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Introduction

Unified Analysis Workshops are co-organized by the International Association of Geodesy's (IAG's) Global Geodetic Observing System (GGOS) and International Earth Rotation and Reference Systems Service (IERS). This was the 5th in a series of workshops that are held every two to three years for the purpose of discussing issues that are common to all the space-geodetic measurement techniques. Attendance at the Workshops are by invitation only with each IAG Service nominating 5-6 experts to attend and participate in the discussions. At this Workshop, the discussions focused on:

- GNSS Systematic Errors and Biases
- VLBI Systematic Errors and Biases
- SLR Systematic Errors and Biases
- DORIS Systematic Errors and Biases
- Site Survey and Co-location
- Reference Systems and Frames
- Conventional Mean Pole
- Standards, Conventions, and Formats
- Interoperability of Portals and Metadata

This report summarizes the Workshop discussions and resulting recommendations.

GNSS Systematic Errors and Biases

Chairs: Tom Herring (MIT, USA)
Michael Moore (Geoscience Australia)

Four primary areas of sources of errors and biases were considered and the following recommendations reached:

(1) The gravity fields used in the GNSS orbit integrations should be updated to match modern fields to make them consistent with the fields being used by the other IAG Services. The update would include the static part of the field and a time variable component. For the GNSS satellite altitudes, temporal variations in only the lowest degree terms would be needed with just the 2^{nd} degree terms possibly being the only ones needed. Projection of the temporal variations past the time when observed changes are available could use a simple annual sine and cosine fit. Planetary bodies in addition to the Sun and Moon should also be included in gravitational force modeling.

(2) Other components of the force models for GNSS should also be updated and validated. The force models associated with radiation forces are the most uncertain and modeling of these forces can be made more consistent with the exchange of attitude information. The IGS plans to develop an attitude format and make attitude information available so that analysis centers can validate their models. The IGS has noted the appearance of the GPS draconitic period and harmonics of this period in time series of various geodetic products

(e.g., positions and Earth orientation parameters). Long orbital arc analyses (longer than the 24-hrs used by most IGS analysis centers) should be investigated to assess the levels of spurious signals in these analyses and to better understand the origin of the draconitic signals.

(3) An updated short-period (diurnal and semidiurnal) model is needed and a method to determine whether this is an ocean-tide only with libration terms added or an empirical model based on VLBI data needs to be established. (GNSS estimates of short period EOP terms might by affected by orbital modeling errors). The number of tidal waves to be included and the representation of the tidal signals also need to be decided.

(4) Site dependent calibration of GNSS antennas are needed since these have a direct effect on the ITRF realization and position offsets when antennas are changed. Tests of the use of antenna specific phase center models are encouraged when these values are available without disturbing an existing antenna installation. Investigation and potential development of an *in situ* antenna calibration system are strongly encouraged. *In situ* calibration would be deployed at core sites where GNSS stations are tied to other geodetic systems.

VLBI Systematic Errors and Biases

Chairs: John Gipson (NASA/GSFC, USA)
Axel Nothnagel (U Bonn, Germany)

The IVS network consists of around 40-50 VLBI stations distributed across the world. VLBI is unique in its ability to measure UT1 and nutation. Together with SLR, VLBI determines the scale of the ITRF. In this session, we focus on error/modeling sources that might have an impact on either scale or EOP parameters determined from VLBI. A long-standing issue is that the scale difference between VLBI and SLR is about 1.4 ppb. In ITRF2014 this problem is handled by 'splitting-the-difference' between VLBI and SLR, with the intrinsic scale of each differing by about 0.7ppb from ITRF2014. In this session, we review various error sources that might have an impact on the scale difference between VLBI and SLR.

The IERS conventions contain a model of diurnal and semi-diurnal variation of EOP ('HF-EOP'). The current IERS HF-EOP model is over 20 years old. The quantity and precision of space geodetic data has improved substantially over this time. Any errors in the HF-EOP model used will result in either changing the values of estimated quantities, or increasing the residuals, or both. We present a HF-EOP model based only on VLBI data and demonstrate that it improves the processing of GNSS satellites. This suggest that in some real sense, the VLBI-derived model is better than the IERS model.

The VLBI action items resulting from the UAW discussions are:

(1) HF-EOP tide models. It is recommended that a task force with members from each of the measurement techniques be established in order to test the different geophysical and empirical HF-EOP tide models that have become available recently. The models should be assessed by each technique and the task force should consider different metrics to assess the models. The objective of the task force is to recommend a new HF-EOP tide model for adoption by the IERS Conventions. Results of the task force should be presented at the EGU conference in 2018.

(2) Gravitational deformation of VLBI antennae. It is recommended that as many VLBI antennae as possible be measured to determine their gravitational deformation. A. Nothnagel has agreed to provide recommendations for making these measurements;

antennae that are being decommissioned or that are used frequently should be measured first. It is further recommended that gravitational deformation of VLBI antennae be taken into account when reducing VLBI observations. This means that the ability to account for gravitational deformation should be implemented in all VLBI data reduction software packages. It is anticipated that measuring all radio telescopes of the IVS will take a long time and will most probably stay incomplete for some time to come. In order to maintain consistency between the products of different IVS ACs, the IVS Analysis Coordinator in conjunction with the IVS board will determine when the modeling of gravitational deformation for different antennas will be turned on. It is expected that the coordinates for each of these telescopes will change and a gradual impact on the scale of the TRF can be expected. The effect of changes in other parameters of interest, such as EOP or station coordinates, is expected to be small but will be studied by comparing solutions with and without gravitational deformation.

(3) Relativistic effects on VLBI observations. It is recommended that experts be consulted to understand the differences evident in the different formulations available for this effect. The impact of these differences should be assessed by using the different formulations in test solutions.

(4) Source structure variability. It is recommended that this be studied by using the CONT14 observations to show the impact of accounting for source structure when reducing VLBI observations. It is further recommended that simulations be used to assess the impact of source structure on VGOS observations and that a strategy for broadband observations be developed.

(5) Mean pole tide model. It is recommended that the new mean pole tide model (see section below on Conventional Mean Pole) be implemented in all VLBI data reduction software packages. But the date to start using the new mean pole tide model in routine operations must be coordinated with the other measurement techniques.

(6) Atmospheric pressure loading. It is recommended that the impact on the station coordinates of removing atmospheric pressure loading be included in the SINEX files so that the effect can be restored if needed. If other loading effects are used when reducing VLBI observations, such as hydrologic or non-tidal oceanic, then their effects should also be reported and they should be reported separately, not as an aggregate.

SLR Systematic Errors and Biases

Chairs: Cinzia Luceri (e-Geos/ASI, Italy)
Erricos Pavlis (JCET/UMBC, USA)

The International Laser Ranging Service (ILRS) contributes to ITRF development unique information that only Satellite Laser Ranging (SLR) is sensitive to: the definition of the origin, and in equal parts with VLBI, the scale of the frame. For the development of ITRF2014, the ILRS analysts adopted a revision of the internal standards and procedures in generating our contribution from the eight ILRS Analysis Centers. The improved results for the ILRS components were reflected in the resulting new time series of the ITRF origin and scale, showing insignificant trends and tighter scatter. This effort was further extended after the release of ITRF2014, with the execution of a Pilot Project (PP) in the 2016-2017 timeframe that demonstrated the robust estimation of persistent systematic errors at the millimeter level. ILRS ACs will now turn this into an operational tool to monitor station performance and to generate a history of systematics at each station, to be used with each re-analysis for future ITRF model developments. This is part of a broader ILRS effort to improve the quality control of the data collection process as well as that of our products. To this end, the ILRS has established a "Quality Control Board—QCB" that consists of members from the analysis and engineering groups, the Central Bureau, and even user groups with special interests. The QCB meets by telecon monthly and oversees the various ongoing projects, develops ideas for new tools and future products. This session focused on the main topic with an update on the results so far, the schedule for the near future and the plans for its operational implementation, along with a brief description of upcoming new ILRS products.

The recommendations resulting from the SLR discussions are:

(1) Quality control. It is recommended that the ILRS Central Bureau help the SLR network improve communication and response to errors that are identified through the quality control process.
(2) Metadata. It is recommended that complete and accurate metadata to improve the discoverability of ILRS data and products continue to be developed.
(3) Time biases. The time biases estimated from the quality control pass-by-pass analyses should be compared with the results of J. Ries. The time bias table from T2L2 should be obtained and the time biases from the pass-by-pass analyses should also be compared to it. The data handling file for the time biases in the ILRS should be refined.
(4) Network-fixed products. The ILRS should release EOPs and station coordinates in a defined TRF (i.e., the current ITRF) in addition to providing loosely constrained SINEX files.
(5) Atmospheric loading. The ILRS should establish a pilot project to study the impact of applying non-tidal atmospheric loading when reducing SLR observations. If successful, the ILRS should provide products based upon removing atmospheric loading effects.
(6) Range and time biases. The ILRS should include in the SINEX file the range and time biases that are applied when reducing SLR observations. This should be done to facilitate research into the effect of estimating range and time biases.

DORIS Systematic Errors and Biases

Chairs: Hugues Capdeville (CLS, France)
Frank Lemoine (NASA/GSFC, USA)

The DORIS technique is composed of a ground network of 55-60 stations, and a satellite constellation. The satellites presently orbit at altitudes of ~800 to 1335 km at a variety of inclinations. For ITRF2014, the DORIS analysis centers implemented a number of improvements to the processing that eliminated errors present in ITRF2008. Nonetheless, the analysis for ITRF2014 as well as the *ex post facto* studies showed that systematic errors still affect the DORIS Doppler observation, the reference frame parameters, or the derived products. These errors are derived from incomplete modeling of the behavior of the DORIS oscillators on the orbiting spacecraft, or from errors in the force models required to accurately model satellite motion for these satellites that orbit at LEO altitudes. This session provided new information and made recommendations for standards of DORIS data processing:

(1) Geocenter. Forward modeling of the geocenter is essential to altimeter satellite POD and helps produce consistency between GPS and SLR/DORIS orbits. Can we consider adoption of forward geocenter modeling as part of the processing for the next ITRF? A lack of such a model means that the orbits are mis-centered (pro). But is the same model applicable for SLR, DORIS, and GNSS (con)? It is noted that a geocenter model can be

derived from DORIS data that is consistent with a Lageos-1 and Lageos-2 geocenter model that considers corrections for loading and biases.

(2) Time variable gravity (TVG). The use of an accurate, highest fidelity possible TVG model is a requirement for LEO satellite modeling in general and for the DORIS constellation in particular. It has been observed that increased radial orbit error and radial orbit drifts with geographic correlations occur if the highest fidelity models are not used. It is recommended that all satellite techniques adopt the highest fidelity TVG modeling that is consistent with the sensitivity of their satellites. In particular, satellite techniques should at least embrace a modern static GRACE+GOCE model and include time variations of the degree-2 coefficients.

(3) Diurnal and semi-diurnal tide models. Different authors analyzing IDS and ITRF2014 products have noticed the presence of a signal near 14 days (Blossfeld et al, 2016; Moreaux et al., 2016; Tornatore et al., 2016). It should be clarified whether this signal is real or is an alias of a subdaily tidal signal. The newly available diurnal and semi-diurnal tide models should be tested in trial solutions. It is requested that self-contained subroutines that implement these models be provided to ease their integration into processing software since their use must be done at the observation level.

(4) Tidal geocenter. This topic was not raised during the Workshop. Do the other techniques apply tidal geocenter models and is there a recommended model to use? Should the same model for tidal geocenter be used as that adopted for diurnal and semi-diurnal EOP variations?

(5) Solar radiation pressure (SRP) modeling. Because of the ubiquity of draconitic signals (at 117 days and its subharmonics) in DORIS products, SRP modeling should continue to be improved, particularly on the Jason satellites. The improvements could include detailed modeling of the solar array motion (quaternions) or other approaches could be pursued such as the use of the UCL model. As a word of caution, the draconitic signals in DORIS products are likely to have other components that are intrinsic to DORIS data and that must also be accommodated.

(6) Ultra-stable oscillator (USO). The Jason-2 T2L2 data have revealed new information about the behavior of the DORIS USO. Using this data, improved models can be derived to accommodate different processes that affect the behavior of the DORIS USO including the South Atlantic Anomaly (SAA), temperature, aging, and 60-day attitude-related SAA effects. Also, the T2L2 data and experience on Sentinel-3 have revealed the presence of a generic problem for the DORIS USO on LEO satellites. While waiting for a precise corrective model for Jason-3, a multi-satellite solution will be provided by applying a strategy to minimize the SAA effect for stations in this area. Models derived from the T2L2 data will also be tested for Jason-2 and Jason-3. Discussions with CNES and other satellite provides about standards for USO (pre-treatment, shielding, provision of telemetry about, e.g., the temperature of the USO box, linking of USO to GNSS as done on Sentinel-3) need to continue. As a result of recent discussions, the DORIS USO will be connected with GPS when possible in order to aid the monitoring of the USO behavior. CNES will also try to pre-irradiate on the ground a series of USOs more strongly than recent flight versions in order to facilitate testing and analysis.

(7) Scale. For the scale, the IDS should continue to investigate this, including looking at the IGS experience regarding modeling and weighting of low-elevation data to see if there is a systematic effect at low-elevation that is presently not being modeled.

Site Survey and Co-location

Chair: Sten Bergstrand (RISE, Sweden)

The connections between geodetic stations on a geodetic site are key components to a reliable combination of different techniques and a crucial component of a Global Geodetic Observing System on an observational level. Local ties are geometric vectors measured between reference points of different instruments, including the full covariance information in both temporal and spatial domain. These ties are obtained with surveying and monitoring instruments such as theodolites, total stations, laser trackers, invar rods and communicated through a coordinate system realized through GNSS antennas. Where available, the discrepancies between the analytic results and the corresponding ties exceed the expected uncertainty of the surveys. These discrepancies indicate the presence of unknown or underestimated uncertainties or unresolved systematic errors of the different techniques. This session was intended to identify the needs that can elevate the contribution of site surveying in the next ITRF. The following is a summary of the discussions and recommendations from this session:

Local ties are vectors between geometric reference points in the ITRF with full covariance information in temporal and spatial domain.

Local tie survey methods are available to determine station's geometric reference points to the desired accuracy. Other perturbations may be of geometric nature and quantified by surveying methods, but are not part of the local ties *per se*. To resolve such perturbations is the responsibility of the services.

Systematic technique errors rather than local tie surveys are dominant error sources in discrepancies between ties and solutions. Differences between analytic solutions and local ties are thus primarily indicators of systematic errors of the techniques on the site, not of the local ties.

Annual site surveys are not necessary unless there are indications of instabilities or survey problems.

References:

(1) Documentation of IERS 2013 Workshop on Local Surveys and Co-locations is available at: http://iersworkshop2013.ign.fr/
(2) Resolution on the nomenclature of space geodetic reference points and local tie measurements is available at: https://www.iers.org/IERS/EN/Organization/WorkingGroups/SiteSurvey/documents.html
(3) The ITRS Center is just about to release "IGN best practice for surveying instrument reference points at co-location sites" as IERS Technical Note 39.

Recommendations:

(1) Optimize a local network setup combination for a bundle adjustment based on instrument specification, e.g. laser tracker (very high accuracy, short distances), theodolites (high accuracy, intermediate distances) and GNSS (low accuracy, long distances).
(2) Development of an *in situ* GNSS antenna calibration method is a high priority; and especially important to commission at GNSS sites with long history.
(3) In a choice between surveying on the one hand sites with and on the other hand without existing local ties, sites without local ties should be prioritized.
(4) For IDS, IGS, ILRS, and IVS specifically:

a. Examine ITRF2014 tie and space geodesy discrepancies available at http://itrf.ensg.ign.fr/ITRF_solutions/2014/ to look for indications of systematic errors.
b. Choose sites with poor consistency between local ties and space geodetic solutions to identify and address problems.

Reference Systems and Frames

Chairs: Zuheir Altamimi (IGN, France)
Richard Gross (JPL, USA)

The terrestrial reference frame (TRF) is the foundation for virtually all space-based, airborne and ground-based Earth observations. Through its tie to the celestial reference frame (CRF) by time-dependent Earth orientation parameters, it is also fundamentally important for interplanetary spacecraft tracking and navigation. The TRF determined by geodetic measurements is the indispensable foundation for all geo-referenced data used by science and society. It plays a key role in modeling and estimating the motion of the Earth in space, in measuring change and deformation of all components of the Earth system, and in providing the ability to connect measurements made at the same place at different times, a critical requirement for understanding global, regional and local change. Providing an accurate, stable, homogeneous, and maintainable terrestrial reference frame to support numerous scientific and societal applications is one of the essential goals of the International Association of Geodesy's (IAG's) Global Geodetic Observing System (GGOS). This session was a forum for discussing the ways and means of improving the TRF, including understanding the deficiencies of the current frames, the possibility of updating them between determinations, and jointly determining them with the CRF. The recommendations resulting from the discussions held during this session are to encourage:

(1) The IERS ITRS Combination Centers (CCs) to consider the possibility of updating their frames between determinations.
(2) The IAG Services to provide the information needed for the CCs to update their frames.
(3) The IERS to identify reference frame users who will benefit from time series reference frames and how these reference frames will satisfy their needs.
(4) The IERS to clarify the locations of up-to-date discontinuities in the coordinate time series of the four techniques.

Conventional Mean Pole

Chairs: Erricos Pavlis (JCET/UMBC, USA)
Nick Stamatakos (USNO, USA)

The Conventional Mean Pole (CMP) model has been provided by the IERS Conventions in a linear form since the 2003 edition. In the 2010 release, the model was initially modified to a cubic one with a linear extrapolation after 2010.0. In 2015, publications of present-day ice sheet mass losses led to a further modification that directed the users to use either a tabular form stored in an online file and maintained by the IERS EOP Center, or a yearly updated subroutine that essentially reproduced the tabular data. The routine that was available from the IERS Conventions portal, allowed the users to select between any of the above options; a useful feature only for comparison purposes, but one that can potentially generate many inconsistent results amongst the IAG Services. In addition to that, the routine was never updated for the current year, and so the Services had no way to use it and were left with the tabular data as the only option. Furthermore, several users had noticed that the online tabular data files were being changed without any notification to the users, which led to a study of some of the versions that were captured at various times, presented at the last Fall AGU [McCarthy and Stamatakos, 2016]. In early 2017, the ILRS adopted a modified version of the online routine, extending its validity with the introduction of a few additional points, so that ILRS operational products could continue to use the same CMP definition and create the least amount of changes in the processing chain. This session was intended to resolve the issue of the definition of the CMP and its proper implementation in a universally acceptable way. The recommendations resulting from the discussions held during this session are:

(1) The IERS Conventions section on the pole tide should be updated to replace the use of the "filtered" mean pole* with the "linear mean pole" model and a clear recommendation should be made to all analysis groups (including the altimetry community) to adopt a common "linear mean pole" model for the pole tide computations.
*http://maia.usno.navy.mil/conventions/2010/2010_update/chapter7/icc7.pdf
    a. The pole tide model is unchanged; only the "mean pole" subtracted from the IERS polar motion changes (a relatively simple code change that avoids issues associated with the need for regular updates on the "mean pole".
    b. All linear fits to the C01 series shown at the UAW do not differ by much more than the nominal 10 mas goal, even when extended up to 2050; a Special Study Group to evaluate different options in developing the "linear mean pole" does not seem warranted at this point.
    c. The specific linear mean pole model recommendation, based on the full extent of the C01 series (1900-2015), is (in milliarcseconds):

$$\overline{Xp} = 55.0 + 1.677*t$$
$$\overline{Yp} = 320.5 + 3.460*t$$

where t is in years past 2000.0.

(2) The IERS should continue to provide a *filtered mean pole table* for purposes of modeling/comparing the long-term trend in C21/S21. The filtering procedure should be clearly defined after some discussions, proposals, and tests between now and prior to the next IERS DB meeting. The spectral response of the filter that produces this now-called filtered pole needs to be made clear.
    a. This table is especially useful in forward modeling C21/S21 for precision orbit determination.
    b. It was noted that C21/S21 are well characterized by the full mean pole and a seasonal variation.

(3) The four geometric techniques (and altimetry) should consider how to implement the "linear mean pole".

(4) The IERS Conventions Centre should consider renaming the "filtered mean pole" term to avoid confusion with the "linear mean pole".

Standards, Conventions, and Formats

Chairs: Daniela Thaller (BKG, Germany)
Detlef Angermann (DGFI-TUM, Germany)

The GGOS Bureau for Products and Standards (BPS) recently compiled a detailed inventory of standards and conventions used within the IAG services for generating their products. The inventory revealed inhomogeneity between individual data sets, and inconsistencies in the analysis chains. The most natural step succeeding the inventory is the identification of present deficiencies, and the provision of recommendations how the inconsistencies can be resolved. All IAG Services need to be involved in this step. For the publication of the products unified, machine-readable and user-friendly formats are required. Modifications, extensions and new definitions need to be coordinated between all producers of geodetic products. This session was a forum for bringing all analysis groups and providers of geodetic products together and to identify the next steps in order to homogenize standards and formats for improved products satisfying the users' needs. The recommendations resulting from the discussions held during this session are:

(1) The UAW endorses the recommendations already given in the Inventory compiled by the GGOS Bureau of Products and Standards, namely:
    a. The used numerical standards, including time and tide systems, must be clearly documented for all geodetic products.
    b. The W0 value given in IAG Resolution No. 1 (2015) should be used as the new reference value for geodetic work.
    c. The development of a new Geodetic Reference System GRS20XX based on best estimates of the major parameters is desired.
(2) Intermediate updates of the IERS Conventions should be citable (e.g., IERS Conventions 2010 Update 1; IERS2010.1).
(3) Work should continue towards ensuring that all techniques use a consistent gravity field model, including time variable gravity (see recommendations from the other UAW 2017 sessions).
(4) A process should be developed by which a new model is evaluated, especially *before* it becomes a conventional model. For example,
    a. Model developers should provide a dedicated test data set.
    b. All techniques should test the model.
    c. In order to coordinate the testing, the IERS should issue a call-for-participation.
(5) A unique EOP format for all products should be derived that has, for example, clearly defined fixed labels and units and the flexibility to use only relevant columns.
(6) The handling of 9-character station names in SINEX files needs to be clarified by the SINEX Working Group. Example descriptions of the following suggested methods should be prepared:
    a. Use an extra block in the SINEX file for SINEX-internal referencing (long station name versus the 4-character abbreviation).
    b. Extend the 4-character station name in the SINEX file (to 9 or even 12 characters).

Interoperability of Portals and Metadata

Chairs: Richard Gross (JPL, USA)
Günter Stangl (BEV, Austria)

GGOS is developing a portal through which the data and products produced by the IAG Services can be served to the user community. Seamlessly providing the Service data and products to the user community through the GGOS portal requires that the GGOS and Service portals be interoperable. In practice, this interoperability is expected to be accomplished through a GGOS-developed interface that serves as an interpreter between the GGOS and Service portals. In this way, the Services can implement their portals as they want without being subject to

GGOS-defined specifications. Similarly, if the user is accessing the GGOS portal through an external portal such as the GEO portal at <http://www.geoportal.org> then the GGOS portal must be interoperable with the external portal. This session was a forum for discussing the status and plans for developing the GGOS and Service portals and for fostering a discussion between GGOS and the Services to ensure the interoperability of the portals that they are developing. The recommendation resulting from the discussions held during this session is that:

(1) The IAG Services develop web portals that are interoperable with each other and with the GGOS portal.