN-REPRO1 results and gave the green light to the EPN Reference Frame Coordinator for the generation of a new cumulative EPN position/velocity solution including the EPN-REPRO1 results.

Currently the EPN working group on Reprocessing conducts a second reprocessing campaign, EPN-Repro2 realized in the IGb08 and it is coordinated by the Bavarian Academy of Sciences and Humanities (BEK). The analysis is being carried out on the EPN data from 1996 till 2013 by five analysis centres. It will include three independent solutions obtained using Bernese 5.2, GAMIT 10.5 and GIPSY 6.2 for the entire EPN and the results of two EPN sub networks processed with Bernese 5.2. The analysis strategy is very much consistent with the recent LAC guidelines for the routine processing of the EPN. The processing of the data is performed as a regional network without orbit, EOP and clock parameter estimation and relies completely on available reprocessed products. Due to the lack of reprocessed combined IGS products (2nd IGS Reprocessing campaign), the reprocessed products provided by CODE and the preliminary reprocessed products by JPL are used.

In preparation of EPN-Repro2, a benchmark test with the different software packages, and based on the same data and network design, has shown good agreement between the different solutions (Völksen et al., 2014). The completion of the EPN-Repro2 daily solutions is expected for February 2014. First results of the combination of the different results will be presented at the next EUREF symposium in June 2015. The importance of the reprocessing activities has also been acknowledge by installing a Dedicated Analysis Centre (DAC) for Reprocessing at the Geodetic Observatory Pecny (GOP).

**EUREF Densification of the ITRS**

*Using the EPN*

Because the number of permanent GNSS tracking sites in Europe has grown considerably, only a selection of these sites (mostly those belonging to the IGS) are included in recent realizations of the ITRS. The latest realization of the ITRS, the ITRF2008, is based on observations from space geodetic techniques (GNSS, DORIS, VLBI, and SLR) up to December 2009.5 and does not take into account any of the IGS/EPN data gathered after that date. Consequently, it cannot reflect the most recent status of the EPN (due to e.g. antenna changes). The limited number of stations and the lack of frequent updates limit therefore the use of the ITRF for national densifications of the ETRS89.

The EUREF TWG decided at its meeting of Nov. 3-4, 2008 in Munich, to release regularly recomputed cumulative official updates of the ITRS/ETRS89 coordinates/velocities of the EPN stations. Using the 15-weekly updates of the EPN site coordinates, the EPN sites are classified in two classes:

- Class A stations with positions at 1 cm accuracy during the time span of the used observations (thanks to providing accurate station velocity estimates);
- Class B stations with positions at 1 cm accuracy at the epoch of minimal variance of each station.
Following the EUREF “Guidelines for EUREF Densifications” (Bruyninx et al., 2013), only Class A EPN stations can be used for EUREF densifications.

Table 1.3a.1 gives an overview of the weekly EPN SINEX files available for the computation of a new EPN cumulative position/velocity solution:

Table 1.3a.1: Overview of the weekly EPN SINEX files including the antenna calibration model used in the analysis.

<table>
<thead>
<tr>
<th>Solution</th>
<th>GPS week Start / End</th>
<th>Antenna Calibration Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPN-REPRO1</td>
<td>835 / 1399</td>
<td>epn_05.atx</td>
</tr>
<tr>
<td>Routine</td>
<td>1400 / 1631</td>
<td>epn_05.atx</td>
</tr>
<tr>
<td>Routine</td>
<td>1632 / Now</td>
<td>epn_08.atx</td>
</tr>
</tbody>
</table>

In order to have a consistent set of weekly SINEX solutions, the EUREF TWG asked the ROB (Royal Observatory of Belgium, see Baire et al. 2011) to correct the solutions before week 1632 to make them consistent with the epn_08.atx antenna calibration model. Using these corrected SINEX files, complemented with the present-day EPN weekly SINEX files, a new cumulative EPN position/velocity solution has been created and tied to the IGS08/IGb08 reference frame (see Kenyeres, 2011; Kenyeres, 2012). The computations were done using the CATREF software (Altamimi et al., 2007) and are again updated each 15-weeks. The resulting station coordinates are available from http://www.epncb.oma.be/_productsservices/coordinates/. Figure 1.3a.2 shows the map of Class A and Class B stations outcome of the latest cumulative EPN solution.

Figure 1.3a.2: EPN site categorization, status May 2015. In green: Class A stations; in red: class B stations.
Using the National GNSS Densification Networks

Many European countries operate national dense GNSS networks, whose stations are not all included in the EPN. In order to take advantage of these data for creating a dense European velocity field, EUREF invited these countries to routinely analyze these data following EUREF guidelines and to submit the weekly positions to EUREF. Several countries (Austria, Bulgaria, Czech Republic, Estonia, France, Germany, Hungary, Italy, Latvia, Poland, Slovakia, Spain, and UK) responded positively and provide now weekly SINEX solutions to the EPN Reference Frame Coordinator who combines these solutions with the weekly EPN solution and then stacks them to get consistent cumulative position/velocity solutions for the resulting densified EPN network (containing today already about a 2500 sites). Thanks to EUREF’s Memorandum of Understanding with CERGN, also a CERGN solution (bi-annual campaigns) was submitted. This work is still in progress (see Kenyeres et al, 2012) and it will be an important input for the new EUREF Working Group on “Deformation Modelling” (see below).

Using Densification Campaigns

EUREF continued the validation of national GNSS campaigns. A report including the necessary information about the measurements, the processing and the validation of the results is delivered to the TWG. After successful evaluation by the TWG the following projects were accepted by the plenary as EUREF densification campaign between 2011, and 2015: “EUREF Serbia 2010” (Serbia), “EUREF-MAKPOS 2010” (Macedonia), “EUREF Faroe Islands 2007” (Faroe Islands), “EUREF BE 2011” (Belgium), ”EUREF Poland 2015” and “Central European Geodynamic Research Network (CERGN”).

EPN Real-time Analysis Project

The EPN Project on “Real-time Analysis” (http://epncb.oma.be/_organisation/projects/RT-analysis) focuses on the processing of the EPN real-time data to derive and disseminate real-time GNSS products.

The EPN regional broadcaster at BKG (Federal Agency for Cartography and Geodesy, http://www.euref-ip.net) is broadcasting satellite orbits in the ETRS89 (realization ETRF2000). Based on these orbit and clock corrections, users can directly derive real-time coordinates referred to ETRS89 at few dm-level (Fig. 1.3a.3; more details are given in Söhne, 2011). Additional solutions for other regional datums, e.g. for SIRGAS95 or SIRGAS 2000, are implemented and could be found at http://products.igs-ip.net.

One aim of the project is to increase the reliability of the EPN real-time data flow and to minimize the possibility of data and products outage. For this purpose, two additional regional broadcasters have been put in operation, one at ASI (Italian Space Agency, http://euref-ip.asi.it/) and one at ROB (http://www.euref-ip.be/). Based on the existence of three regional broadcasters, several stations and national broadcasters started uploading their data in parallel to all of the broadcasters.

To ensure the product generation without interruption and without jumps, it is necessary to have a back-up processing running in an identical environment. This scheme could be implemented on a second computer at the same facility or, to overcome problems at the facility itself, at another place. In case of an outage in the production scheme at the master facility the broadcaster will switch to the backup solution using the same source table entry (mount
point). Therefore the user will notice neither any interruption nor any change in the origin of the streamed data.

While for the first step of the estimation of parameter corrections, i.e. satellite orbits and clocks, a globally distributed network (50-60 stations) is sufficient, any further steps, e.g. improved ambiguity fixing, ionosphere and troposphere corrections which go for an improved accuracy of the real-time Precise Point Positioning (PPP), require a denser network of real-time stations like the EPN or SIRGAS could provide.

**New EUREF Working Groups**

*Multi-GNSS Working Group*

In 2012 the EUREF TWG set up a new Working Group on “Multi GNSS”. As written above, a number of station managers provide GNSS signals on top of the GPS and GLONASS L1 and L2 signals. Before introducing Galileo, BeiDou or new GPS signals into EPN routine operation they must be carefully checked. One goal of the WG is to test and evaluate the new formats (RINEX 3, RTCM Multi Signal Messages) on content and data quality. New processing techniques have to be used or even developed for analysis of the new signals. Finally, recommendations must be prepared which of the new signals should be declared as mandatory for further use within the EPN. EUREF members are actively contributing to the development of quality check software by developing and using two software packages: G-Nut/Anubis [1.2.1] (Vaclavovic and Dousa, 2015) and BNC [2.12] (Weber and Mervart, 2009). Both allow useful operations such as RINEX header manipulation and the generation of data quality statistics. The EPN Central Bureau today already routinely cross-checks the
RINEX v3 headers against the site log information (similarly to what is done for the RINEX v2 data) and also verifies the conformity of the RINEX v3 headers w.r.t. to the RINEX v3 format description. Station managers are notified in case errors occur.

**Deformation Modeling Working Group**

In 2012 the EUREF TWG set up a new Working Group on “Deformation Models”. The objective of this WG is to create a crustal deformation model for Europe to 1) improve the knowledge of surface deformations in Eurasia and adjacent areas and 2) manage and use the national realizations of the ETRS89 by studying the behaviour of geodetic reference frames in the presence of crustal deformations. The Working Group aims at making more precise the concept of ‘Stable part of Europe’ underlying the definition of ETRS89. At the mm/yr level, areas of departure from the rigid rotation model of ITRS velocities about an Eurasian Eulerian pole are clearly visible in the Mediterranean area (Greece, Southern Italy, for example). Vertical motion due to Glacial Isostatic Adjustment (GIA) is clearly observed in the Fennoscandia, causing the vertical datum to be accordingly adjusted periodically. The Working Group attempts a geophysical understanding of the non-rigid behaviour of the European crust, with the objective to monitor the evolution of the deformation of national coordinate grids caused by geophysical phenomena, and predict when the deformation exceeds a certain tolerance. When this occurs, the NMCA’s are recommended to generate an update of the National realization of the ETRS89 and/or EVRS.

**EPN Densification Working Group**

The EPN Densification Working Group was created in the beginning of June 2015.

The primary goal of the EPN Densification is to realize a continental-scale (European), homogeneous, high quality position and velocity product in an homogeneous reference frame, for a very dense network of GNSS stations, and this with comparable quality from Greenland to Crete, from Svalbard to Gran Canarias.

Consequently, the EPN Densification is a joint venture of agencies and institutions from European countries which operate and/or analyse the data from dense national GNSS networks (in addition to their EPN stations) and are willing to submit the results of their data analysis (daily or weekly position SINEX files) routinely to EUREF.

To achieve its goal, the EPN Densification combines the national GNSS networks on the product level (daily or weekly position SINEX files) with the multi-year positions & velocities of the EPN stations and express them homogeneously in the ITRS/ETRS89 with the EPN as the backbone. Additionally, to support the station managers and guarantee the reliability of the combination, the station metadata (station naming, site logs) of the participating densification stations will maintained, cross-checked, harmonized and centrally managed by EUREF to avoid inconsistencies.

The EPN Densification products shall be used - in close cooperation with the EUREF Deformation Models Working Group - to support the ETRS89 realization not only over the stable part of Europe, but also over tectonically deforming areas like the Mediterranean region. The velocity product will be useful for general and specific tectonic studies, supporting the better understanding of the processes at deforming regions.
The EPN Densification will exploit the huge potential lying in these active GNSS networks both for geodesy and earth sciences. All the activities of the EPN densification require efficient cooperation between the data suppliers (e.g. NMCAs) and the geophysical community. Beside the well built structure and communication channels of the EPN, a close cooperation with other communities such as EPOS is foreseen.

**European Vertical Reference System (EVRS)**

In 1994 the IAG Sub-commission for Europe (EUREF) started the work on the Unified European Leveling Network (UELN) and resumed and enhanced previous projects, which existed in the Western and Eastern part of Europe separately. A European Vertical Reference System (EVRS) was defined in 2000 and the associated realization was named EVRF2000.

During the following years about 50% of the participating countries provided new national leveling data to the UELN data centre. Therefore a new realization of the EVRS was computed and published under the name EVRF2007. The datum of EVRF2007 is realized by 13 datum points distributed 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). The results of the adjustment are given in geopotential numbers and normal
heights, which are reduced to the zero tidal system. At the EUREF symposium June 2008 in Brussels, Resolution No. 3 was approved proposing to the European Commission the adoption of the EVRF2007 (Figure 1.3a.4) as the mandatory vertical reference for pan-European geo-information.

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

In the meantime, the UELN is continuously enhanced using additional or updated levelling data submitted by different countries. EUREF received in 2009 the European part of first order leveling network of Russia. Together with connection measurements between the national networks of Finland and Russia it was possible to close the loop around the Baltic Sea and strengthen the adjustment process. In addition, the new first order leveling data of Latvia (2011), and Spain (2012) were received by EUREF. For the next years Belarus and Ukraine announced to provide their levelling data and join the UELN. A new UELN adjustment will be computed after receiving the new data.

**Promotion and Adoption of the ETRS89 and EVRS**

Since 1989, many European countries have defined their national reference frames in ETRS89 by calculating national ETRS89 coordinates following the EUREF guidelines. The difference of the ETRS89 coordinates adopted in each country for a set of EPN stations with respect to the ETRS89 coordinates recently estimated by the EPN is now monitored on a regular basis by EUREF (Brockmann, 2010). These national ETRS89 coordinates can differ from the latest cumulative EPN coordinates due to e.g. differences in datum definition (different ETRFyy frames) and differences in used observation periods.

![Figure 1.3a.5: Difference between official ETRS89 coordinates adopted in the different countries and the latest EPN cumulative coordinate solution](image)
The results of the comparison show an agreement of a few cm (see Figure 1.3a.5). In addition, EUREF recently provided a new questionnaire to the NMCA on the utilization of the ETRS89 and EUREF products in their country and the first results were presented by Ihde et al. (2011). Up to now, 60% of the contacted countries replied to the questionnaire. About 85% stated that they adopted the ETRS89 in their country while other 10% were still working on this issue.

INSPIRE (Infrastructure for Spatial Information in Europe) was adopted in March 2007 by the Directive 2007/2/EC of the European Parliament and the Council. The goal of INSPIRE is to deliver an interoperable and integrated European spatial information service to users from different communities. The INSPIRE Directive addresses 34 spatial data themes needed for environmental applications, with key components specified through technical implementing rules. “Coordinate Reference Systems” (CRS) is one of the important themes. It establishes the geographical reference for many other themes. This makes INSPIRE a unique example of a legislative “regional” approach.

To ensure that the spatial data infrastructures of the member states are compatible and usable in a trans-boundary context, the Directive requires that common Implementing Rules (IR) are defined and applied in a number of specific areas (metadata, data specifications, network services, data and service sharing and monitoring and reporting).

These IRs are adopted as Commission decisions or regulations and are binding in their entirety. The Commission is assisted in this process by a regulatory committee composed of representatives of the member states and chaired by a representative of the Commission (known as the comitology procedure). Thanks to the efforts of the EUREF TWG, the ETRS89 and the EVRS, defined by EUREF, play now a fundamental role in the CRS IR.

The descriptions of national and pan-European geodetic reference systems are available by a Service System for European Coordinate Reference Systems (CRS). Transformation parameters between national geodetic reference systems and the European ETRS89 and EVRF2007 were calculated and provided. Additionally, an online-transformation capability for coordinates and heights of single points is implemented.

References


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

Chair: Claudio Brunini (Argentina)
Vice-chair: Laura Sánchez (Germany)

Structure

• SC1.3b-Working Group I: Reference system, chair: Virginia Mackern (Argentina)
• SC1.3b-Working Group II: SIRGAS at national level, chair: William Martínez (Colombia)
• SC1.3b-Working Group III: Vertical datum, chair: Sílvio R. de Freitas (Brazil)

Overview

The IAG Sub-commission 1.3b (South and Central America) encompasses the activities developed by the "Geocentric Reference System for the Americas" (SIRGAS). Its main objective is the definition, realization and maintenance of a state-of-the-art geodetic reference frame in Latin America and the Caribbean, including both, the geometrical and physical components. The present SIRGAS activities concentrate on:

- Maintenance and improvement of the ITRF densification in the SIRGAS Region;
- Contribution to the IGS through the operation of the IGS–RNAAC–SIR;
- Definition and realization of a gravity field-related vertical reference system in Latin America and the Caribbean;
- Promotion, coordination and support of national activities oriented to the use of SIRGAS as official reference frame in the individual countries;
- Measuring and modelling non-linear changes in the position of the reference stations;
- Monitoring vertical movements of tide gauges with GNSS;
- Expanding SIRGAS capabilities for real time GNSS positioning;
- Monitoring the ionosphere and neutral atmosphere with GNSS;
- Supporting the initiatives of the Regional Committee of the United Nations Global Geospatial Information Management for the Americas (UN-GGIM: Americas);
- Organizing and developing capacity building activities;
- Outreach through focused symposia, conferences, lectures, and articles.

In addition to being a Sub-commission of the IAG Commission 1, SIRGAS is at the same time a Working Group of the Cartographic Commission of the Pan American Institute for Geography and History (PAIGH). The linkage with the IAG ensures compliance with the policies of the Association and facilitates the access of the region to the IAG components. The interaction with PAIGH ensures agreement with the targets of the "2013-2015 Action Plan to Expedite the Development of Spatial Data Infrastructure of the Americas" that SIRGAS signed with PAIGH and other Pan American organizations in November 2012⁴. Thanks to the common work with the IAG and the PAIGH, 14 countries in the region have already adopted SIRGAS as the official reference frame for Geodesy and Cartography, according to the recommendation issued in 2001 by the "United Nations Cartographic Conference for the Americas" (New York, USA, January 22-26, 2001).

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At present, more than 50 institutions from 19 countries, including the national mapping agencies of Latin America, are committed to SIRGAS in a voluntary partnership. The main body of the organization is a Directing Council composed by one representative of each member country, one of IAG and one of PAIGH. This Council states the fundamental policies whose accomplishment is under the responsibility of an Executive Committee and the corresponding activities are conducted by the three working groups described in the following.

**SC1.3b-WGI: Reference System**

This WG is responsible for the analysis of the SIRGAS Reference Frame. This frame is composed by ca. 400 continuously operating GNSS stations, from this stations 235 track GLONASS, 16 GALILEO and 2 BEIDOU. The SIRGAS Reference Frame includes 58 formal IGS stations; however, in order to improve the distribution of the ITRF sites in this region, 40 additional SIRGAS stations are being processed by the IGS Global Analysis Centres since January 2012 and they are also included in the IGS Reprocessing 2. GNSS data are produced, archived, and processed according to the IERS and IGS standards and conventions to generate:

- Loosely constrained weekly solutions as input for the computation of cumulative (multi-year) solutions and to be integrated into the IGS polyhedron;
- Weekly station positions aligned to the ITRF to be used as reference for surveying applications in Latin America;
- Multi-year solutions with station positions for a given epoch and constant velocities to model the kinematics of the reference frame.

Since more and more Latin American countries are qualifying their national reference frames by installing GNSS continuously operating stations and these stations shall be consistently integrated into the continental reference frame, the SIRGAS-CON network comprises: (1) One core network (SIRGAS-C), primary densification of ITRF in Latin America, with a good continental coverage and stable site locations to ensure high long-term stability of the reference frame; and (2) National reference networks (SIRGAS-N) improving the densification of the core network and providing accessibility to the reference frame at national and local levels. Both, the core network and the national networks satisfy the same characteristics and quality; and each station is processed by three analysis centres.

The SIRGAS-C network is processed by the IGS-RNAAC-SIR (i.e. DGFI-TUM, Germany). The SIRGAS-N national networks are computed by the SIRGAS Local Processing Centres: CEPGE (Ecuador), CNPBD-UNA (Costa Rica), CPAGS-LUZ (Venezuela), IBGE (Brazil), IGAC (Colombia), IGM-Cl (Chile), IGN-Ar (Argentina), INEGI (Mexico), and SGM-Uy (Uruguay). These processing centres deliver 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. The processing strategy guarantees that each regional SIRGAS-CON station is included in three individual solutions. The SIRGAS Combination Centres are IBGE and the IGS-RNAAC-SIR (DGFI-TUM). INEGI and IGN use the GAMIT/GLOBK software\(^2\), while the others use the Bernese GNSS Software V. 5.2\(^3\). The accuracy of the final SIRGAS coordinates is estimated to be ±2.0 mm in the North and the East, and ±4.0 mm in the height. All Analysis Centres follow unified standards for the computation of the loosely constrained solutions. These standards are based in general


on the conventions outlined by the IERS and the GNSS-specific guidelines defined by the IGS; with the exception that in the individual SIRGAS solutions the satellite orbits, satellite clock offsets, and Earth orientation parameters (EOP) are fixed to the final weekly IGS values (SIRGAS does not compute these parameters).

To estimate the kinematics of the SIRGAS reference frame, a cumulative (multi-year) solution is computed (updated) every year, providing epoch positions and constant velocities for stations operating longer than two years; stations active during shorter time spans are omitted from the cumulative solutions. The coordinates of the multi-year solutions refer to the latest available IGS reference frame and to a common reference epoch, e.g., the most recent released SIRGAS multi-year solution SIR11P01 refers to IGS08 (ITRF2008), epoch 2005.0. It includes weekly normal equations from January 2, 2000 to April 16, 2011 for 230 stations with 269 occupations. Its averaged rms precision is estimated to be ±1.0 mm horizontally and ±2.4 mm vertically for the station positions at the reference epoch, and ±0.7 mm/yr horizontally and ±1.1 mm/yr vertically for the constant velocities.

Because the switch to the ITRF2008 (i.e. IGS08/IGb08) for the generation of the IGS products caused a discontinuity of some millimetres in the station position time series, the computation of multi-year solutions for the SIRGAS reference frame was discontinued until getting weekly normal equations referenced to the IGS08/IGb08 and covering a time span of at least three years. The two recently computed multi-year solutions SIR13P01 and SIR14P01 cover the period starting in April 2010, after the big earthquake in Chile. The main objective of these solutions is to identify and to model secular effects in the kinematics of the SIRGAS reference frame caused by that earthquake. At present, the entire SIRGAS network is being reprocessed from January 1997 using the latest IERS/IGS procedures and standards.

The loosely constrained weekly solutions as well as the weekly SIRGAS station positions and the multi-year solutions are available at ftp://ftp.sirgas.org/pub/gps/SIRGAS/ or at www.sirgas.org.

SC1.3b-WGII: SIRGAS at national level

After the determination of the first SIRGAS realisation in 1995, the South American countries concentrated on the modernization of their local geodetic datums through national densifications of the continental network and the determination of transformation parameters to migrate the existing geo-data from the old reference systems to SIRGAS. At the beginning, these densifications were realized by passive networks (i.e. pillars); today, most of the countries are installing continuously operating GNSS stations, which serve not only as local reference frame, but also as referential for daily applications based on satellite navigation and positioning. From 2000, the Central American countries started also to face these activities. The current undertakings of the SC1.3b-WGII concentrate on:

- Coordinating the SIRGAS activities to support the initiatives of the Regional Committee of the United Nations Global Geospatial Information Management for the Americas (UN- GGIM: Americas); especially the divulgation and practical adoption of the Resolution on the Global Geodetic Reference Frame for Sustainable Development released by the General Assembly of the United Nations at 26th of February, 2015.
- Supporting those countries interested on adopting SIRGAS as official reference frame. It includes advice on the establishment and processing of national GNSS reference networks, determination of transformation parameters between the classical geodetic datums and SIRGAS, alignment of the existing geo-data into SIRGAS, and generation of documents of
guidance to orientate local users approaching SIRGAS. During the last two years, significant advances were achieved in Bolivia, Costa Rica, Guatemala, and Honduras.

- Promoting the availability of the SIRGAS Reference Frame in real time by improving the transfer facilities at the reference stations and by installing a service called "Experimental SIRGAS Caster". Argentina, Brazil, Chile, Colombia, Uruguay, and Venezuela report major advances in this field.

- Coordinating local GNSS campaigns on passive points (where no continuously operating stations exist) to increase the availability of epoch station positions to detect deformations of the reference frame, especially in those areas affected by earthquakes (Argentina, Chile, Colombia, Costa Rica, Honduras, Guatemala, México, Peru, and Venezuela).

SC1.3b-WGIII: Vertical datum

Through this WG, SIRGAS is committed to the definition and realization (and further maintenance) of a gravity field-related vertical reference system in Latin America and the Caribbean, following the advice of the IAG Joint Working Group 0.1.1 on Vertical Datum Standardization. On-going tasks include

- Continental adjustment of the first order vertical networks in terms of geopotential numbers referred to a common $W_0$ value;
- Determination of a unified (quasi)geoid model for the region (under the responsibility of the IAG SC 2.4b, ‘Gravity and Geoid in South America’);
- Transformation (unifications) of the existing height systems into the new one.

Great efforts have been dedicated, and have still to be dedicated, to

- The collection and validation of the existing databases containing levelling and gravity data as well as tide gauge registrations;
- Transcription of old field notebooks to digital format;
- Levelling field works to connect the fundamental points of the vertical networks with the SIRGAS reference stations and with the main national tide gauges;
- More levelling connections between neighbouring countries.

Outreach and capacity building activities

- **SIRGAS 2011 General Meeting:** Heredia, Costa Rica, August 8 - 10, 2011. Hosted by the Universidad Nacional and attended by 116 participants from 17 countries.

- **SIRGAS 2012 General Meeting and technical visit to the Geodetic Observatory TIGO:** Concepción, Chile, October 29 - 31, 2012. Hosted by the Universidad de Concepción and the Instituto Geográfico Militar of Chile and attended by 135 participants from 15 countries.

- **SIRGAS 2013 General Meeting and celebration of the 20th anniversary of SIRGAS:** Panama City, October 24 - 26, 2013. Hosted by the Instituto Geográfico Nacional "Tommy Guardia" and attended by 184 participants from 28 countries.

- **Symposium SIRGAS 2014:** La Paz, Bolivia, November 24 - 26, 2014. Hosted by the Instituto Geográfico Militar and attended by 260 participants from 19 countries.

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4 This caster is hosted by the Universidad Nacional de Rosario, Argentina (www.fceia.unr.edu.ar/gps/caster).
• **Second workshop of the SIRGAS-WGIII (Vertical Datum).** Rio de Janeiro, Brazil. December 3 - 9, 2012. Hosted by the Instituto Brasileiro de Geografia e Estatística and attended by 11 participants from 9 countries.

• **Third workshop of the SIRGAS-WGIII (Vertical Datum).** Curitiba, Brazil. May 18 - 22, 2015. Hosted by the Universidade Federal do Paraná and attended by 30 participants from 9 countries.

• **Third SIRGAS/IAG/PAIGH School on Geodetic Reference Systems:** it took place together with the SIRGAS 2011 General Meeting in August 3-5, 2011 in Heredia, Costa Rica. It was attended by 116 participants from 17 countries.

• **Fourth SIRGAS/IAG/PAIGH School was devoted to the Real Time GNSS Positioning** and was carried out between October 24 and 26, 2012. It was hosted by the Universidad de Concepción and the Instituto Geográfico Militar of Chile and was attended by 50 colleagues from 16 countries. This School was possible thanks to the support of the Federal Agency for Cartography and Geodesy (BKG) of Germany.

• The **fifth SIRGAS School** was named **School on Reference Systems, Crustal Deformation and Ionosphere Monitoring.** It was a capacity building activity of the project **Monitoring crustal deformation and the ionosphere by GPS in the Caribbean,** which was supported by the IUGG, IAG (International Association of Geodesy), the IASPEI (International Association of Seismology and Physics of the Earth's Interior), and the IAGA (International Association of Geomagnetism and Aeronomy). The main objective of this project was to invite the Caribbean countries to participate actively in geodetic and geophysical initiatives going on in the Central and South American region, in order to enable the use of acquired data for practice and science in their countries, and to promote geosciences. The School was hosted by the Instituto Geográfico Nacional "Tommy Guardia" in Panama City, Panama, from October 21 to 23, 2013 and it was attended 145 participants from 28 countries.

• The **sixth SIRGAS School** was concentrated on **Vertical Reference Systems.** This school was hosted by the Bolivian Instituto Geográfico Militar and Escuela Militar de Ingeniería in La Paz, Bolivia, from November 20 to 23, 2014 and it was attended 34 participants from 13 countries.

• **Capacity building on Geodetic Reference Systems** in Santiago de Chile, Chile, between September 26 and 30, 2011. It was organized by the Instuto Geográfico Militar of Chile with the support of the DGFI-TUM (Germany) and the IAG. It was attended by 120 Chileans.

• **Training courses on precise GNSS data processing.** This activity is possible thanks to the agreement between the University of Bern and the DGFI-TUM to provide with the Bernese Software Latin American institutions intending to establish a SIRGAS Analysis Centre. In this period, three courses were carried out:
  - Instituto Geográfico Militar of Chile, Santiago de Chile, Chile, between September 26 and 30, 2011. 5 attendants.
  - Escuela de Topografía, Catastro y Geodesia, Universidad Nacional, Heredia, Costa Rica from December 3 to December 7, 2012. 15 attendants.
  - Instituto Geográfico Militar of Bolivia, La Paz, Bolivia, between May 27 and 31, 2013. 15 attendants.

• **Participation in the following meetings:**
- STSE-GOCE+Height System Unification Progress Meeting 2, Frankfurt am Main, Germany. December 2011.
- IGS Workshop 2014, Pasadena, California, USA. June 2014.
- EGU General Assembly. Vienna, Austria. April 2015

Publications:


Cisneros Revelo D.A.: Análisis de la red nacional GPS pasiva enlazada al sistema de referencia SIRGAS95 y su evolución hacia la nueva infraestructura soportada por la red GNSS de monitoreo continuo del Ecuador. Instituto Geográfico Militar, Ecuador, 2013
Pazmiño Orellana E.R., Bravo Chancay E.F.: Protocolo de utilización de datos de la red GNSS de monitoreo continuo del Ecuador a través de la WEB, un servicio con fines de investigación, proyectos de desarrollo, seguridad nacional y comunidad en general. Instituto Geográfico Militar, Ecuador, 2013
Cruz Ramos O., Sánchez L.: Efectos en el marco de referencia SIRGAS del terremoto del 7 de noviembre de 2012 en Guatemala. DGFI, Munich, Nov. 16, 2012
Cruz Ramos O., Sánchez L.: SIRGAS and the earthquake of November 7, 2012 in Guatemala. DGFI, Munich, Nov. 16, 2012

INEGI: Procesamiento de datos GPS considerando deformaciones del marco geodésico en el tiempo. INEGI, México, 2012


INEGI: El cambio del marco de referencia terrestre internacional (ITRF) en México. INEGI, México, 2011

INEGI: Obtención de coordenadas con GPS en ITRF y su relación con WGS84 y NAD27, INEGI, México, 2011

Sánchez L., Seitz M.: Recent activities of the IGS Regional Network Associate Analysis Centre for SIRGAS (IGS RNAAC SIR). DFGI Report No. 87, 2011


Acknowledgments

The operational infrastructure and results described in this report are possible thanks to the active participation of many Latin American and Caribbean colleagues, who not only make the measurements of the stations available, but also operate SIRGAS Analysis Centres processing the observational data on a routine basis. This support and that provided by the International Association of Geodesy (IAG) and the Pan-American Institute for Geography and History (PAIGH) is highly appreciated.

More details about the activities and new challenges of SIRGAS, as well as institutions and colleagues working on can be found at www.sirgas.org.
Sub-Commission 1.3c: Regional Reference Frame for North America (NAREF)

Co-Chairs: Michael Craymer (Canada), Neil Weston (USA)

Introduction

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 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. For more information and publications related to these working groups, see the regional Sub-Commission web site at <http://www.naref.org/>.

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. Neil Weston, respectively. Dr. Weston replaced Dr. Jake Griffiths as the U.S. co-chair in 2013.

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. Meetings of the working group were held in 2011, 2012 and 2013 during the AGU Fall Meetings in San Francisco.

Originally, the regional densification of the ITRF and IGS network consisted of weekly combinations of different regional weekly solutions across the entire North American continent using different GPS processing software. Contributors and some details of their solutions are given in the Table 1.3c.1 (below). In addition to these contributions, NRCan plans to implement PPP solutions for the same set of stations in their Bernese contribution. This will provide redundant solutions for all NRCan stations.

<table>
<thead>
<tr>
<th>Contributor</th>
<th>Software</th>
<th>Region</th>
<th>No. Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGS</td>
<td>PAGES</td>
<td>USA &amp; territories (CORS network)</td>
<td>1853</td>
</tr>
<tr>
<td>Scripps</td>
<td>GAMIT</td>
<td>North America</td>
<td>1291</td>
</tr>
<tr>
<td>MIT</td>
<td>GIPSY+Bernese Combination</td>
<td>Western North America</td>
<td>1373</td>
</tr>
<tr>
<td>NRCan</td>
<td>Bernese</td>
<td>Canada, Greenland &amp; northern USA</td>
<td>485</td>
</tr>
<tr>
<td>INEGI</td>
<td>GAMIT</td>
<td>Mexico</td>
<td>44</td>
</tr>
</tbody>
</table>

Not all stations in the Scripps and MIT solutions are being used because of the very high density of sites in southern California and some local areas of the Plate Boundary Observatory network. Presently, only those stations in the U.S. common with the NGS CORS solution will be included in the combinations.
Because of the increasing number of stations and the expected imminent generation of IGS repro2 orbits, no weekly combinations have been performed since GPS week 1583 due to the limitations of the SINEX combination software at that time. An enhanced version of the software has been development by NRCan to handle thousands of stations with greatly improved processing efficiency. The first version of the software has just been released. It I planned to attempt to restart the weekly NAREF combinations in the near future.

In the meantime, NGS has computed a multi-year solution of the CORS network covering the US, Mexico and Caribbean region, in addition to a set of global reference frame sites (see Fig. 1.3c1). This solution used data up to GPS week 1631, repro1 and IGS05 products. The solution was aligned to IGS08 and corrected for IGS08 antenna calibrations. A similar solution was also computed by CGS covering the northern have of North America, including Greenland (see Fig. 1.3c2). This solution was based on weekly solutions using data up to GPS week 1631 and the Bernese GPS Software 5.0. Because of the sparse permanent GNSS network in Canada, the solution was densified with campaign solutions of the high accuracy Canadian Base Network (CBN).

With the exception of INEGI, reprocessing of the regional networks are planned in conjunction with the IGS08 repro2 effort. Most contributors (NGS, NRCan, Scripps) plan to create their regional solutions as densifications of their global contributions to repro2 using their own orbits submitted to the IGS. INEGI has just completed their own reprocessing with repro1 orbits and has no immediately plans to reprocess again.
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 (NAD83) 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.

Although the best realization of a geocentric reference frame at the time it was introduced in 1986, it is now well known that NAD83 is offset from the actual geocentre (and thus ITRF) by about 2 meters. It is also well known that the NNR-NUVEL-1A plate motion model, used to keep NAD83 aligned with the North American tectonic plate, is biased by about 2 mm/yr. These problems make NAD83 incompatible with modern geocentric reference frames used internationally and by all GNSS positioning system. Consequently, there is a need to replace NAD83 with a high accuracy geocentric reference frame that is compatible with ITRS/ITRF.

It is expected that NAD83 will not be replaced until 2022 when it is also planned to replace the vertical datum in the USA with one based on a geoid. There have been preliminary discussions at NGS and NRCan on the various options for defining a regional geocentric reference frame. It has generally been agreed that the new reference frame will be aligned exactly with the latest realization of ITRF at that time at some adopted reference epoch. In the meantime, discussions are underway on the best method of fixing such a frame to the North American plate, including the selection of a set of reference frame stations representing stable North America and the estimation of the motion of the North American tectonic plate.

In the meantime, NGS is installing a new high level network of 10-20 highly stable Foundation CORS sites across the U.S. that will be contributed to the IGS. Unlike most of the other CORS network in the U.S., these sites will be owned and operated by NGS and built and operated to IGS standards. Referred to as Foundation CORS, this network will provide a more stable foundation for the new reference frame in the U.S. Attempts will be made to co-locate these GNSS stations with other techniques in order to create true GGOS stations. The first of these sites was installed in Miami is late 2014.
There have also been informative discussions with the public in the US during two Federal Geospatial Summits organized by NGS in 2010 and 2015. Active promotion of the new reference frame and vertical datum are planned in the near future.

**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/datums 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 frame is now defined in terms of a time-dependent 7-parameter Helmert transformation from ITRF96. Transformations from/to other subsequent versions of ITRF are obtained by updating the NAD83-ITRF transformation with the official incremental fourteen parameter transformations between ITRF versions as published by the IERS. The last update to the NAD83-ITRF transformation was for ITRF2008 in late 2010. A new update will be provided as soon as the new ITRF2014 is released.

**Other Activities**

Commercial real-time kinematic (RTK) services and their networks of base stations have grown over the years (see Fig. 1.3c.3). They are effectively providing access to the NAD83 reference frame for many users. Because these networks are not always integrated into the same realization of NAD83, CGS began a program of validating the NAD83(CSRS) coordinates of these services to ensure they are properly integrated into the NAD83(CSRS) reference frame. CGS is now providing monthly coordinate and velocity solutions for 6 of the largest RTK services in Canada; a total of more than 800 stations (see Fig. 1.3c.4). Compliance agreements have signed with the three 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 RTK services are integrated into the latest realization of NAD83(CSRS). NGS is also working towards a similar program to validate their commercial RTK services.

![Figure 1.3c.3: Growth of the six largest commercial RTK networks in Canada.](image-url)
The International Great Lakes Datum (IGLD) is a vertical datum based on dynamic heights. It is used for monitoring water resources in the Great Lakes Basin. The datum needs periodic updating about every 30 years to account for the effects of glacial isostatic adjustment. The current velocity field, based on the CGS multiyear solution in SC1.3c-WG1, is given in Fig. 1.3c.5. The current realization, IGLD 1985, is based on NAVD88 transformed to dynamic heights. This datum is now in need of updating and planning has begun for the implementation of new geoid-based realization (IGLD 2020). IGLD 2020 is expected to use the latest North American geoid at the time of adoption. To support this update, improve the modelling of GIA and monitor the stability of reference benchmarks at IGLD water level gauges, repeated GPS surveys have been conducted in 1997, 2005 and 2010. New survey campaigns are also planned for 2015 and 2020.
Figure 1.3c.5: Great Lakes velocity field based on CGS solution up to GPS week 1631.
Sub-Commission 1.3d: Regional Reference Frame for Africa (AFREF)

Chair: Richard Wonnacott (South Africa)

Introduction

This report summarizes the main activities related to the IAG Sub Commission 1.3d (Africa) for the period 2011-2015. This report focuses on the activities of the Africa Geodetic Reference Frame (AFREF). Many persons and institutions have contributed, either directly or indirectly, to the activities of the Sub-Commission and AFREF. The author wishes to thank all those who have contributed and at the same time apologize in advance for credits that may have been inadvertently omitted in this report.

Reference Frame

The major activity within Africa in relation to the activities of Commission 1 Reference Frames and in particular SC 1.3d Africa is the establishment of a network of permanent GNSS base stations in support of an effort to unify the reference frames in Africa. The project is known as the Africa Reference Frame project (AFREF). Prior to March 2013 the project fell within United Nations Committee for Development Information, Science and Technology (Geo-information) (CODIST-Geo). Since March 2013, the oversight and supervisory functions of CODIST-Geo (including AFREF) were transferred to the United Nations Global Geospatial Information Management: Africa (UN-GGIM: Africa).

Four of the seven major objectives of AFREF relative to this report are to:

- 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; and
- Assist in establishing in-country expertise for implementation, operations, processing and analyses of modern geodetic techniques, primarily GPS.

In pursuance of these objectives, permanent GNSS base stations are being set-up throughout most of Africa. Approximately 90 stations have been installed and are registered on the AFREF Operational Data Centre which was installed to download and archive data from these stations. Of these 90 stations, however, only 60 have provided data to the ODC in 2015. For the period 1 January to 20 May 2015, an average of 48 stations provided data daily, albeit not always the same 48 stations.

The stations have been installed by a variety of agencies, organizations and projects such as the Africa Array (seismology), AMMA-GPS (meteorology) and SCINDA (ionosphere) projects. A number of the National Mapping Authorities have also established permanent GNSS networks within their own countries.

A two-week period was identified in Dec 2012 (Days 337 to 350) during which daily data from an average of 50 stations were downloaded. This data, together with a further 50 global stations, was processed by 4 processing centres and combined by the IGN, Paris to provide a
set of static co-ordinates based on ITRF2008 at epoch 2012 Day 340 (GPS Week 1717) to be used for everyday surveying and mapping operations.

The four processing centres were:

- Ardhi University, Tanzania / University of Purdue, USA
- Hartebeesthoek Radio Astronomy Observatory, South Africa
- Surveying and Mapping Division, Ministry of Lands, Tanzania
- University of Beira Interior, Portugal

Figure 1: Stations for which a set of static co-ordinates was processed using data between Days 337 and 350 in 2012. The lack of freely available CORS data in the area from Angola through Central Africa, Sudan and Sahara and North African countries remains of concern.
Figure 2. Distribution of Global stations used in the computation of static AFREF co-ordinates. Blue squares = AFREF stations, Red circles = Global stations

Table 1: WRMS in Easting, Northing and UP per Analysis Centre per week

<table>
<thead>
<tr>
<th>Solution</th>
<th>Week 1717</th>
<th>Week 1718</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td># E N U</td>
<td># E N U</td>
</tr>
<tr>
<td></td>
<td>Sta mm</td>
<td>Sta mm</td>
</tr>
<tr>
<td>HartRAO</td>
<td>80 1.4 1.0 4.9 79 1.2 1.1 5.0</td>
<td></td>
</tr>
<tr>
<td>DSM</td>
<td>84 1.2 0.9 3.9 86 1.2 1.0 3.8</td>
<td></td>
</tr>
<tr>
<td>Ardhi</td>
<td>75 1.0 0.9 3.4 77 0.9 0.8 3.4</td>
<td></td>
</tr>
<tr>
<td>SEGAL</td>
<td>87 1.3 1.7 6.7 85 1.3 1.8 6.0</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: WRMS values of the alignment to ITRF2008 using 42 Global reference stations, in East, North and Up in mm for the two weeks that were processed.

<table>
<thead>
<tr>
<th></th>
<th>E mm</th>
<th>N mm</th>
<th>U mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Week 1717:</td>
<td>2.9</td>
<td>3.2</td>
<td>7.4</td>
</tr>
<tr>
<td>Week 1718:</td>
<td>3.0</td>
<td>3.4</td>
<td>7.6</td>
</tr>
</tbody>
</table>

The computation of static co-ordinates for the remaining stations is in progress.
The second phase will be routine processing of the network to provide a velocity field. Data from the stations currently in place is being processed and used by IAG Working Group on Regional Dense Velocity Fields

Once the set of static co-ordinates has been published, the National Mapping Authorities will have to commence with determining the relationship between the new ITRF2008 based AFREF reference frame and the existing in-country reference frame in order to preserve all historical geospatial data and reference material.

**Capacity Building**

Workshops on the establishment and processing of permanent GNSS stations and networks are held annually at the Regional Centre for Mapping of Resources for Development in Nairobi, Kenya. Partially as a result of these workshops, a number of countries have either established or have commenced with the establishment of in-country CORS networks.
Sub-Commission 1.3e: Regional Reference Frame for South-East Asia and Pacific (APREF)

Chair: John Dawson (Australia)

Overview

To improve regional cooperation that supports the realisation and densification of the International Terrestrial Reference frame (ITRF). This activity is carried out in close collaboration with the United Nations Global Geospatial Information Management (UN-GGIM) Asia Pacific - Geodetic Reference Framework for Sustainable Development Working Group (formerly known as the Geodetic Technologies and Applications Working Group of the Permanent Committee for GIS Infrastructure in Asia and the Pacific - PCGIAP).

The 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.
• To outreach to developing countries through symposia, workshops, training courses, and technology transfer activities.

Activities

The activities of sub-commission 1.3e have focussed on the Asia Pacific Reference Frame (APREF) project. Table 1.3e.1 summarizes the current commitments to APREF. APREF products presently consist of a weekly combined regional solution, in SINEX format and a cumulative solution, which includes velocity estimates.

In addition to those stations contributed by participating agencies, the APREF analysis also incorporates data from the International GNSS Tracking Network including stations in the Russian Federation (16), China (10), India (3), French Polynesia (2), Kazakhstan (1), Thailand (1), South Korea (3), Uzbekistan (1), New Caledonia (1), Marshall Islands (1), Philippines (1), Fiji (1), and Mongolia (1).

GNSS data from a CORS network of approximately 480 stations, contributed by 28 countries is now available and processed by four Analysis Centres (ACs): Geoscience Australia, the Curtin University, the Department of Sustainability and Environment in Victoria, Australia, and the Institute of Geodesy and Geophysics, Chinese Academy of Sciences.

The APREF project websites was established as http://www.ga.gov.au/scientific-topics/positioning-navigation/geodesy/asia-pacific-reference-frame. The weekly ITRF coordinate estimates in SINEX format, coordinates time series and velocity solutions for the APREF stations are published on the APREF website.
Table 1.3e.1: Responses to the APREF Call For Participation. Responding agencies have indicated whether they would undertake analysis, provide data archive and product distribution or supply data from GNSS stations

<table>
<thead>
<tr>
<th>Country/Locality</th>
<th>Responding Agency</th>
<th>Proposed Contribution</th>
<th>Analysis</th>
<th>Archive</th>
<th>Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Afghanistan</td>
<td>National Geospatial-Intelligence Agency, USA</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Alaska, USA</td>
<td>National Geodetic Survey (USA)</td>
<td></td>
<td></td>
<td>90</td>
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<tr>
<td>American Samoa</td>
<td>National Geodetic Survey (USA)</td>
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<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Australia</td>
<td>Geoscience Australia</td>
<td>x</td>
<td>x</td>
<td></td>
<td>132</td>
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<tr>
<td>Australia</td>
<td>Curtin University of Technology</td>
<td>x</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Australia</td>
<td>University of New South Wales</td>
<td>x</td>
<td></td>
<td></td>
<td>1</td>
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<tr>
<td>Australia</td>
<td>Department of Environment and Resource Management, Queensland</td>
<td></td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Australia</td>
<td>Department of Sustainability and Environment, Victoria</td>
<td>x</td>
<td></td>
<td></td>
<td>96</td>
</tr>
<tr>
<td>Australia</td>
<td>Department of Lands and Planning, Northern Territory</td>
<td></td>
<td></td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Australia</td>
<td>Department of Primary Industries, Parks, Water &amp; Environment, Tasmania</td>
<td></td>
<td></td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Australia</td>
<td>Radio and Space Weather Services, Bureau of Meteorology</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Australia</td>
<td>Land and Property Management Authority, New South Wales</td>
<td></td>
<td></td>
<td></td>
<td>128</td>
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<tr>
<td>Brunei</td>
<td>Survey Department, Negara Brunei Darussalam</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Cook Islands</td>
<td>Geoscience Australia</td>
<td></td>
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<tr>
<td>Cook Islands</td>
<td>Geospatial Information Authority of Japan</td>
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<tr>
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</table>

In addition to APREF, the sub-commission has and will continue to coordinate an annual GNSS campaigns along with APREF so that countries without Continuously Operating Reference Stations (CORS) can connect their national geodetic infrastructure to the regional/global network. Four annual GNSS campaigns have been carried out since 2011; the analysis reports for these campaigns have been distributed to participant member countries.
Sub-Commission 1.3f: Regional Reference Frame for Antarctica (SCAR)

Chair: Mirko Scheinert (Germany)

Observation Campaigns

Observation campaigns in the framework of the Scientific Committee on Antarctic Research (SCAR) Expert Group on Geodetic Infrastructure (GIANT) took place every austral summer from 2011 until 2015 (SCAR Epoch Crustal Movement Campaigns). The respective data and data of further Antarctic GNSS stations are archived in the SCAR GNSS Database maintained at TU Dresden. For the time period since 1995, data of about 50 stations have now been stored in the database.

Data analysis

The analysis of the data acquired during the SCAR Epoch Crustal Movement Campaigns are regularly analysed in order to come up with an up-to-date realization and densification of the terrestrial reference frame in Antarctica. Results were presented at the SCAR meetings in Portland (USA), 2012, and Auckland (NZ), 2014. A detailed report on the latest analysis incorporating data from 1995 until 2013 is given by Rülke et al. (2015). Using a modified version of the Bernese GNSS Software v5.0 station coordinates and velocities were inferred with respect to the TRF solution IGS08.

Meetings

Regular meetings took place in the framework of the SCAR Meetings, namely the XXXII SCAR Meeting in Portland (USA), July 2012, and the XXXIII SCAR Meeting in Auckland (NZ), August 2014. The goals of SC 1.3f are well reflected in the working plan of the SCAR Expert Group on Geodetic Infrastructure in Antarctica (GIANT), especially in GIANT subproject “GNSS observations for geodetic and geodynamic applications”.

References

Working Group 1.3.1: Integration of Dense Velocity Fields into the ITRF

Chair: Carine Bruyninx (Belgium), co-chair: J. Legrand (Belgium)

1. Introduction

The objective of the Working Group (WG) “Integration of Dense Velocity Fields into the ITRF” is to provide a global GNSS-based dense, unified and reliable velocity field referenced in the ITRF (International Terrestrial Reference Frame) and useful for geodynamical and geophysical interpretations.

2. Working Group Members

- Zuheir Altamimi
- Carine Bruyninx (Chair)
- Mike Craymer
- John Dawson
- Jake Griffiths
- Ambrus Kenyeres
- Juliette Legrand (Co-chair)
- Laura Sanchez
- Álvaro Santamaría Gómez
- Elifuraha Saria

3. Activities

The WG originally started by combining multi-year position/velocity solutions submitted by the IAG regional reference frame sub-commissions (APREF, EUREF, SIRGAS, NAREF) and global (ULR, Santamaría-Gómez et al. 2011) and IGS analysis centres. However, the level of agreement between the solutions was not satisfactory and the combination was affected by geographically correlated biases (Legrand et. al. 2012).

In 2012, the WG therefore decided to start combining weekly position solutions instead, allowing to mitigate the biases. All initial contributors agreed with this approach and in addition, AFREF also started to submit its first solutions.

3.1 Data Set

The list of submitted solutions is shown in Table 1. The solutions contain in total more than 4000 stations and consist (for each contributor) of the weekly SINEXs (cleaned or with a list of outliers to be removed), a cumulative solution and associated residual position time series, the position and velocity discontinuities that should be used for the cumulative solution, and the station site logs (if available). Only 2679 stations (# selected stations) with enough data to estimate reliable velocities (data span > 3 year, present in at least 104 weekly SINEXs and present in at least 50% of the weekly SINEXs within the data span) have been retained for further analysis (stations in blue and red in Figure 1).
Table 1: Weekly solutions submitted to the WG.

<table>
<thead>
<tr>
<th>AC</th>
<th>Solution</th>
<th>Data span (year)</th>
<th>Antenna calibrations</th>
<th>Before GPS week 1631</th>
<th>After GPS week 1631</th>
<th># initial stations</th>
<th># selected stations</th>
<th># new stations wrt ITRF2008</th>
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</thead>
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<td><strong>2679</strong></td>
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</table>

Figure 2: Map of the network; in red: sub-network used to mitigate the aliasing effect.

3.2 Methodology

The multi-year station positions & velocities have been computed in a two-step approach: first the individual weekly solutions were combined on the weekly level and then in a second step, the weekly combined positions were accumulated in order to estimate the dense global velocity field. All the combinations have been performed using the CATREF Software (Altamimi et al., 2007).

3.2.1 Combination of the individual weekly solutions:

The IGS weekly solution is used as reference and the “regional” individual weekly solutions are aligned to it using seven Helmert parameters. In order to solve the datum defect that affected some of the solutions, minimum constraints were added to the individual input solutions prior to the combination. The constraints used (translation, rotation and/or scale) were identified for each solution and missing constraints were added when necessary.
In order to mitigate the impact of the disagreements between the individual solutions and to stabilize the alignment of the individual solutions during the weekly combinations, the weekly combinations are done in 4 iterative runs:

1. Rough cleaning of the weekly solutions: allows identifying, for example, geographically different stations with identical 4-character ids and domes numbers, errors in the antenna type or antenna height used during the processing or also differences in the data modelling which are too large to be neglected. In this run, the network was restricted to stations present in at least 2 solutions and covariance matrices were neglected and set to the identity matrix.

2. Combination of the weekly solutions for a subset of stations. The a priori weighting ($\sigma_1$) of the covariance matrices is based on the formal errors in the individual weekly SINEXs. This run allows to estimate, each week, the Helmert transformation parameters between the individual weekly solutions and the IGS weekly solution and the variance factor ($\sigma_2$) for each solution.

3. Combination of the weekly solutions for a subset of stations using the variance factors ($\sigma_2$) estimated in the previous run. This run allows to estimate, each week, the Helmert transformation parameters between the individual weekly solutions and the IGS weekly solution.

4. Combination of the weekly solutions for the full network using the variance factor ($\sigma_2$) and the Helmert transformation parameters estimated in the previous run.

The RMS of the weekly combinations is between 2 to 5 mm (see Figure 2).

![Figure 3: RMS of the weekly combinations as a function of time in mm (Up in red and 2D horizontal in blue)](image-url)
3.2.2 Computation of the multi-year solution:

The multi-year positions and velocities are expressed in the IGS08 frame. In order to mitigate the aliasing effect [Collilieux et al. 2011], a global and well distributed sub-network, containing the igs08 core stations plus a few good quality stations with more than 10 years of data, was used to estimate the transformation parameters between the weekly combined solution and the cumulative solution. Then, these transformation parameters were re-used with the full network, preserving the non-linear signals embedded in the time series.

During the stacking of the combined weekly positions, discontinuities are introduced in order to take into account jumps in the position coordinate time series and changes in the velocities, see section 3.2 - Discontinuities for more information on how the discontinuities have been handled.

3.3 Issues and Lessons learned

3.3.1 Metadata

From the beginning, this WG faced issues linked to station naming or metadata.

When a station belongs to several networks, each network has a version of the site log. In order to populate our site log database, we downloaded site logs from each network to discover that they were not identical. In few cases, the differences were problematic (e.g. antenna type, different dates or hours of antenna/receiver installation or removal, elevation cut off). Unfortunately, these few important cases were drowned in a bunch of, difficult to handle, sit log format or version differences.

The information coming from the submitted weekly SINEX files and site logs was cross-checked wrt the IERS domes numbers list (ftp://itrf.ign.fr/incoming/codomes_coord.snx). More than 6000 triplet of 4-character ids/DOMES/PT were present in the original raw SINEXs. After the check, this number dropped to about 4000 unique stations. From them, 2000 stations were unknown to the IERS and we attributed them virtual domes numbers.

Coordinates and some station mistakes were corrected in the IERS list thanks to feedback sent to its responsible.

A lot of the position inconsistencies can be explained by the use of an incorrect antenna height or antenna type during the data analysis. Unfortunately, we identified incorrect reporting of station metadata used during the analysis in some SINEX headers. This incorrect information, together, with the inconsistent site logs, made an automated process, able to handle the metadata problems, unreliable. As a consequence, in case of a disagreement between solutions, all the information was manually checked.

3.3.2 Antenna modelling

As shown in Table 1, some solutions used the igs05.atx antenna calibration model before GPS week 1631 and igs08.atx after GPS week 1632 (IGS, EUR, GSB, NGS, SIR), while others used igs08.atx (APR, AFR) for the whole period. In addition, the EUR solution also used individual antenna calibrations when available. This situation entailed systematic biases affecting some stations.
A possible way to mitigate these biases is to apply the Rebischung (et al. 2012) model. However, due to erroneous or missing antenna metadata in the submitted weekly SINEXs and to the imperfection of the model for some stations, we decided not to apply the model and to handle the disagreement between solutions on a station per station basis by excluding solutions for the affected station. In order to handle the position changes at GPS week 1632 due to the antenna calibration model switch, position discontinuities have been added when necessary. Therefore, the impact on the velocity field has been properly mitigated. Nevertheless, the mix of the antenna calibration models (igs05.atx, igs08.atx and individual antenna calibrations) is the main drawback of this combination.

### 3.3.3 Discontinuities

All discontinuities provided by the contributors have harmonized and merged. During this process, the all residual position time series were manually screened together with the information on station hardware changes, earthquakes (larger the magnitude 5 occurring in the area of each station from http://earthquake.usgs.gov), and suspected changes in the antenna calibration model. All the discontinuity dates were checked and set to the exact date of hardware installation or earthquake.

### 3.4 Results

The velocity field derived from the combination is shown in Figure 4 (horizontal) and Figure 5 (vertical).

![Figure 4: Horizontal velocity field expressed in the IGS08.](image-url)
Figure 5: Vertical velocity field expressed in the IGS08.

In addition to the velocities, for each station, several types of time series are produced:

- Residual position time series of the individual solutions (e.g. Figure 6 left for DAEJ in Korea);
- Residuals of the weekly combination plotted as a time series;
- Residual position time series of the combined solution (e.g. Figure 6 right for DAEJ in Korea);
- Position time series of the combined solution;
- De-trended position time series of the combined solution with the mean position and velocity removed. They allow visualising the size of the discontinuities and the change in the velocities;
- Residual position time series of the combined solution after removing the 6 and 12-month seasonal signals.
Figure 6: Residual position time series with respect to cumulative solution of individual weekly regional solutions (left) and weekly combined solution (right).

Figure 7: Weekly RMS of the cumulative solution in mm.
All these plots are available online as interactive plots. The web site will soon be open publicly.

The weekly RMS (Figure 7) of the combination is at the same level as the RMS of the individual solutions. The time series of the combination are however longer (+4% of data span) and more populated (+11% of weeks).

3.5 Conclusion

Based on the weekly SINEX position solutions from the different reference frame sub-commissions, the Working Group computed a combined velocity field including more than 2600 stations.

From the beginning, the WG's biggest challenge, and the most time consuming issue, was metadata management (due to incomplete knowledge or conflicting information). Examples are station naming (DOMES number or 4-character id) conflicts, incorrect reporting of station metadata used during the analysis in the SINEX headers, or the use of incorrect antenna heights during the data analysis. However, a rigorous check of all the metadata resulted in a unique list of discontinuities for each of the 2600 stations contributing to the final velocity.

The combination was successful showing longer and more populated time series compared to the individual solutions. In addition, the combination on a weekly level allows increasing the reliability of the velocity field thanks to the redundancy. All the results will be available online at http://iagvf.oma.be.

4. Working Group Communications


Legrand J., Bruyninx C., Griffiths J., Craymer M., Dawson J., Kenyeres A., Santamaría-Gómez A., Sánchez L., Saria E., Altamimi Z., Densification of the ITRF velocity field through a collaborative approach (oral), IAG Scientific Assembly 2013, 01-06 September 2013, Potsdam, Germany


5. Working Group Papers


6. References


Working Group 1.3.2: Deformation Models for Reference Frames

Chair: Richard Stanaway (Australia)

Introduction

WG 1.3.2 "Deformation Models for Reference Frames" was formed at the IUGG in Melbourne, Australia in July 2011. The main aim of the WG has been to focus research in deformation modelling into the rapidly emerging field of regional reference frames used in applied geodesy, particularly positioning and GIS. Deformation models and other time-dependent transformation models provide linkages between global reference frames such as ITRF, regional reference frames and local reference frames commonly used for land surveying and mapping. In 2011 there was no consistent approach and methodology to perform high precision transformations between these reference frames.

WG 1.3.2 has been working closely with FIG Commission 5 (Positioning and Measurement), specifically FIG Working Group 5.2 (Reference Frames) as there has been a great deal in common with the aims of both working groups. The members of WG 1.3.2 comprise a wide spectrum of researchers from different fields of geophysics, geodesy, land surveying and GIS.

Working Group members

The WG currently consists of 19 members:

Richard Stanaway, University of New South Wales, Sydney, Australia
Christopher Pearson, University of Otago, Dunedin, New Zealand
Paul Denys, University of Otago, Dunedin, New Zealand
Kevin Kelly, ESRI, Redlands, California, USA
Rui Fernandes, University of Beira Interior, Covilhã, Portugal
Craig Roberts, University of New South Wales, Sydney, Australia
Graeme Blick, Land Information New Zealand, Wellington, New Zealand
Chris Crook, Land Information New Zealand, Wellington, New Zealand
Nic Donnelly, Land Information New Zealand, Wellington, New Zealand
John Dawson, Geoscience Australia, Canberra, Australia
Mikael Lilje, Lantmäteriet, Gävle, Sweden
Laura Sánchez, Deutsches Geodätisches Forschungsinstitut, München, Germany
Rob McCaffrey, Portland State University, Portland, Oregon, USA
Yoshiyuki Tanaka, Earthquake Research Institute, University of Tokyo, Japan
Sonia Alves, Instituto Brasileiro de Geografia e Estatística, Rio de Janeiro, Brazil
Norman Teferle, University of Luxembourg, Luxembourg
Laura Wallace, University of Texas, Austin, Texas, USA
Yasushi Harada, Tokai University, Shizuoka, Japan
Daphné Lercier, Trimble, Nantes, France

Summary of WG activities from 2011 to 2015

Considerable research on deformation modelling has been completed by WG members in Japan, South America, Australia, New Zealand, Europe and the USA. Significant earthquakes
since 2011 including those in Chile, Japan and New Zealand have resulted in localised
def ormation models being developed to support land surveying activities necessary for
recovery and reconstruction in those countries. Geodetic analysis of co-seismic displacement
and post-seismic decay from significant earthquakes has resulted in improved models that can
be incorporated in the next realisations of ITRF and the development of more complex epoch
reference frames that incorporate non-linear modes of deformation.

Background

The existing hierarchy of geodetic reference frames is necessary to support a wide range of
different research activities within the Earth sciences and real-world applications. The ITRF is
considered to be the fundamental geodic terrestrial reference frame from which other frames
are derived or linked by transformation and deformation models. Coordinates within ITRF are
necessarily kinematic in nature to account for deformation arising from geophysical
phenomena such as plate tectonics, earthquakes, volcanism, loadings and post-glacial
rebound. Anthropogenic affects such as subsidence arising from water abstraction and mining
also contribute to coordinate kinematics. Space geodetic positioning techniques such as GNSS
intrinsically provide positions within ITRF or closely aligned frames such as WGS-84.

The Earth’s surface is broadly composed of stable tectonic plates where plate-fixed reference
frames can be defined by plate motion models (PMM), which quantify the rotation of the
stable portion of a tectonic plate with respect to adjoining plates or the ITRS. In plate
boundary regions, deformation is more complex, warranting the application of active fault
locking and deformation models. Deformation models can also be used within stable plates to
model localised and intraplate deformation. Episodic deformation (e.g. from earthquakes) can
also be modelled to enable propagation of coordinates across deformation events. These
deformation models (referred to as patches in some literature e.g. Blick et al., 2006) can
include both co-seismic displacement and post-seismic relaxation coefficients.

Deformation classically refers to change of shape described by strain tensor diagrams that
define the magnitude and orientation of the deformation. In the context of rotating rigid
tectonic plates deformation would be zero within the plate and non-zero with respect to
adjoining plates and deforming zones. Absolute deformation can refer to displacement of
features on the Earth’s surface with respect to the axes of a no-net-rotation (NNR) geocentric
frame. Relative deformation can refer to the displacement rate (shortening or extension)
between adjacent points. Relative deformation within stable tectonic plates is close to zero,
even if the absolute deformation will be non-zero to account for plate rotation.

Poles of rotation of stable plates can be estimated by inversion of observed site velocities and
other geophysical observations such as slip vectors estimated from earthquake data. Inter
seismic strain accumulation should be accounted for in any inversion using realistic fault
locking models. Geologically derived poles of rotation for plates will differ slightly from
those derived by inversion of inter seismic site velocities due to the fact that geologically
derived velocities include far-field co-seismic deformation over considerably longer periods
than any space geodetic time series can provide.

Plate-fixed (or ground-fixed) reference frames have formed the basis for many regional
reference frames and national geodetic datums to support land surveying and mapping
activities at a more prosaic level. The increased usage and precision of GNSS positioning
since the 1990s, however, has highlighted the disparity between ITRF and ground-fixed
frames. This disparity requires a significant paradigm shift in how emerging positioning
technologies will interact with spatial data infrastructure defined by coordinates in ground-fixed reference frames that have been the mainstay of surveying, mapping and civil engineering.

Summary of WG 1.3.2 research activities (2011-2015)

WG members from Japan (Yoshiyuki Tanaka and Yasushi Harada) have been analysing data from the dense GEONET CORS network in Japan in order to improve Japanese crustal deformation models, particularly post-seismic deformation in the aftermath of the great Tōhoku earthquakes of March 2011. Related work in Japan has been conducted by Atsushi Yamagiwa and Yohei Hiyama of the Geospatial Information Authority of Japan to develop deformation models for use with the Japanese Geodetic Datum JGD2000 (Figure 1), (Kato et al., 2011; Tanaka et al., 2011; Yamagiwa and Hiyama, 2013).

![Figure 1. Correction parameters developed for coordinates in Japan - Horizontal component](image-url)
Development of geodetic deformation models is well advanced in New Zealand, particularly after the Canterbury earthquake sequence between 2010 to 2012. Chris Crook and Nic Donnelly from Land Information New Zealand (LINZ) have revised the New Zealand Deformation Model which models inter-seismic deformation in New Zealand. They have recently released deformation patches which model the co-seismic and post-seismic deformation from the Canterbury earthquakes (Crook, 2013). Other WG researchers (Paul Denys, Chris Pearson and Laura Wallace) have provided insights into localised deformation in New Zealand and geophysical modelling and definition of rigid crustal blocks. Nic Donnelly is currently researching how local deformation models can be estimated from remote sensing techniques such as InSar and LiDar. This research is being conducted at the University of New South Wales.

In Australia, a next-generation geodetic datum, which will be fundamentally kinematic in nature is being developed by the geodesy team at Geoscience Australia, led by WG member John Dawson. A deformation model for Australia has been developed by Richard Stanaway and Craig Roberts (Stanaway et al., 2013; Stanaway and Roberts, 2015). This work is being done in close co-operation with the LINZ members of the WG under the aegis of the Cooperative Research Centre for Spatial Information (CRC-SI). A Stable Australian Plate Reference Frame (SAPRF) has also been developed and was presented at the IAG Commission 1 REFAG Symposium at Luxembourg in October 2014.

In May 2012, a combined IAG, FIG and ICG workshop "Reference Frames in Practice" was held in Rome prior to the FIG Working week (Figure 2). WG 1.3.2 members Mikael Lilje, John Dawson, Richard Stanaway and Graeme Blick provided substantial input into the workshop with presentations on deformation models being developed in Australia and New Zealand. This workshop was a great success, and similar workshops were also run in June 2013 as part of the South-East Asian Surveyors Congress in Manila, The Philippines, and in Suva, Fiji in September 2013 at the FIG Pacific Small Island Developing States Symposium.
Kevin Kelly and colleagues at Esri are continuing to develop a grid format (e.g. Esri Geodetic data Grid eXchange Format - GGXF) that can support deformation models and other time dependent transformations (e.g. 14 parameter) in GIS. This is a very important contribution to the WG, as the dynamic (kinematic) nature of international and regional reference frames currently mitigates against their use for most surveying and mapping purposes where precision and repeatability is important over time. A 4D GIS will enable spatial data within a GIS to seamlessly maintain alignment with kinematic reference frames and positioning technology.

Chris Pearson and colleagues Richard Snay, Jeff Freymueller and Rob McCaffrey have been continuing development of the US Horizontal Time-Dependent Positioning software (currently version 3.2) used to transform coordinates in North America, particularly within the deforming zone of the Western United States (Figure 3), (Snay and Pearson, 2010; Pearson and Snay, 2011; Snay et al., 2013; Pearson et al. 2013 and 2014). Rob McCaffrey has been developing geophysical modelling tools (e.g. DEFNODE) which currently underpin the HTDP (Pearson, Snay and McCaffrey, 2012). Rob McCaffrey and colleagues have also been continuing research into the deformation field of the NW USA (Payne et al., 2012; McCaffrey et al., 2013) and California (Parsons et al., 2013; Petersen et al., 2014).

Figure 3. Visualization of the HTDP3.1 velocity field relative to NAD 83(2011). Predicted velocities on 1 degree grid are shown in black. The pixel size in this figure represents the cell spacing in the HTDP velocity grid, coarse in the east where the velocities change very slowly and becoming finer in the tectonically active regions along the west coast.
Rui Fernandes is continuing valuable research in Africa, with the development of a velocity field within the Nubian, Somalian, Arabian and Eurasian plates (Fernandes et al., 2013; Neves et al., 2014). Findings were presented at FIG and IAG conferences in 2013. Laura Sánchez, Hermann Drewes and Sonia Alves have been involved with development of a high precision deformation model for the South American and Caribbean regions (Figure 4) as part of ongoing development of SIRGAS (Sánchez et al., 2013, 2015).

Fig. 4. Horizontal deformation model for South America and the Caribbean (VEMOS2014, Sánchez, Drewes and Schmidt, 2014)
Important research has also been completed by members outside the WG. In particular Kreemer et al. (2014) have updated the Global Strain Rate Model version 2.1 (GSRM) which is a very significant improvement on GSRM version 1 with the inclusion of 22511 site velocities to define the Euler poles of 50 tectonic plates and a dense strain rate grid in 14% of the Earth surface located in deforming zones (Figure 5).

![Figure 5. Contours of the second invariant of the model strain rate field. White areas were assumed to be rigid plates (from Kreemer et al., 2014)](image)

Chatzinikos et al., (2015) describe the application of a velocity model in Greece to support the Hellenic semi-kinematic geodetic datum. A similar approach has been developed for the Indonesian geodetic datum (Hasanuddin Abidin and colleagues) and Papua New Guinea (Paul Tregoning, Laura Wallace, Richard Stanaway and Robert Rosa).

Daphné Lercier from the Paris Observatory and colleagues from the IGN LAREG have developed a parametric post-seismic decay model that is planned to be implemented in future realisations of ITRF (Lercier et al., 2014; Métivier et al., 2014). ITRF is currently realised as a secular frame with allowance for co-seismic offsets and velocity changes at specific epochs. This approach does not support non-linear deformation and the logarithmic or exponential character of post-seismic deformation. Consequently, ITRF is compromised in portions of the Earth surface that have been subjected to observable seismic deformation that has occurred after the release of the latest realisation of ITRF. Major earthquakes result on significant deformation over a range of thousands of kilometres from the epicentre (Figure 6). Tregoning et al., (2013) have also studied the effects of recent large earthquakes on the global reference frame. Co-seismic and post-seismic deformation must be modelled in global geodetic analysis, particularly to support precise orbit determination and real-time positioning in seismically affected areas. The use of epoch reference frames currently overcomes this current limitation of ITRF.
Fig. 6. Theoretical cumulative co-seismic ground displacement between 1 January 1991 and 31 December 2010 depending on the magnitude (M) range of EQ., Métivier et al., 2014)
Proposal for reformulation of the WG for 2015 - 2019

Considerable progress has been made with research into modelling of the global deformation field since the formation of the WG in 2011 in parallel with WG 1.3.1 (Integration of Dense Velocity Fields into the ITRF). For the period 2015 - 2019 it is proposed to integrate the findings of WG 1.3.1, the EUREF WG on Deformation Models and the work of Kreemer et al., (2014) into developing a global deformation and transformation model schema that can be used to support realisation of regional and local reference frames from ITRF to support GIS and positioning technologies such as Network RTK (NRTK). This will require development of a standardised deformation model format that can be accessed from international registries of geodetic parameters such as ISO/TC211 and EPSG.

References


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Yamagiwa, A., and Hiyama, Y.; Revision of Survey Results of Control Points, Coordinates, March 2013.
Sub-Commission 1.4: Interaction of Celestial and Terrestrial Reference Frames

Chair: Johannes Böhm (Austria)
http://iag.geo.tuwien.ac.at/sc14

Structure

• Working Group 1: Geophysical and Astronomical Effects and the Consistent Determination of Celestial and Terrestrial Reference Frames (Chair: Z. Malkin)
• Working Group 2: Co-location on Earth and in Space for the Determination of the Celestial Reference Frame (Chair: S. Lambert)
• Working Group 3: Maintenance of the Celestial Reference Frames and the link to the new GAIA frame (Chair: C. Ma)

The interaction between the terrestrial and celestial frames has become an important issue in the last years, in particular due to the different estimation strategies of the International Terrestrial Reference Frame (ITRF: combination of different space geodetic techniques) and the International Celestial Reference Frame (ICRF: VLBI-only solution from a single analysis centre). Considering that

"...the IUGG ... urges that highest consistency between the ICRF, the International Terrestrial Reference Frame (ITRF), and the Earth Orientation Parameters (EOP) as observed and realized by the IAG and its components such as the IERS should be a primary goal in all future realizations of the ICRS" (IUGG Resolutions 2011),

one of the primary goals of this Sub-Commission was to evaluate whether the CRF benefits from (or at least is not degraded by) a combination of VLBI observations with those from other space geodetic techniques. If the latter is proven, the next ICRF should be determined within a combined solution from different techniques. Seitz et al. (2011, 2012) have derived very interesting results, indicating that the combination with other space geodetic techniques has only a very small effect on the source coordinates. Exceptions with larger differences are found for VLBI Calibrator Survey (VCS) sources in right ascension with differences up to 1 mas (see Figure m.1). These particular sources are only observed with the regional VLBA network and are thus likely to benefit from Earth rotation parameters from Global Navigation Satellite Systems (GNSS). The impact of using polar motion estimates from GNSS for the analysis of VCS sessions was also shown in presentations by Krásná et al. (2014) and Mayer et al. (2015).

The next ICRF (ICRF-3) is expected for 2018, and it will probably be the last ICRF in the radio for some time, because then GAIA will provide a frame in the optical with significantly more quasars and stars and of similar precision. An important task is the link between the ICRF and sources in the optical domain - a task which is covered by Working Group 3 of this IAG Sub-Commission as well as by the ICRF-3 Working Group of the International Astronomical Union (IAU) chaired by Chris Jacobs. Consequently, a very close co-operation was held between those two groups, and a very fruitful joint meeting between the communities was organized at the European Working Meeting on VLBI for Geodesy and Astrometry (EVGA) in early March 2013 in Espoo, Finland.

In addition to work related to ICRF-3, many investigations have been carried out with respect to improved geophysical and astronomical models and their impact on terrestrial and celestial references frames and EOP, as well as with respect to new observations scenarios like VLBI observations to satellites which are potentially useful for a better linking between the frames. More details are provided below in the sub-sections on the three Working Groups.
Working Meetings of Sub-Commission 1.4

Annual meetings were held to discuss topics related to the interaction of celestial and terrestrial reference frames. Three of them were held as splinter meetings during the General Assemblies of the European Geosciences Union (EGU) and one was held as a joint meeting with the ICRF-3 Working Group of the IAU. All agendas and presentations of the Sub-Commission meetings are accessible at: http://iag.geo.tuwien.ac.at/sc14/meetings/

IAG SC 1.4 Meeting on 25 April 2012 in Vienna during the EGU 2012

A meeting of IAG Sub-Commission 1.4 was held on 25 April 2012 at TU Wien. Four presentations were given to stimulate the discussion on future improvements of terrestrial and celestial reference frames, and in particular the consistency between them. For example, Robert Heinkelmann reported about the efforts at DGFI aiming at the consistent determination of the ITRF and ICRF in one combination solution, and Lucia Plank presented simulation results of the observation to satellites with VLBI radio telescopes, i.e., on linking the kinematic and dynamical reference frames.

Joint Meeting of the IAU WG on ICRF-3 and the IAG Sub-Commission 1.4 in Espoo, Finland on 7 March 2013

An important joint meeting with large participation was held between the IAU Working Group on the ICRF-3 (chaired by Chris Jacobs) and the IAG Sub-Commission 1.4 and its Working Groups on 7 March 2013. It took place immediately after the Working Meeting of the European VLBI Group for Geodesy and Astrometry (EVGA) in Espoo, Finland. Both groups are having similar goals, e.g., the best possible ICRF-3. Additionally, an IUGG resolution is requiring, that the ICRF-3 will be fully consistent with all space geodetic techniques, i.e., not only with VLBI but also with GNSS, SLR, and DORIS. This joint meeting served well the purpose to introduce the two communities to each other.

IAG SC 1.4 Meeting on 1 May 2014 in Vienna during the EGU 2014

This meeting was based on six presentations, e.g., by Hana Krásná on the impact of seasonal station variations on Earth orientation parameters and the celestial reference frame. She showed that neglected station motions in the reduction of observations can have a significant impact on sources which are only observed a few times as well as on Earth orientation parameters if the neglected station motions are dominated by common modes over the sites. Chopo Ma reported about the IVS source monitoring program for ICRF-3 and Gaia transfer sources, and Lucia Plank showed simulation results for the connection of dynamical and kinematical reference frames by the use of observations to satellites.

IAG SC 1.4 Meeting on 16 April 2015 in Vienna during the EGU 2015

The final Sub-Commission 1.4 meeting was mainly devoted to issues related to source coordinates and source structure corrections. For example, Oleg Titov reported about observational ICRF activities in Australia and Chopo Ma provided information on CRF-related work at Goddard Space Flight Center. Lucia Plank presented her work on simulated source position offsets due to source structure and considered adapted scheduling strategies to account for it.
Working Groups of Sub-Commission 1.4

Working Group 1.4.1: Geophysical and Astronomical Effects and the Consistent Determination of Celestial and Terrestrial Reference Frames

Chair: Zinovy Malkin (Russia)

Working Group 1 was dealing with geophysical and astronomical effects on the consistent determination of celestial and terrestrial reference frames. There have been many papers and presentations on related topics in the past four years, some of which are summarized below. Ongoing topics of research are the galactic rotation and seasonal station motions.

Malkin (2013) outlines several problems related to the realization of the international celestial and terrestrial reference frames at the millimetre level of accuracy, with emphasis on ICRF issues. He considers the current status of the ICRF, the connection between the ICRF and ITRF, and considerations for future ICRF realizations. Several urgent tasks to improve the existing CRF and TRF realizations are proposed and discussed.

Böhm et al. (2011) compare the influence of two different a priori gradient models on the terrestrial reference frame as determined from VLBI observations. One model has been determined by vertical integration over horizontal gradients of refractivity as derived from data of the Goddard Data Assimilation Office (DAO), whereas the second model (APG) has been determined by ray-tracing through monthly mean pressure level re-analysis data of the European Centre for Medium-Range Weather Forecasts. The authors compare VLBI solutions from 1990.0 to 2011.0 with fixed DAO and APG gradients to a solution with gradients being estimated, and find better agreement of station coordinates when fixing DAO gradients compared to fixing APG gradients. As a consequence, the authors recommend that gradients are constrained to DAO gradients, in particular in the early years of VLBI observations (up to about 1990), when the number of stations per session is small and the sky distribution is far from uniform. Later than 1990, the gradients can be constrained loosely and the a priori model is of minor importance.

Heinkelmann and Tesmer (2013) assess systematic effects between VLBI terrestrial and celestial reference frame solutions caused by different analysis options. Comparisons are achieved by sequential variation of options relative to a reference solution, which fulfils the requirements of the IVS analysis coordination. Neglecting the total NASA/GSFC Data Assimilation Office (DAO) a priori gradients causes the largest effects: Mean source declinations differ by up to 0.2 mas, station positions are shifted southwards, and heights are systematically larger by up to 3 mm, if no a priori gradients are applied. The effect is explained with the application of gradient constraints. Antenna thermal deformations, atmospheric pressure loading, and the atmosphere pressure used for hydrostatic delay modeling still exhibit significant effects on the TRF, but corresponding CRF differences (about 10 μas) are insignificant. The application of the Niell Mapping Functions (NMF) can systematically affect source declinations by up to 30 μas, which is in between the estimated axes stability (10 μas) and the mean positional accuracy (40 μas) specified for the ICRF-2. Further significant systematic effects are seasonal variations of the terrestrial network scale (±1 mm) neglecting antenna thermal deformations, and seasonal variations of station positions, primarily of the vertical component up to 5 mm, neglecting atmospheric loading. The application of NMF instead of the Vienna Mapping Functions I results in differences of station heights of up to 6 mm.
Krásná et al. (2013) reaffirm results firstly shown by MacMillan and Ma (1997) with a larger span of data (27 years) including recent, very precise data obtained by the VLBI technique. If tropospheric gradients are neglected, the TRF will experience a scale change of 0.65 ppb compared to a TRF with estimated gradients. Furthermore, clear trends in the north and height components are visible. In the CRF, there is a mean systematic change in the estimated declinations of 0.36 mas with a maximum of about 0.5 mas. On the other hand - concerning the choice of mapping functions (VMF1 or Global Mapping Functions) - only small systematic changes between the reference frames can be observed, e.g. a mean height difference of −0.5 mm over the stations in the terrestrial reference frames.

Liu et al. (2012) show that the effect of the Galactic aberration strongly depends on the distribution of the sources that are used to realize the ICRS. According to different distributions of sources (of the ICRF-1 and ICRF-2 catalogues) the amplitude of the apparent rotation of the ICRS is between 0.2 and 1 μas per year. It was shown that this rotation has no component around the axis pointing to the Galactic centre and has zero amplitude in the case of uniform distribution of sources. The effect on the coordinates of the Celestial Intermediate Pole (CIP) is between about 1 to 100 μas after one century from J2000.0, while the effects on the Earth rotation angle (ERA) are between 4 and several tens of μas after one century. Thus, the Galactic aberration is responsible for a variation with time of the orientation of the ICRS axes and consequently for systematic errors in the determination of the EOP, which refer to the ICRS. The effect on the ICRS and EOP increases with time and is not negligible after several decades. With high-accuracy astrometry and the increasing length of the available VLBI observation time series, this effect should be considered, particularly in constructing the next realization of the ICRS. Observations of more radio sources, especially in the southern hemisphere, should be developed to more homogeneously distribute defining sources in the ICRF to minimize that effect. Rigorous algorithms to account for the Galactic aberration during VLBI data processing are provided by Malkin (2014).

Malkin (2011) as well as Krásná and Böhm (2014) investigate the impact of seasonal station motions on EOP and reference frames. They find that a significant annual term is present in the position time series for most stations; however, the annual signals found at co-located VLBI and GPS stations at some sites differ substantially in amplitude and phase. The semi-annual harmonics are relatively small and unstable, and for most stations no prevailing signal is found in the corresponding frequency band. Test computations show that systematic errors in UT1 estimates caused by seasonal station motion can exceed 1 μs for Intensive sessions and can reach 10 μs for multi-baseline sessions. On the other hand, no systematic propagation of the seasonal signal into the orientation of celestial reference frame is found, but position changes occur for radio sources observed non-evenly over the year.

Several studies were devoted to developments in troposphere modelling for improving the accuracy of the terrestrial reference frames. Halsig et al. (2014) investigate the effect of modelling atmosphere turbulence and find improvement of baseline length respectabilities for VLBI observations, especially for $C_n$ values estimated from GNSS. Based the CONT11 VLBI experiment, Eriksson et al. (2014) show that the application of ray-traced atmospheric delays decreases baseline respectabilities and improves station position precision.
Working Group 1.4.2: Co-location on Earth and in Space for the Determination of the Celestial Reference Frame

Chair: Sebastien Lambert (France)

Working Group 2 covered the co-location on Earth and in space for the determination of the CRF. This WG also included the combination of different space geodetic techniques. Over the last years, a lot of simulation work has been carried out towards co-location in space, e.g. at ETH Zürich, Bonn University, or Technische Universität Wien. Upcoming satellite missions like GRASP or MicroGEM will provide the possibility to use ties on the satellite in addition or instead of ties on ground, but also GNSS satellites can be used for observations with VLBI telescopes, as e.g. demonstrated by Wettzell and Onsala.

Seitz et al. (2011) show the first results of a consistent computation of CRF, TRF, and the EOP series linking both frames. The CRF is slightly influenced by the combination in two different ways: by the combination of the EOP and by the combination of the station networks. It is shown that both effects are small. The effect of combining the station networks – mainly driven by the misfits between local ties and results of space geodetic techniques – reaches up to 2 mas, but is much smaller for most of the sources. The mean difference is about 10 μas. However, small but clearly systematic effect can be seen. The combination of the EOP also leads to small changes in the source positions. Sources close to the celestial South Pole are affected by a maximum of ±1 mas. A further systematic effect (~0.5 mas maximum) is detected for some of the sources with declinations between + and −40°. The reasons are not known. The integral impact of the combination on the CRF is small and not significant w.r.t. the axis stability (10 μas) and the noise floor (40 μas) of ICRF-2.

![Figure m.1: Differences in source positions between the combined TRF-CRF solution and a VLBI-only solution: declination (upper plot), right ascension (lower plot) (from Seitz et al., 2012).](image)
In continuation of their work, Seitz et al. (2012) deal with the consistent realization of ITRF and ICRF by combining normal equations from VLBI, SLR, and GNSS. The results for the CRF are compared to a classical VLBI-only CRF solution and it turns out that the combination of EOP from the different space geodetic techniques impacts the CRF, in particular the VCS (VLBA Calibrator Survey) sources (see Figure m.1).

Plank et al. (2013), in their proceedings paper for the EVGA meeting in Espoo, Finland, discuss and simulate VLBI observations to satellites at different altitudes, like the proposed GRASP mission at 2000 km and a GPS satellite at 20200 km height. Figure m.2 illustrates the benefit of VLBI observations to satellites allowing for space ties in addition to the local ties. These additional constraints are expected to have a positive impact on the consistency between terrestrial and celestial reference frames.

Figure m.2: Concept of co-location in space. A satellite that can be tracked by several space geodetic techniques (e.g. VLBI, SLR, GNSS) realizes a space-tie, directly connecting the frames determined by the different techniques (from Plank et al., 2013).
**Working Group 1.4.3: Maintenance of Celestial Reference Frames and the link to the new GAIA Frame**

*Chair: Chopo Ma (U.S.A.)*

Working Group 3 dealt with the maintenance of the ICRF and the link to the new GAIA frame. This WG was the main link to the ICRF-3 WG by the IAU, and it guaranteed that the requirements for both communities were fulfilled: the best possible ICRF-3 as well as the consistency of the ICRF-3 with other space geodetic techniques.

A lot of activities were stimulated towards observing new observation campaigns, in particular for sources in the southern hemisphere. For example, the AUSTRAL network was applied since the second half of 2013 to observe sessions dedicated to southern sources. Furthermore, a VLBA proposal by David Gordon et al. entitled "Second Epoch VLBA Calibrator Survey Observations for ICRF3" was approved and eight days of VLBA observations were used to re-observe many single epoch sources. The VLBA broadband RDBE system was used, which gave much greater sensitivity than the original VLBA Calibrator Survey sessions. For 2063 VCS sources that were re-observed the position errors were improved on average by a factor of ~4. Furthermore, Bourda et al. have provided a list of GAIA transfer sources that will be observed regularly by the IVS to improve their radio positions.

**References**

A complete list of references related to Sub-Commission 1.4 can be found at: [http://iag.geotuwien.ac.at/sc14/bibliography/](http://iag.geotuwien.ac.at/sc14/bibliography/)


**Joint Working Groups of Commission 1**

**Joint Working Group 1.1: Tie Vectors and Local Ties to Support Integration of Techniques**

*Chair: Peirguido Sarti (Italy)*

The Joint Working Group focuses on the provision of accurate tie vectors for ITRF computation. The estimation of tie vectors at co-location sites relies on several different and inter-connected phases that contribute and impact the final accuracy.

The JWG has been acting to focus the attention on tie vectors estimation and their importance in the ITRF computation, to bring together and discuss different approaches adopted locally at ITRF co-location sites and to compare the different methods with the purpose of assessing the accuracy of tie vector estimation procedures.

The JG has been meeting in a timely manner since 2004, usually at the most important international scientific meeting venues. A detailed list of the meetings can be found at the following web address: http://www.iers.org/nn_10900/IERS/EN/Organization/WorkingGroups/SiteSurvey/sitesurvey.html?__nn=true.

The activities of the JWG are closely linked to the realization of the ITRS and aims at spreading know-how and at defining standards to be adopted as reference in the tie vector estimation process.

So far, different surveying approaches and computation methods are adopted worldwide, mainly on a site-dependent base, which is determined by the surveying crew capabilities. There is a stringent necessity to validate the tie vectors that have been recently estimated as well as re-survey a number of co-location sites whose tie vectors are old (up to 25 years) and whose formal precision are dubious.

The JWG has boosted the discussion and brought together a very large number of scientists and surveyors whose interest are related to the ITRF, GGOS, space geodetic data analysis and local geodetic surveys. Indeed, the number of members of the JWG should reflect the large (33) number of members of the IERS WG and should therefore be updated.

The JWG has the merit to have finally brought together expertise covering the aspects of tie vector surveying and estimation, ITRF combination and space geodetic data analysis and provision of techniques specific solutions used in the combination.

**Workshop on Site surveys and Co-locations – Paris – May 2013**

The second workshop on site surveys and co-location sites took place in May 2013 in Paris. The web page of the meeting (http://iersworkshop2013.ign.fr/?page=scope) nicely and efficiently resumes relevant information such as the scopes of the workshop, its location, the list of participants, the list of presentations and the .pdf files containing the oral contributions. A very important product of the workshop was a list of recommendations that were identified with the contributions of all participants. The document sets actions, deadlines and the person in charge of the specific actions.
Main items and topics were identified and relate to the definition of a clear nomenclature and terminology to be adopted for local tie aspects, to the models to be adopted in the local tie survey data reduction, to the survey priority list for the next ITRF2013 computation, to the surveying frequency, to the creation of a local survey data archive and the preparation of a draft document containing the site survey guidelines and specifications.

This last aspect has been a long-term objective of the working group whose solution is needed but is far from trivial. A coordinated effort of the whole surveying community is needed and the JWG is the best context to approach the topic and try to solve it with an international coordinated effort.
Joint Working Group 1.2: Modelling Environmental Loading Effects for Reference Frame Realizations

Chair: Xavier Collilieux (France)

Overview
The accuracy and precision of current space geodetic techniques are such that displacements due to non-tidal surface mass loading are measurable. Although some models are available, there are still open questions regarding the application of loading corrections for the generation of operational geodetic products. The goal of this working group is to ensure that the optimal usage of loading model is made for Terrestrial Reference Frame (TRF) computation.

Working group meetings
- April 2013: EGU general assembly
- May 2014: EGU general assembly
- October 2014: REFAG 2014. Notes of the meeting can be found on the IAG commission 1 website.

Main activity
The working group activity has been dominated by the IERS campaign “for space geodetic solutions corrected for non-tidal atmospheric loading”, an action following the Unified Analysis Workshop 2011. A call for participation has been sent to the analysis technique coordinators of every service in the beginning of 2012. A 6-year loading data set has been generated at The Global Geophysical Fluid Center (GFC) to be used a priori in the data processing of the space geodetic technique observations. Analysis Centers from the four technique services have submitted 12 individual solutions from GNSS, Satellite Laser Ranging (SLR, Very Long Baseline Interferometry (VLBI) and Doppler Orbitography Integrated by satellite (DORIS). These solutions have been analyzed to determine:
  • The effect of non-tidal atmospheric loading on the TRF datum and the Earth Orientation Parameters (EOPs)
  • The effect of non-tidal atmospheric loading on individual averaged coordinates and velocities
  • The level of agreement between a priori corrections and a posteriori corrections

Preliminary results have been presented at the EGU in 2013. They were of primary importance for the generation of the next ITRF. This campaign has been successful since it has allowed dialogues between modeling experts and technique ACs. The results of the analyses have been summarized in a paper in preparation (Collilieux et al., to be submitted). The main conclusions are:
  • A posteriori and a priori corrections are similar at less than 0.2 mm WRMS
  • for GPS/DORIS/VLBI after 6-parameter transformation.
  • WRMS >=0.3 mm for SLR core stations
  • but small effect on estimated long-term coordinates (> 3 years)
  • Effect of atmospheric gravity in SLR analysis, even on EOPs.
Although they inform about the impact of the corrections on the daily/weekly and long-term geodetic products, only one model from one contribution (atmosphere) has been tested in this campaign. Future works are needed to investigate the level of agreement of all available loading models, which will be the main task for the next couple of years. It is crucial that users be aware of the strengths and limitations of the available models. In addition, the modeling of loading deformation related to ice melting should be a priority for the next term of the commission 1 in addition to missing lakes or other water basin contribution. Finally, a consistent model of geocenter motion and low degree gravity potential coefficients would be worth recommending in the future to be used by the 4 technique services.

Membership

• Z. Altamimi (France)  
• J. Böhm (Austria)  
• J.P. Boy (France)  
• L. Métivier (France)  
• X. Collilieux (chair, France)  
• R. Dach(Switzerland)  
• T. Herring (USA)  
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• E. Pavlis (USA)  
• Jim Ray (USA)  
• C. Sciarretta (Italia)  
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• D. Thaller (Germany)

Publications


Call for space geodetic solutions corrected for non-tidal atmospheric loading, GGFC website, http://geophy.uni.lu/files/call_new2.pdf
Joint Working Group 1.3: Understanding the Relationship of Terrestrial Reference Frames for GIA and Sea-Level Studies

Chair: Tilo Schöne (Germany)

Overview

Studies about long-term and/or regional sea level changes are depending in many ways on a global terrestrial reference frame. Radar altimeters (RA) measure sea level heights from space in a TRF, while tide gauges measure sea level at local spots with a local vertical reference. Both sea level information sources are connected and combined within a common reference frame for example by, adding GNSS or other space geodetic techniques to tide gauges. On the other hand, only a few tide gauges worldwide have such a connection to the TRF but are useful for many studies. To correct those gauges for at least the long-term ‘geological’ vertical displacement, GIA corrections are commonly applied.

The use of GNSS information in sea level science, the combination and assimilation of GNSS information into Glacial Isostatic Adjustment (GIA) models, the correction of GIA effects on altimetry or tide gauges, or combined studies using information from the different sources requires a common understanding of the individual reference frame realizations.

Today the ITRF realization and their respective updates form the basis for the individual space geodetic techniques. But, in researcher’s daily work, individual realizations may more often be used. For example, the IGS time series are in a respective IGS frame close to ITRF, or satellite orbits for radar altimetry are using Laser- and DORIS-augmented frames. GIA models employ their own ITRF-independent reference.

A major topic is about effects on RA satellite orbits from various external forces. Today, none of the RA satellites have complete kinematic orbit determination allowing directly constraining altitudes to the ITRF. Thus the derived orbit is dependent also on modeling of external forces and the effect of static and time variable gravity field models. Effects of the reference frame uncertainties on orbit determination may be predictable, while effects of the gravity field can heavily mask the impact.

Activities

Due to the non-availability of new GNSS@TG reprocessing and new ITRF, studies concentrated on the evaluation of static- and time variable effects in orbit determination (e.g., Rudenko et al., 2014a) and in effects of reference frame (ex-)changes (e.g., Couhert et al., 2014). Both effects are of interest, since the effects of time-variable coefficients in the gravity field map in apparent hemispheric changes in sea level. Also recently studies were published demonstrating the effects of vertical land motion models (VLM) on RA-derived sea level time series (e.g., Watson et al., 2015).

Earlier studies focusing on effects on ERS-1, ERS-2, and ENVISAT have been extended to Topex/Poseidon and JASON-1. The reference frames underlying the orbit determination included ITRF2005, ITRF2008, but orbit determination also uses SLRF2008 (for laser tracking stations) and DPOD2008 (for DORIS tracking stations). The effects of the inclusion of the later both reference frames have not yet studied in detail, but should be once the new ITRF is available. Still a pitfall for the reference frame is the missing inclusion of the PRARE system requiring inhomogeneous inclusion into each ITRF realization (Rudenko et al. 2102).
However, it needs to be recognized that currently reference frame effects in RA satellites still have smaller effects on the radial component than other orbit modeling effects, like gravity (e.g., Esselborn et al., in press).

Trend of radial orbit differences for different processing centres (ESOC/GFZ/GSFC) and different orbit standards (C/D): Jason-1 a: GDR (C) minus ESOC (D) and b: GDR (C) minus GSFC; Envisat c: GDR (C) minus ESOC (D) and d: GDR (C) minus GFZ (D)

Time series of Envisat radial orbit differences for two sites located at areas of high RMS: 32°S / 42°E and 15°N / 155°E. Both orbits originate from GFZ and differ only by the geopotential field used (EIGEN-GL04S_annual and EIGEN-6S). These time series are equivalent to sea level changes when updating the orbit model. (Esselborn et al., in press)

Important contributions for the understanding of reference frame issues in sea level research are summarized in Collilieux and Altamimi (2013) and in the External Evaluation of the Terrestrial Reference Frame: Report of the Task Force of the IAG Sub-commission 1.2 (Collilieux et al., 2014).

Outlook

Until the release of the IGS TIGA Working Group and IGS repro2 results, the studies necessary for this task cannot fully continued and performed. After the release and the availability of the new ITRF studies for reference frame issues for the combination of GNSS time series and GIA corrections with tide gauge and altimetry time series will be performed outside the JWG 1.3 but within this scope. Also under study will be loading effects in the near- and at-shore GNSS stations at tide gauges and their relation to tide gauge time series. Also the reference frame studies for radar altimetry will be extended to more recent other missions, like Topex/Poseidon, Jason-1, Jason-2. The studies will be extended to better understand time variable gravity field effects on altimetric orbits and reference frame issues (ITRF2013). This study is still under the ESA CCI initiative.

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Joint Working Group 1.4: Strategies for Epoch Reference Frames

Chair: Manuela Seitz (Germany)

Overview

The objectives of the Joint Working Group 1.4 are the realization of global short-term reference frames (epoch reference frames) and the development of strategies for their application for datum realization (alignment) of regional short-term reference frames. Epoch reference frames have a lot of advantages compared to ITRF, even if their long-term stability does not reach the level of ITRF stability. It is recommended that epoch reference frames shall be provided as add-ons to ITRF solutions.

The JWG has 13 members from eight countries. The work of the group is presented in 15 publications and 18 presentations. Additionally, the Website (http://www.dgfi.badw.de/index.php?id=403) improves the visibility of the activities of the Working Group. The work of the JWG is strongly linked to the activities of the IERS WG Combination on observation level (COL). During the last four years two COL meetings are organized in Munich, in May 2012 and in May 2013.

Computation of epoch reference frames

The computation of Epoch Reference Frames is - like the ITRF computation - based on the combination of the space geodetic techniques VLBI, SLR, GNSS and DORIS. This combination can be done at different levels of the Gauß-Markov adjustment model (Seitz, 2012). We perform the combination at the level of normal equations and at the level of observations in order to identify the individual strengths of these combinations methods. The flowchart for the computation of weekly epoch reference frames at the normal equation level is given by Fig.1.4.1.

Figure 1.4.1: Strategy for the computation of epoch reference frames developed and applied at DGFI.
Weekly normal equations of the satellite techniques are combined first and then the VLBI normal equations are included session by session. The combined parameters are station positions, terrestrial pole coordinates, LOD and nutation rates. In a second step also gravity field coefficients are adjusted consistently. The most important steps in the combination, which are also central components of the research activities, are the introduction of local tie information, the weighting of the techniques and the datum realization.

The following research activities were performed with respect to the computation of epoch reference frames and the improvement of their accuracy and stability:

- **Improvement of datum realization for weekly SLR solutions by including 10 spherical SLR satellites (Bloßfeld et al. 2015b)**
  In addition to LAGEOS1 and 2, in particular LARES contributes significantly to the decorrelation of estimated parameters and hence to an improved determination of the geodetic datum. Figure 1.4.2. shows the RMS of weekly translation and scale parameters for the LAGEOS only, the three satellite and a 10 satellite solution. ILRS now also plans to include LARES in the routinely product generation.

- **Combination of SLR, GNSS and VLBI for the computation of weekly reference frames**
  The resulting station positions and EOP are compared to a multi-year TRF solution (ITRF). The non-linear station motions - not considered in ITRF and mainly caused by non-tidal atmospheric, hydrologic and oceanic loading but also by local effects - has an impact on the consistently estimated EOP series. Clear annual and semi-annual signals with amplitudes of up to 39.4 μas could be identified in the EOP difference series of ITRF and epoch reference frames (Bloßfeld et al. 2014).

- **Impact of time interval of epoch reference frames on datum stability**
  In order to improve the stability of datum realization for epoch reference frames (which does not reach the ITRF level of stability) different solution series are computed with a temporal resolution of one week, two weeks and four weeks. The analysis of the different datum parameter series shows that the RMS improves with increasing time interval but anyway all series represent the annual signal very well (Bloßfeld et al. 2015a). Therefore, from the view of datum realization a four-weeks solution should be preferred. But, the approximation of the station motions becomes more imprecise increasing the time interval and therefore, the ideal time interval must be defined depending on the main application of epoch reference frames.

- **Extending parameterization of epoch reference frames by temporal-highly resolved gravity field coefficients**
  The simultaneous estimation of TRF, EOP and gravity field coefficients is one of the goals of GGOS. For this task, SLR plays an important role, as it is the only technique which allows for the determination of all of these parameter groups with reliable accuracy (Bloßfeld, 2015c). It could be shown that the combination of 10 SLR satellites leads to a clear de-correlation of the estimated parameters in the SLR solutions and the combination with GNSS further reduces the correlations between the translation and orientation of the solution due to the good global distribution of the GNSS network (Bloßfeld 2015).

- **Combination of GNSS and SLR at the observation level**
  The studies related to the combination at the observation level were performed mainly at the University of Berne (AIUB) and the Bundesamt für Kartographie und Geodäsie (BKG) and are linked to the activities of the IERS Working Group on Combination at the Observation Level (COL). Therefore GNSS and SLR observations to GNSS satellites are combined and TRF, orbits and EOP are estimated consistently. The results show that the
origin (centre-of-mass derived from SLR observations) can be transferred very well in the combined TRF solution even if no local ties at co-location sites are used. This allows for a validation of local ties on the Earth.

Figure 1.4.2: RMS of weekly translation and scale parameters of three different SLR solutions w.r.t. SLRF2008. Blue: LAGEOS1 and 2, Red: LA1, 2 and LARES, Green: 10 satellite solution. While the inclusion of LARES improves the RMS values significantly, only for z-translation a further improvement could be shown using all 10 satellites.

In summary the results of the research activities show that
- Datum realization for epoch reference frames can be improved by using an SLR solution which includes at least LARES in addition to LAGEOS1 and 2,
- The time series of weekly epoch reference frames approximate the complete station motion (linear and non-linear part) very well,
- The neglect of non-linear station motions in long-term reference frames affects the consistently estimated EOP-series by annual and semi-annual signals (Bloßfeld et al. 2014),
- Epoch reference frames do not provide such a high long-term stability as long-term reference frames. With regard to the geodetic datum four-weeks solutions show the highest stability. But non-linear station motions are characterized by short-term effects, which can be approximated better with a weekly or even shorter resolution,
- The integration of 10 spherical SLR satellites in the SLR solution and the combination of the techniques allow for a simultaneous estimation of TRF, EOP and gravity field coefficients in epoch reference frame solutions with high accuracy,
- The weekly combination at the observation level of GNSS and SLR (via satellite co-location) leads to very promising results, which allow the transfer of the SLR-derived centre-of-mass of the Earth to GNSS station network with very high accuracy and for a validation of the local ties at ground sites.

The advantages and disadvantages of epoch reference frames compared to ITRF are:
- Epoch reference frames approximate non-linear station motion very well.
- Highly resolved TRF, EOP and gravity field coefficients can be estimated consistently with reliable accuracy (GGOS goal).
• Annual and semi-annual geocenter variations can be derived with high accuracy from four-week epoch reference frames.
• EOP are not affected by non-linear signals in station motions.

**Application of epoch reference frames**

Regional GNSS-based epoch reference frames are meanwhile standard within the International GNSS Service (IGS), e.g., for Europe (EUREF) or Latin America and the Caribbean (SIRGAS) and are important in particular for real-time applications. To realize the geodetic datum of the regional epoch reference frames, they are aligned to the ITRF or long-term IGS solutions. Since these long-term solutions do not consider non-linear station motions - which are fully included in the epoch-wise estimated station positions -, the alignment is in particular affected by the seasonal signals in the station positions, which are mainly caused by atmospheric and hydrological mass load changes but also by very local – sometimes unknown – effects. Therefore, the weekly SIRGAS solutions are now aligned to the weekly IGS solution. This improves the consistency of the time series of weekly SIRGAS solutions significantly and demonstrates the importance of epoch reference frames.

![Diagram](image)

**Figure 1.4.3:** Transformation between epoch reference frames and national frames for regions affected by deformations. The approach considers also the transformation of positions of new stations into the national frame.

For GNSS-applications, which should be related to a national reference frame, a transformation between the global or regional reference frame, in which the GNSS positions are obtained, and the national frame have to be performed. The reference epochs of the frames often differ by some years. The transformation is in particular problematic for regions affected by seismic events, which usually induce large non-linear station motions. Figure
1.4.2 shows the developed concept of how a transformation between a regional epoch reference frame and a national reference frame (and vice versa) should be performed, including also the transformation of the positions of new stations into the national frame. Besides a 7-parameter similarity (Helmert) transformation, a deformation model is considered (Drewes and Heidbach, 2012), describing the deformations of the network in time.

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