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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 6th 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 the 2019 Workshop the discussions were focused on:

(1) Systematic Errors and Biases in DORIS Observations
(2) Systematic Errors and Biases in GNSS Observations
(3) Systematic Errors and Biases in VLBI Observations
(4) Systematic Errors and Biases in SLR Observations
(5) Gravity Models for Precise Orbit Determination
(6) Global Space Geodesy Infrastructure
(7) Standards, Conventions, and Formats
(8) Digital Object Identifiers for Geodetic Data Sets
(9) Global Unified Height System
(10) Reference Systems and Frames
(11) Site Survey and Co-location

This report summarizes the Workshop discussions and resulting recommendations.

DORIS Systematic Errors and Biases

Chairs: Hugues Capdeville (CLS, France)
Petr Štěpánek (GOP, Czech Republic)

The session started with the presentation "South Atlantic Anomaly Compensation" by Guilhem Moreaux, describing the possible ways to compensate the instability of the DORIS onboard oscillator due to the South Atlantic Anomaly (SAA). This effect is important in particular for SPOT-5 and the Jason satellites and results in a bias of the estimated station coordinates in the South Atlantic–South America region. Then we followed with the topic "Scale in DORIS Solutions" presented by Petr Štěpánek, focusing on the long-term stability of the scale and on the systematic effects of low elevation measurement editing and (down)weighting and related inventions in the proposed strategy for ITRF2020 reprocessing. Since the DORIS space segment is based on LEO satellites having various size, shape, orbit and other characteristics, another important topic is "Mitigation of Non-conservative Force Model Error for DORIS Satellites", presented by Frank Lemoine. It is important to mitigate systematic errors due to imperfect non-conservative force modeling such as radiation pressure and atmosphere drag, and in particular a signal at draconitic periods for non-sun-synchronous satellites and seasonal variations. The recommendations resulting from the DORIS discussions are:

(1) *South Atlantic Anomaly*. Various strategies have been developed including direct observation correction, estimating more frequency parameters, "renaming" the SAA stations for affected satellites, and deleting or downweighting the most affected data. Test campaigns during 2007 for Jason-1 and SPOT-5 and during 2017-2018 for Jason-2 and Jason-3 are recommended in order to specify the optimal strategy for reprocessing the DORIS data for the ITRF2020 submission.

(2) *Scale*. Much better stability and consistency of the DORIS scale is being obtained now than was obtained in the solutions for the ITRF2014 submission. It is recommended that Analysis Centers should use their own modeling and preprocessing procedures instead of the data accessories found in the Doppler observation files. It is also recommended that corrected values of the antenna phase center offset (PCO) be used (Hy-2A) and that low elevation data should be downweighted.

(3) *Non-conservative force modeling.* In order to mitigate the 117-day signal in DORIS geodetic products, it is recommended that quaternions be used for Jason satellites and to adjust 1Cr/arc. It is also recommended that more recent albedo and infrared models be used. It is noted that the imperfection of available thermosphere models at DORIS satellite altitudes remains a limiting factor in determining the orbits of the DORIS satellites.

(4) *IDS reprocessing schedule*. Tests of different processing strategies for the ITRF2020 submission are not yet finished so final recommendations are not yet available. But the deadline to deliver the AC solutions is September 2020. While the start of the IDS reprocessing campaign for ITRF2020 has not yet been determined, it is expected to start sometime during January to March 2020 with the oldest data being reprocessed first.

GNSS Systematic Errors and Biases

Chair: Michael Moore (Geoscience Australia)

The discussions held during the GNSS session were largely concerned with preparing the GNSS submission to ITRF2020. The IGS contribution to ITRF2020 will use multi-GNSS observations (GPS+Glonass+Galileo) to define the reference frame and will include estimation of scale for the first time. The IGS submission to ITRF2020 will then become part of the IGS operational products at a time to be decided by the participating Analysis Centers. In the meantime, ITRF2014 will be maintained as the basis for the operational products. It is anticipated that improvements in orbit modeling, through updates to the solar radiation pressure models, will help reduce draconitic signals currently present in GNSS time series. Finally, geodetic troposphere products are valuable, especially from reprocessing runs, so please keep these results and make them available.

VLBI Systematic Errors and Biases

Chair: John Gipson (NASA/GSFC, USA)

The discussions held during the VLBI session were also largely concerned with preparing for ITRF2020:

(1) *Models*. The IVS contribution to ITRF2020 will include four new models, two of which are specific to VLBI and two of which are in common with other techniques. The two VLBI-specific models are galactic aberration which causes a change in the apparent source position due to rotation of the solar system about the galactic center, and gravitational deformation of the VLBI antennas which causes a change in the path length and which therefore affects the VLBI observable. The two models in common with the other techniques are the new pole tide model and the new high frequency EOP model.

(2) *Timetable*. Currently, all IVS analysis software has been modified to use the four new models. The IVS Combination Center will organize the vetting of the submissions by distributing a list of trial sessions. It is expected that on or about December 1, 2019, the IVS Combination Center will begin to accept trial solutions using the new models. After the trial solutions are vetted by the IVS Combination Center, the Analysis Centers will submit two sets of solutions: one using the old ITRF2014 models and the other using the new ITRF2020 models. Then on or about January 1, 2020 the IVS Analysis Centers should stop submitting solutions using the old ITRF2014 models and should only submit solutions using the new ITRF2020 models. During January 2020 the IVS Analysis Centers will reprocess prior years with the new ITRF2020 models. In the autumn of 2020, all solutions will be redone, if necessary, using updated gravitational deformation models.

(3) *Gravitational deformation*. Currently, the IVS has models for only six of the roughly 60 IVS (and cooperating) antennas. The IVS Directing Board recommends that all IVS antennas have surveys done in order to determine the effect of gravitational deformation. Several groups are already planning on performing these surveys in 2020. If they are completed and the results analyzed by the fall of 2020 then the IVS will redo its submission for ITRF2020 using all available models.

(4) *IVS submission*. The IVS SINEX files submitted for ITRF2020 will include radio source position information. The IVS submission will also include results from new broadband VGOS stations. While station loading effects will be included a priori in the IVS processing as is done in routine operations, the SINEX files submitted for ITRF2020 will be modified so that the loading effects can be removed a posteriori. Finally, we expect the IVS submission to ITRF2020 to be more robust than previous submissions because it will be based on results from several new VLBI analysis packages.

SLR Systematic Errors and Biases

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

The discussions held during the SLR session concerned improvements to the analysis of SLR data, preparations for ITRF2020, and possible new ILRS products. José Rodríguez gave a talk on upgraded center-of-mass modeling for geodetic SLR targets. The signature of the targets in SLR measurements has been the subject of research for many years and has been identified as a significant source of error, affecting primarily the scale of the SLR-determined TRF. Our current understanding of this was reviewed and areas for further investigation were identified. The status and initial results of the ILRS Station Systematic Error Modeling (SSEM) Pilot Project was presented by Cinzia Luceri and the steps needed to apply these results to the development of the ILRS contribution to ITRF2020 were outlined. A description of the various tasks undertaken to prepare for the development of the ILRS contribution to ITRF2020 and their current status was presented by Erricos Pavlis. The timeline for the completion of all outstanding tasks as agreed by the ILRS Analysis Centers during their meeting on October 1, 2019 was presented. Mathis Blossfeld gave a talk on the development of a future product based on multiple SLR targets. Over the past year the ILRS Analysis Standing Committee has discussed the development of new products beyond those used for TRF development. These new products would be based on an expanded number of targets and would exploit existing and future data. In particular, the benefits of delivering accurate estimates of low degree harmonics of the gravitational field and the relative value of the available targets was described. Finally, Krzysztof Sosnica proposed a model for correcting SLR data for horizontal tropospheric refraction gradients. The importance of including horizontal gradient corrections for tropospheric refraction during the reduction of SLR data for geodetic products was illustrated. An analytical model for this was developed and applied in the analysis presented at the meeting. The repercussions of this correction on various estimated parameters were quantified.

Gravity Models for Precise Orbit Determination

Chairs: Erricos Pavlis (JCET/UMBC, USA)
Jean-Michel Lemoine (CNES, France)
Michael Moore (Geoscience Australia)

IGS was the first to raise the question about a uniform approach to modeling gravity, tides, and temporal variations from a single source for all satellite techniques. A first attempt to address their concern during their Potsdam 2019 Analysis meeting showed that all satellite techniques are interested in a single point of service, but with different preferences for each technique and sometimes each Analysis Center. The purpose of this session was to examine what each technique does now operationally and during ITRF reprocessing events, and to find out who in the community is willing to provide (or already provides) such a service. John Ries gave a presentation on the GRACE/GRACE-FO products and the SLR-derived supplements which is the basis for what is done within the ILRS. His presentation outlined the rationale and approach in replacing the lowest degree harmonics in GRACE/GRACE-FO products with estimates obtained from the analysis of SLR data on multiple spherical targets. Erricos Pavlis summarized the approach devised by JCET to develop a forecast of low degree harmonics for use in operational analysis by the ILRS Analysis Centers. The sources of the underlying information were detailed and the steps followed were given. Providing the results on a publicly accessible server in the near future was requested and agreed to. Rolf Dach gave a presentation on COST-G, the new Product Center of the International Gravity Field Service (IGFS). COST-G is the evolution of the EGSIEM project and it is operationally combining Swarm gravity field solutions on a quarterly schedule with a latency of 3 months from solutions contributed by AIUB, ASU, IfG and OSU. GRACE-FO combinations are foreseen but are not yet done. The generation of gravity field combinations with short latency (e.g., daily products with 5-day latencies, as in the case of EGSIEM) is not foreseen. Jean-Michel Lemoine gave a presentation on the gravity models used at CNES. CNES develops a wealth of gravitational products from the analysis of GRACE/GRACE-FO and SLR data from LAGEOS, LAGEOS -2, Starlette, Stella, and Ajisai, including degree-1 terms, dealiasing products, tidal models, etc. The forecasting and post-casting of such SLR and GRACE-based results was also presented. Mean-field models such as EIGEN-GRGS.RL04.MEAN-FIELD are updated on roughly an annual basis; there is no possibility of a monthly service for such products at the moment. The last presentation, given by John Moyard, focused on an alternate way of describing mass variations observed by DORIS to answer the question: Is it possible to improve TOPEX/POSEIDON orbit performance by identifying some corrections on the geopotential using DORIS missions? The developed procedure uses mascons with EIGEN-GRGS.RL04.MEAN-FIELD as the underlying mean field.

Global Space Geodesy Infrastructure
Chair: Michael Pearlman (CfA, USA)
In this session, updates were given from the space geodesy techniques and reports were given from the major network players on the current state of the network and its components, current issues limiting performance, current improvements underway, and projected capability over the next 5 and 10 years.

(1) *DORIS*. There is a very comprehensive network of DORIS ground stations. The 4th generation DORIS beacon is currently under deployment (since June 2019) which allows larger distance between the beacon and the antenna (50m vs 15m previously) thanks to a signal amplifier at the foot of the antenna. Three new DORIS co-located sites were installed in 2018: with GNSS at Mangilao, Guam island; with SLR at San Juan, Argentina; and with VLBI and GNSS at Ny-Alesund, Svalbard. A network densification (10 additional stations) is being discussed with CNES and IGN.

(2) *VLBI*. VGOS is transitioning to an operational status. Bi-weekly, 24-hour sessions will be increasing to weekly sessions as resources permit. The VGOS network is increasing from 6 to 25 stations in the next 2 years. The IVS will begin VGOS intensive observations two times-a-week in late 2019-2020. A 14-station S/X network has been shown to give EOP precision similar to that given by GNSS at biweekly cadence.

(3) *SLR*. Significant increase in network capability can be expected over the next 3 years. Unfortunately, there are still large geographic voids in the network. The network will continue to have a mix of new technology and legacy equipment. But progress is being made in dealing with systematics.

(4) *GNSS*. The GNSS community is a broad-based, well organized, resilient community exerting strong control, including quality control, of a complicated system. This is achieved by involving their members in all aspects of the process. It is recommended that regular communication channels among the different techniques be established in order to ensure that no co-location opportunities are lost or delayed and that issues impacting each other's infrastructure can be discussed in a timely fashion.

(5) *PSMSL*. The Permanent Service for Mean Sea Level (PSMSL) will issue the PSMSL dataset with a digital object identifier (DOI). This is likely to be done on an annual basis. PSMSL is setting-up a GNSS-Interferometric Reflectometry (GNSS-IR) data portal to preserve, archive and distribute sea level data from GNSS-IR. PSMSL will be making available software to automatically quality control near real-time sea level data which can be used to produce mean sea level data and which will improve data flow to PSMSL.

Co-locating techniques is key to determining the terrestrial reference frame. But many co-located (core) sites will not be at ideal locations or have ideal observing conditions. While the original goal was to have 32 well-distributed core sites, 32 sufficiently "good" locations may not exist or may not be in accessible locations. While new technology stations are being deployed, many are not being co-located with other techniques. Since core site deployment will occur over many years, we will have a mix of new and legacy technologies for many years to come. As a result, co-location (non-core) sites will continue to play a vital role in our data products well into the future. The quality of our products will result from observations acquired by a mix of core sites, co-location sites, and different technologies. As a result, it will be important to adhere to proper operational and engineering procedures and to make the best use of data once it leaves the field. Fortunately, many groups are taking the initiative to join the effort, build new stations, or upgrade existing stations. There are many DORIS-GNSS co-locations, and we should not forget about the co-locations that currently exist in space. Analysts will need to be creative in order to make the best use of this mix of data. In summary, this is a challenging program with very important scientific and societal benefits. There is a great opportunity here to participate in the analysis and scientific interpretation of our data. We need to engage students and young scientists in our enterprise. Ultimately, our success will depend on the partnerships that we develop.

Standards, Conventions, and Formats

Chairs: Nick Stamatakos (USNO, USA)
Detlef Angermann (DGFI-TUM, Germany)

The IERS Conventions describe the reference systems realized by the IERS, in addition to developing and maintaining the models and procedures used to support this endeavor. The reference systems and procedures of the IERS are based on the resolutions of international scientific unions. It is highly recommended that planned major updates and changes to the IERS Conventions (from 2010 version) be discussed at the UAW meeting so that the several component members of the IERS and IAG/GGOS are aware of these upcoming changes, can identify potential impacts to their respective component, and have influence on the realization of these proposed changes in the IERS Conventions text and associated software. The discussions held during the session and the recommendations made were largely concerned with revising the IERS Conventions:

(1) *Review of Section 1.1.* An IAG resolution in 1983 recommended that the zero-tide system be used for both gravity field parameters and for the figure of the Earth (geometry). And an IAG resolution in 2015 on the IHRF recommended that the mean-tide system be used to support oceanographic and hydrologic modeling. But the current practice is to use a tide-free system for geometry (ITRF), a zero-tide system for gravity, and a mixed system for physical heights derived from leveling. It is recommended here that the inconsistency concerning the treatment of the permanent tide be resolved within the IAG in order to support GGRF developments and user needs.

(2) *Review of Section 1.2.* Because a consistent set of numerical standards does not exist within the IAG, it is recommended that: (1) the numerical standards that are used, including time and tide systems, be clearly documented for all geodetic products; and (2) a new Geodetic Reference System (GRS20XX) be developed that is based on best estimates of the major ellipsoidal parameters.

(3) *Review of Chapter 5*. During the presentation of Nick Stamatakos, guiding principles for the simplification of the IERS Conventions were given. It was suggested that the revision of Chapter 5 could be used as a test of the implementation of these guiding principles. It is recommended that: (1) users be encouraged to provide their comments on these guiding principles; and (2) chapter contributors use these guiding principles when revising their chapters.

(4) *Review of Nutation Models*. Issues affecting the accuracy and consistency of the presently available precession-nutation models were discussed during the presentation of José Ferrándiz. It is recommended that: (1) the amplitudes of the leading nutation terms of the IAU2000 theory be updated and a shortened series for certain operational purposes be tested; (2) the inconsistencies found in the precession-nutation models be corrected; (3) the available FCN models be tested and consideration be given to the question of whether or not the IERS should recommend an FCN model to use; and (4) the tasks of the joint IAU/IAG Working Group on Improving Earth Rotation Theories and Models be prioritized in order to get results in two years.

(5) *Review of High Frequency EOP Models*. John Gipson gave a report on the activities of the ad hoc IERS Working Group on high-frequency EOP models. Following a series of extensive tests, it was found that the Gipson and the Desai & Sibois models were the two that performed the best amongst all those tested. It is recommended that the Desai & Sibois / Egbert TPX08 model be used in the IERS Conventions.

(6) *Review of IAA Solutions*. Dmitry Pavlov reviewed the characteristics of the VLBI, LLR, and GNSS solutions determined at the Institute of Applied Astronomy (IAA) of the Russian Academy of Sciences (RAS). He recommended that: (1) a simpler formulation for ocean loading, including the use of the HARPOS format, be considered; and (2) LLR data be used in EOP combinations.

Digital Object Identifiers for Geodetic Data Sets

Chairs: Allison Craddock (NASA/JPL, USA)
Kirsten Elger (GFZ, Germany)

In this session, Martin Sehnal gave a broad-scope overview of DOIs for geodetic datasets, Kirsten Elger built on Martin's overview with expert examples and suggested strategies that were revisited during the panel discussion, and Pierre Fridez gave a case study of how one of our contributing organizations currently implements DOIs. The panel discussion addressed the development of future-focused strategies for using DOIs in current and emerging geodetic technologies. The discussions held during the session regarded: (1) the need to identify what the community needs from consistent usage of DOIs for data in terms of being able to discover data, permanently cite data, and acknowledge the data providers; (2) the need to formulate a strategy for assigning DOIs to data in the face of the opportunities and risks for doing this; and (3) the need to identify our goals for implementing DOIs for geodetic data sets such as having a consistent method for data citation across all IAG Services, to support those who are providing the data, and to provide quantitative support detailing the use of geodetic data sets and other resources. The GGOS Working Group on this is planning to meet at AGU 2019 and EGU 2020 to discuss these and other aspects of assigning DOIs to geodetic data sets.

Global Unified Height System

Chair: Laura Sánchez (DGFI-TUM, Germany)

IAG Resolution No. 1 released during the IUGG 2015 General Assembly outlines 5 conventions for the definition of the International Height Reference System (IHRS). The definition is given in terms of potential parameters: the vertical coordinates are geopotential numbers ($-\Delta W_P = C_P = W_0 - W_P$) referring to an equipotential surface of the Earth's gravity field realized by the conventional value $W_0 = 62\ 636\ 853.4\ m^2s^{-2}$. The spatial reference of the position P for the potential $W_P = W(\mathbf{X})$ is given by coordinates **X** of the International Terrestrial Reference Frame (ITRF). This Resolution also states that parameters, observations, and data shall be related to the mean tidal system/mean crust. At present, the main challenge is the realization of the IHRS; i.e., the establishment of the International Height Reference Frame (IHRF): a global network with regional and national densifications, whose geopotential numbers referring to the global IHRS are known. According to the GGOS objectives, the target accuracy of these *global* geopotential numbers is $1 \times 10^{-2}\ m^2s^{-2}$. In practice, the precise realization of the IHRS is limited by different aspects; for instance, there are no unified standards for the determination of the potential values W_P; the gravity field modelling and the estimation of the position vectors **X** follow different conventions; the geodetic infrastructure is not homogeneously distributed globally, etc. This may restrict the expected accuracy of $1 \times 10^{-2}\ m^2s^{-2}$ to some orders lower (from $10 \times 10^{-2}\ m^2s^{-2}$ to $100 \times 10^{-2}\ m^2s^{-2}$). The objective of this session was to summarize advances and present challenges in the establishment of the IHRS/IHRF. Special care was given to the collocation of ITRF and IHRF reference stations and the harmonization of the standards applied in the determination of geometric and physical coordinates.

Reference Systems and Frames

Chairs: Zuheir Altamimi (IPGP-IGN, France)
Richard Gross (NASA/JPL, USA)
Manuela Seitz (DGFI-TUM, Germany)

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 inconsistencies of the current TRFs and the possibility of jointly determining them with the CRF. The recommendations resulting from the discussions held during this session are to:

(1) urge the IGS to preserve the alignment of its operational products (orbit, clocks, EOP) to ITRF2014 until ITRF2020 is published;

(2) urge the IVS to provide the atmospheric loading (atml) corrections (if applied) to the right-hand side of the normal equation in the SINEX files, i.e. $A^T P(\delta Y_{atml})$;
(3) urge the ILRS to provide the range bias estimates with covariance in their weekly SINEX files;
(4) encourage the IDS to mitigate IDS-specific systematic errors that impact the TRF parameters (origin and scale);
(5) and invite the GGFC to provide a unified loading model including all contributions (atmosphere, hydrology, and ocean) for all ITRF2020 sites.

Site Survey and Co-location
Chairs: Sten Bergstrand (RISE, Sweden)
Zuheir Altamimi (IPGP-IGN, France)
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 recommendations resulting from the discussions held during this session are to:
(1) re-form/re-activate the IERS Working Group on Site Survey and Co-location, set objectives for the working group, clarify reporting expectations, engage the IAG Services in the working group, hold annual meetings, disseminate knowledge of antenna deformation measurements, issue guidelines, liaise with the tide gauge community, and distribute publications related to the activities of the working group;
(2) understand deflection-of-vertical (DoV) contributions to local tie measurements;
(3) work on GNSS weakness on small scale;
(4) and prioritize surveying more sites rather than surveying sites more often.