Section 7:

ILRS Analysis Activities

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Introduction

SLR and LLR Analysis Centers (ACs) and Associate Analysis Centers (AACs) utilize the laser ranging data to generate ILRS derived products on an operational basis, typically daily or weekly depending on the product, using accepted standards. These official ILRS products include positions and velocities of ILRS network stations, Earth Orientation Parameters (EOPs), and precise orbits for selected satellites (LAGEOS and Etalon). AACs generate specialized products, such as station data quality reports. Two Combination Centers (CCs) generate operational ITRF products based upon the individual AC solutions; these products include daily/weekly station positions and daily resolution Earth orientation products and weekly combination of satellite orbit files for LAGEOS-1/-2 and Etalon-1/-2. Lunar Associate Analysis Centers (LAACs) process data from lunar-capable stations in the ILRS network to generate a variety of scientific products.

A list of currently approved ILRS ACs, CCs, AACs, and LAACs is maintained on the ILRS website at: *https://ilrs.gsfc.nasa.gov/science/analysisCenters/index.html* and listed in Tables 7-1, 7-4, 7-5, and 7-7.

ILRS Analysis Centers

Eight centers have been qualified as ILRS Analysis Centers (see Table 7-1). These centers are required to provide weekly submissions of Earth orientation parameters and station coordinates and precise orbit products (LAGEOS-1 and -2 and Etalon-1 and -2) that are included in the production of the official ILRS combination product. The Analysis Centers are appointed based on their demonstrated performance in both the rigor of their analyses and the punctuality with which their weekly solutions have been submitted to the ILRS Combination Centers.

Table 7-1. ILRS Analysis Centers (ACs)

Code	AC Title and Supporting Agency
ASI	Agenzia Spaziale Italiana, Centro di Geodesia Spaziale "G. Colombo" (ASI/CGS), Italy
BKG	Bundesamt für Kartographie und Geodäesie (BKG), Germany
DGFI	Deutsches Geodätisches Forschungsinstitut-Technische Universität München (DGFI-TUM), Germany
ESA	European Space Agency/ European Space Operations Centre (ESA/ESOC), Germany
GFZ	Helmholtz Centre Potsdam German Research Centre for Geosciences (GFZ), Germany
GRGS	Groupe de Recherche de Géodésie Spatiale (GRGS), Paris Observatory, France *(not active since mid-2016)*
JCET	Joint Center for Earth Systems Technology/Goddard Space Flight Center (JCET/GSFC), USA
NGSF	NERC Space Geodesy Facility (NSGF), United Kingdom

ASI/CGS (Agenzia Spaziale Italiana, Centro di Geodesia Spaziale "G. Colombo"), Italy

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Areas of Interest

The ASI Space Geodesy Center "G. Colombo" (CGS) has contributed to ILRS since the beginning of the Service activities both as a fundamental station and analysis center (AC). The data analysis team is daily involved in the analysis of SLR, VLBI and GNSS data, collected by the worldwide networks, to estimate fundamental geodetic parameters. The SLR data analysis activities at the ASI/CGS started in the 80’s and, since then, have been focused primarily on global, extended solutions in support of the reference frame maintenance. Its main interest is in the areas of tectonic plate motion, crustal deformation, Earth rotation and polar motion, Earth gravitational field, Terrestrial Reference Frame, satellite orbit determination, climate change.

The analysis center participates in national and international programs on advanced SLR applications, like Quantum Communication and Space Debris Tracking.

The ILRS Governing Board recognized the center’s continuous and rigorous contribution and appointed the ASI/CGS as one of the official ILRS Analysis Centers when the ILRS AC structure was finalized (2004).

Information on the CGS and some of the analysis results are available at the CGS website GeoDAF (Geodetic Data Archiving Facility, *http://geodaf.mt.asi.it*).

Recent Progress and Analysis Center Improvements

In the year 2016-2019, the ASI/CGS has been deeply involved in the ILRS activities, mainly in support of the reference frame maintenance and under the coordination of the Analysis Standing Committee (ASC).

The ASI AC main contributions were:

- ILRS official products:
    - weekly submission of loosely coordinate/EOP solutions estimated using LAGEOS and Etalon data and following the project requirements. The product is the ASI/CGS input to the official ILRS combined SSC/EOP product. Figure 7-1 below shows a comparison between the ASI solution and the combined ILRS-A in terms of 3 dimensional WRMS of the core site residuals with respect to ITRF. It is clear the use of the new model ITRF2014 at the beginning of July 2017.

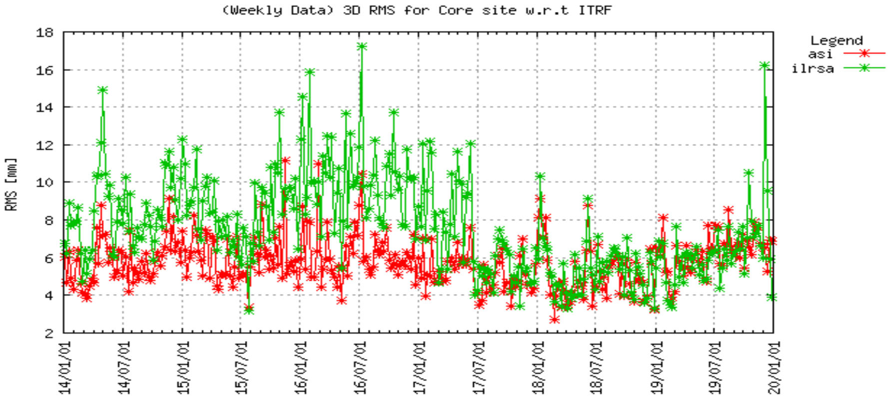

Figure 7-1. ASI and ILRSA 3D coordinate residual WRMS A.

  - daily submission of loosely coordinate/EOP solutions estimated using LAGEOS and Etalon data and following the ASC requirements. The product is the ASI/CGS input to the official ILRS combined EOP product.
  - weekly orbits: estimated state vectors of the 4 satellites, LAGEOS and Etalon, are distributed weekly, as requested by the ASC, in the ITRF reference frame as input to the official ILRS combined orbit product.
- "Station Bias determination and monitoring": the characterization of station systematic errors started in the 2000 and then was turned into a specific ASC Pilot Project with the aim to recover real errors from the data analysis. Figure 7-2 below is one of the first time series submitted in 2018 showing a clear range bias not included in the applied model. In the reported period several time series of weekly station range biases were submitted to the ILRS Combination Centers, according to the ASC guidelines. More details in the ASC report in this volume.

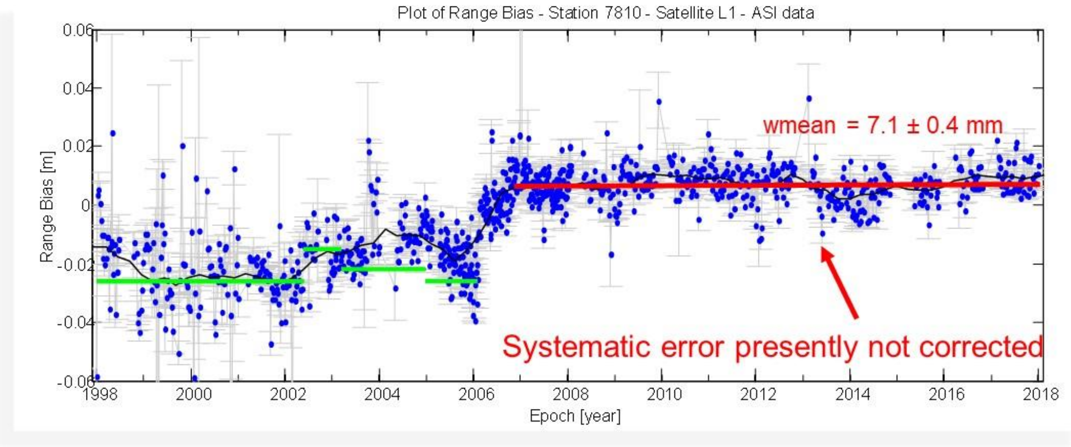

Figure 7-2. Zimmerwald range biases for LAGEOS.

- "Station qualification": ASI/CGS is one of the ACs designated by the ASC to validate the data from new or upgraded sites or after an earthquake.
- "CRD validation": ASI/CGS is one of the ACs designated by the ASC to validate the data submitted by the station in the new CRD format.
- Participation to all the ASC Pilot Projects.

The ASI/CGS analysis activities extend beyond the accomplishment of its role within ILRS and were addressed in the following main application fields.

- International Terrestrial Reference System (ITRS) maintenance:
  - production of IERS oriented products (global SSC/SSV and EOP time series) regularly performed as ASI/CGS operational EOP series: 1-day estimated EOP, from LAGEOS and Etalon data, are available at the IERS website *ftp://hpiers.obspm.fr/iers/series/operational/*;
  - generation of the multi-year solution, from LAGEOS-1 and -2 data (since 1983). Global network SSC/SSV and 3-day EOP (x, y, LOD) are the main parameters estimated in this solution and available under request.
- EOP excitation functions: production of the geodetic excitation functions from the ASI/CGS estimated EOP values for IERS (available on the ASI geodetic website *http://geodaf.mt.asi.it*): the daily geodetic excitation functions are produced every Tuesday along with the operational weekly SLR solution, staked and compared whenever possible with the atmospheric excitation functions from the IERS SBAAM, under the IB and non-IB assumption, including the "wind" term;

- Orbit determination of space targets (e.g., space debris) using positioning data acquired with the Space Debris Observatory at ASI/CGS.

Technical Challenges and Future Plans

Most of the current activities will continue, with particular attention to the ILRS and IERS oriented products.

The activities for the next ITRF2020 started in 2019 and will continue in the next 2 years in order to fulfill the ASC request for the generation of the ILRS contribution. Weekly loosely solutions, from 1993.0 to 2021.0, with estimated site coordinates and EOPs and obtained using LAGEOS, Etalon and LARES data will be prepared according to the ASC guidelines.

Deeper investigations will be directed to the low degree geopotential zonals and precise orbit determination.

CC/AC/AAC/LAAC Personnel

The Italian Space Agency is the owner of the Space Geodesy Center and is the decision-making body, Giuseppe Bianco, director of the ASI/CGS, is the ASI manager of the Analysis Center. The activities of the Analysis Center are performed by e-GEOS S.p.A. (formerly Telespazio) since the very beginning in the 80's. The team is composed by 6 people involved in SLR, VLBI and GNSS data analysis. The SLR data analysis activity is coordinated by Vincenza Luceri.

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Areas of Interest

Within the Analysis Standing Committee (ASC), the SLR Analysis Center (AC) at BKG derives Terrestrial Reference Frame (TRF) solutions from ILRS SLR data for the "pos+eop" routine daily and weekly services as well as for pilot projects scheduled. Within the routine operations, LAGEOS and Etalon SLR data are processed in 7-day arcs, and all parameters (station positions, Earth Rotation Parameters, orbits, range biases) are estimated on the observation level in one common step. Additionally, several QC steps (Helmert transformations, orbit comparisons) are performed. The analysis software used is the Bernese GNSS Software in its SLR development version (see Dach et al., 2015, Thaller et al., 2009, and Thaller et al., 2012). The upgrading of the analysis software to meet the ILRS ASC requirements is done in cooperation with AIUB.

During the reporting period the following reports were produced:

Koenig D, Grahsl A, Thaller D (2017) BKG's Contribution to the ILRS Pilot Project on Systematic Errors, Proceedings of the 2017 ILRS Technical Workshop, Riga, 2017, URL: *https://cddis.nasa.gov/2017_Technical_Workshop/docs/papers/session2/ilrsTW2017_s2_paper_DKoenig.pdf*.

Koenig D, Meyer U, Thaller D, Dach R (2018) The BKG Reprocessing for the ILRS Pilot Project on Systematic Errors, Geophys. Res. Abstr., Vol. 20, EGU2018-13137, 2018, EGU General Assembly 2018.

Koenig D, Meyer U, Thaller D (2018) Further Studies on the Influence of Range Biases, Proceedings of the 21st International Workshop on Laser Ranging, Canberra, 2018, URL: *https://cddis.nasa.gov/lw21/docs/2018/papers/Session5_Koenig_paper.pdf*.

Recent Progress and Analysis Center Improvements

In November 2016, the person in charge of the SLR-AC at BKG switched from Maria Mareyen to Daniel Koenig with a vacancy of several months.

BKG has contributed TRF solutions to the SSEM pilot project (PP) according to the specifications requested by the ASC. The results obtained by the BKG solution were presented at the ILRS Workshops 2017 (Riga) and 2018 (Canberra) as well as at the EGU General Assembly 2018. Especially interesting during the current reporting period have been the difference of the TRF scale w.r.t. SLRF2014 as well as the behavior of the ground stations' range biases (RB).

For illustration, in Figure 7-3 the Differential Scale (DS) between a LAGEOS-only solution and the a priori SLRF2014 is plotted. It can be seen that in case of RB for each station (SSEM-PP) there is higher scatter as opposed to the case of RB set up only for selected stations. On the other hand, forming annual mean values (not shown here) reveals that in the SSEM-PP case the DS time series stays roughly more stable at negative values whereas in the case of RB set up only for selected stations the mean values clearly rise from negative to positive values.

An investigation of RB time series stemming from different solutions suggests that the time series obtained for stations McDonald (7080) as well as Yarragadee (7090), see Figure 7-4, represent the two types of RB behavior of all other core stations. Eminently, the RB estimated for Yarragadee form time series of very low scatter and median of only a few mm. However, a small but significant offset of the

Etalon combined RB of solution LS_EC ('LS_EC (Etalon)') w.r.t. the LAGEOS combined RB ('LC') is detected. Though staying remarkably stable the RB time series for McDonald reveal a larger scatter as well as some outliers.

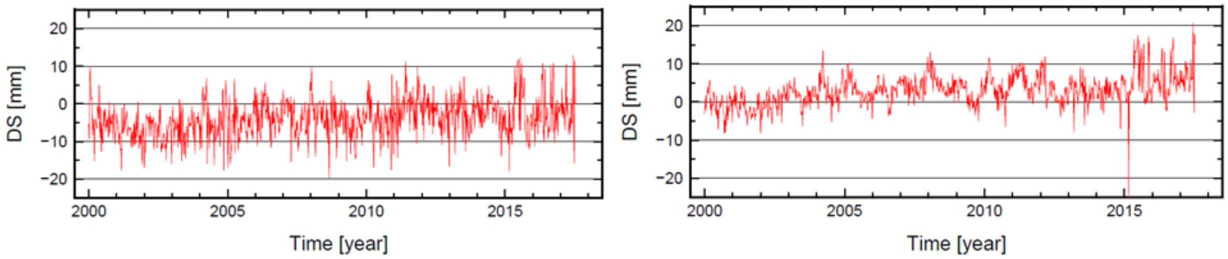

Figure 7-3. Differential scale between a LAGEOS-only solution and SLRF2014 (a priori) (left: SSEM-PP with separate range biases for LAGEOS-1 and -2 for each ground station, right: solution following specifications of operational processing, i.e., range bias for selected stations only).

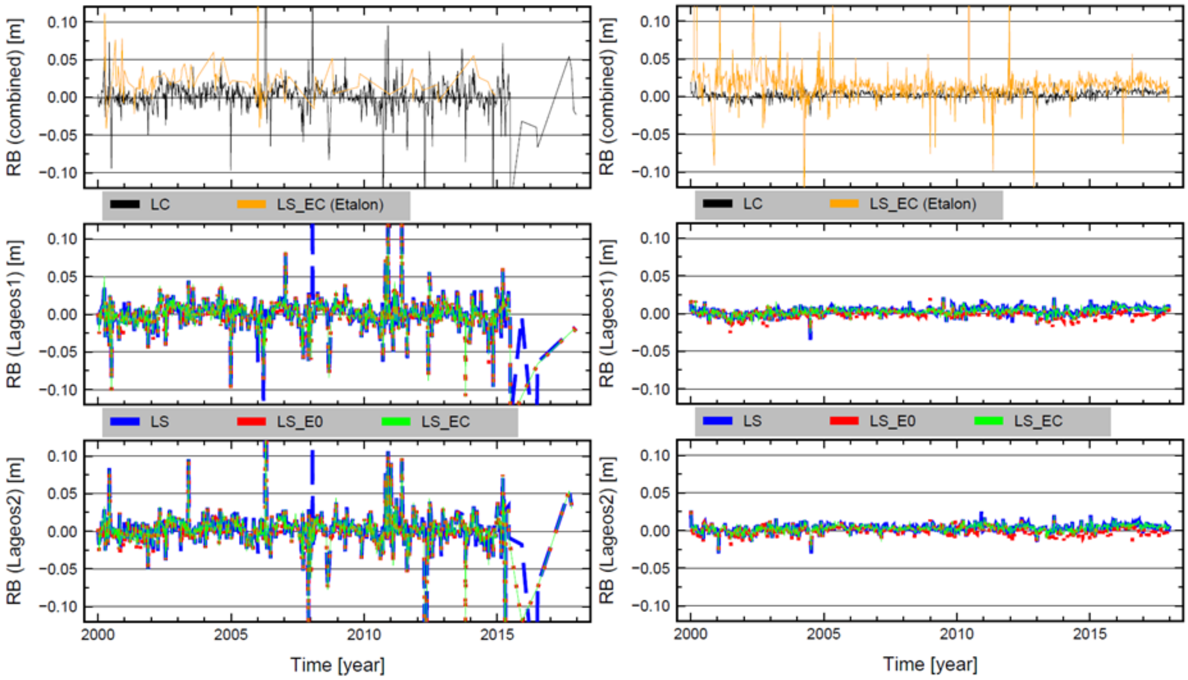

Figure 7-4. Range Biases (RB) estimated (left: McDonald 7080, right: Yarragadee 7090; 'LC': LAGEOS-only/combined RB, 'LS': LAGEOS-only/separate RB, 'LS_E0': LAGEOS+Etalon/separate RB for LAGEOS/no RB for Etalon, 'LS_EC': LAGEOS+Etalon/separate RB for LAGEOS/combined RB for Etalon)

In order to meet the ASC requirements for deriving the TRF solutions required (operational and PP) the SLR analysis software used has steadily been upgraded by implementing the IERS2010 mean-pole, the proper handling of SLR wavelength information, and the processing of the new satellite Center-of-Mass (CoM) tables provided by NSGF. Moreover, the transition to ITRF2014 with PSD corrections as a priori TRF was implemented.

Technical Challenges and Future Plans

Over the next two years it is intended to augment the capabilities of the AC by developing tools for visualizing TRF results as well as QC figures on a webpage. Concerning SLR processing, the BKG contribution to ITRF2020 will be the overwhelming challenge for the reporting period to come. This especially implies to derive Etalon orbits covering the years 1993-1999 as well as to include LARES as a fifth satellite, and to estimate low-degree gravity field coefficients (see Sośnica et al., 2015 and Meyer et al., 2019).

Apart from the operational ILRS-AC activities, BKG is supporting the development of SLR data analysis capacities in Latin America. This cooperation with the SIRGAS community has been established in 2017 with a first workshop on SLR in Latin America. Several lectures about SLR, ILRS and global reference frame were given by Daniela Thaller within the SIRGAS 2017 Symposia held in Mendoza (Argentina):

http://www.sirgas.org/fileadmin/docs/Boletines/Bol22/SIRGAS2017_Report.pdf

As a follow-up activity, a second SLR Workshop in Latin America was organized in conjunction with the SIRGAS 2019 Symposia held in Rio de Janeiro (Brazil). Up to 25 participants from eight countries attended this 3-day workshop with an intense program of introductory lectures and exercises on SLR data handling and SLR data analysis using the Bernese GNSS Software version 5.2:

http://www.sirgas.org/fileadmin/docs/Boletines/Bol24/Symposium_SIRGAS2019_summary.pdf

BKG will continue to support the SIRGAS community with their efforts to establish SLR data analysis capacities in Latin American countries.

Figures 7-5: The second SIRGAS SLR Workshop held at IBGE (Instituto Brasileiro de Geografia e Estatística), Rio de Janeiro (Brazil), November 6-8, 2019, with exercises on SLR data processing using the Bernese GNSS Software.

AC Personnel

- Dr. Daniela Thaller, Head of unit
- Dr. Daniel Koenig, responsible for operations

References and Publications

Dach, R., S. Lutz, P. Walser, and P. Fridez (eds). Bernese GNSS Software, Version 5.2. Astronomical Institute, University of Bern, Bern, Switzerland, 2015. ISBN 978-3-906813-05-9. doi: 10.7892/boris.72297. *ftp://ftp.aiub.unibe.ch/BERN52/DOCU/DOCU52.pdf*.

Meyer, U., K. Sośnica, D. Arnold, C. Dahle, D. Thaller, R. Dach, A. Jäggi (2019): SLR, GRACE and SWARM Gravity Field Determination and Combination. Remote Sens. 2019, 11, 956. Doi: 10.3390/rs11080956

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Sośnica, K., A. Jäggi, U. Meyer D. Thaller, G. Beutler, D. Arnold, R. Dach (2015): Time variable Earth's gravity field from SLR satellites. J Geod 89(10), pp. 945-960. doi: 10.1007/s00190-015-0825-1

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Areas of Interest

The ILRS AC at Deutsches Geodätisches Forschungsinstitut- Technische Universität München (DGFI-TUM) contributes to all ILRS Analysis Standing Committee (ASC) routine station coordinate and Earth orientation parameter products named "v170" (daily-shifted 7-day loose-constrained solution) and "v70" (weekly-shifted 7-day loose-constrained solution). These solutions are based on the analysis of SLR observations to the spherical geodetic satellites LAGEOS-1/-2 and Etalon-1/-2 downloaded from the Eurolas Data Center (EDC). The EDC is, in addition to the ILRS AC, also hosted at DGFI-TUM together with the ILRS Operation Center under the supervision of M.Sc. Christian Schwatke. Moreover, DGFI-TUM provides reduced-dynamic orbit solutions of the prior mentioned satellites in the SP3c file format with a 60 second and 120 second temporal resolution, respectively.

In addition to the routine contributions to the ILRS ASC which are submitted to the ILRS Combination Centers hosted at ASI (Italy) and NASA GSFC/UMBC (Maryland, USA), DGFI-TUM also provides input to the ILRS ASC pilot projects such as the "v230" project on systematic errors of ILRS ground stations. DGFI-TUM also evaluates the impact of the station-dependent SLR time biases derived from the T2L2 experiment.

Besides the ILRS ASC contributions, DGFI-TUM routinely computes 7-day orbit solutions of the Low Earth-Orbiting (LEO) satellites LARES, Larets, Ajisai, Stella and Starlette. Based on these observations, an SLR constellation solution for the TRF, the EOP and Earth's gravity field coefficients is routinely computed (Bloßfeld et al., 2016b, Bloßfeld et al., 2018a). An important role also plays the combination of GRACE and SLR NEQs for the consistent estimation of low and high degree time-variable Stokes coefficients (Haberkorn et al., 2016). In the past, also the whole mission periods of GFZ-1, Westpac and the Russian BLITS satellite were analyzed. Relatively new is the analysis of SLR observations to non-spherical satellites such as the Jason satellites. Up to now, the whole mission periods of Jason-1, Jason-2 and Jason-3 have been processed.

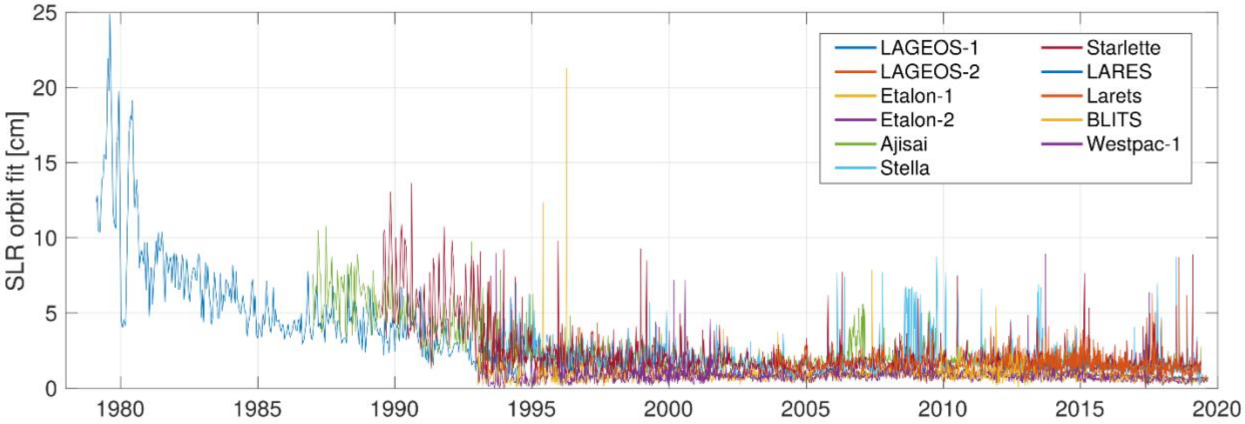

Figure 7-6: Arc-wise RMS of SLR observation residuals for multiple (non-)spherical satellites.

DGFI-TUM also contributes with SLR simulations to the standing committee on Performance Simulations and Architectural Trade-offs (PLATO) of the Global Geodetic Observing System (GGOS). Here, DGFI-TUM quantifies the impact of new SLR ground stations and improved quantitative performances of existing SLR ground stations on geodetic parameters.

AS a member of the ILRS Quality Control Board (QCB), DGFI-TUM tries to contribute to the preservation of the high quality SLR observations provided by the ILRS ground stations.

Finally, the DGFI-TUM SLR group published several SLR-related papers in the last years and gave numerous oral and poster presentations at different scientific conferences. A PhD thesis with the topic “*The key role of Satellite Laser Ranging towards the integrated estimation of geometry, rotation and gravitational field of the Earth*” was published in 2015.

Recent Progress and Analysis Center Improvements

In March 2018, Dipl.-Ing. Horst Müller retired after working nearly 40 years at DGFI-TUM. He was the head of the ILRS AC over multiple years, and significantly contributed to the development of the DGFI Orbit and Geodetic parameter estimation Software (DOGS). He originally designed the architecture of the routine processing operations at DGFI-TUM and served for many years as the primary network administrator at our institute.

Moreover, just 2 months before Horst Müller, Dr.-Ing. Michael Gerstl was also retired from DGFI-TUM. Dr. Gerstl was the primary developer of the DOGS software and helped many colleagues world-wide with his profound knowledge in mathematics and theoretic geodesy. Michael Gerstl worked from January 1981 for DGFI-TUM and is still active at our institute.

In the last years, the scope of our institute changed from the routine processing of SLR observations of the four main ILRS targets (LAGEOS-1/-2 and Etalon-1/-2) towards a long-period multi-satellite SLR processing. Up to now, we finished the orbit analysis of all spherical satellites which were and still are orbiting the Earth’s. In total, 17 satellites are processed over their full mission period and might be incorporated, in the near future, into our multi-satellite SLR solution.

Since some years, DGFI-TUM computes SLR-based time-variable Earth’s gravity fields (low-degree spherical harmonics up to degree and order 10) and provides them to scientific users world-wide (Bloßfeld et al., 2018b). Recently, DGFI-TUM also works on a multi-institutional SLR-based gravity field normal equation (NEQ) time series, where multiple institutions contribute to.

In the past three years, we use SLR observations to estimate thermospheric density scaling factors since spherical SLR satellites at very low altitudes (spherical satellites ANDE-C, ANDE-P and Spinsat) are very valuable to calibrate accelerometer-based thermospheric density models (Panzetta et al., 2018, Rudenko et al., 2018b, Xiong et al., 2018). During this analysis, also the processing of SLR observations to non-spherical satellites (primarily Jason-1/-2/-3 satellites) was implemented in DOGS together with the observation-based (satellite body quaternions and solar panel rotation angles) attitude handling. Moreover, the DOGS software is now capable to process DORIS observations. Up to now, the three Jason altimetry missions are reprocessed using SLR and DORIS observations.

At DGFI-TUM, SLR observations are also used for the joint estimation of the terrestrial and celestial reference frame in one common adjustment (Kwak et al., 2018). Therefore, SLR NEQs from DGFI-TUM are combined with NEQ from the other geodetic space techniques GNSS, VLBI and DORIS. Moreover, the most recent realizations of the TRF (ITRF2014, DTRF2014 and JTRF2014) are evaluated based on SLR analysis (Bloßfeld et al., 2018, Rudenko et al., 2018).

Technical Challenges and Future Plans

Over the next two years, the primary focus will be put on the further development of the DOGS software in order to finalize a common precise orbit determination (POD) based on SLR (and DORIS) observations. For this purpose, also other non-spherical satellites such as TOPEX/Poseidon, HY-2A/B, Sentinal-3A/B, Saral and Cryosat-2 will be implemented. Currently under investigation is the refined satellite attitude realization based on attitude observations (satellite body quaternions and solar panel orientation angles).

Another important topic will be the development of the parallel orbit integration in DOGS in order to be able to combine multiple satellites at the observation level of the Gauss-Markov adjustment model (currently combined at NEQ level) and to process inter-satellite links in the future.

Besides the ILRS AC, DGFI-TUM also operates an IERS ITRS Combination Centre. In the framework of the new ITRS realization computed in 2021 (ITRF2020), DGFI-TUM will extensively work on the analysis of the ILRS contribution to the ITRF2020 and also contribute as an ILRS AC to this solution. Therefore, LAGEOS-1/-2 and Etalon-1/-2 observations will be reprocessed between 1983 and 2021. In addition, alternative TRF products are investigated (Bloßfeld et al., 2016a).

Finally, DGFI-TUM will further work on the simulation of future ILRS networks and station performances within the framework of the GGOS PLATO group (Kehm et al., 2017, Männel et al., 2018). Moreover, several externally funded projects are planned which might offer the opportunity to do further research on the SLR techniques and its usability in up-to-date Earth's system research.

AC Personnel

- Dr.-Ing. Mathis Bloßfeld (ILRS AC head, member of ILRS QCB)
- Dipl.-Ing. Alexander Kehm (ILRS AC backup)
- M.Sc. Christian Schwatke (ILRS EDC/OC chair)

Figure 7-7: DGFI-TUM ILRS AC/DC personnel (left to right): M.Sc. Christian Schwatke, Dipl.-Ing. Alexander Kehm, Dr.-Ing. Mathis Bloßfeld) in front of the Mount Stromlo Observatory (Canberra, Australia).

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Areas of Interest

The navigation support office (OPS-GN) at the European Space Operations Centre (ESOC) of the European Space Agency (ESA) is active in all three international satellite geodesy services: the IDS, IGS, and ILRS. A unique feature of the ESOC participation in these three services is that its contributions to all three techniques are based on the same software, called NAPEOS.

ESOC has been a full analysis centre of the IGS since its beginning in 1991. In 2008 ESOC undertook a significant effort to become a full analysis centre also in the IDS and ILRS. As AC in the three techniques it also participated in the reprocessing efforts for the ITRF2008 and the ITRF2014 and is now also participating in the reprocessing for the ITRF2020 in all three services.

The participation in all three techniques is considered as a “first step”. Our ultimate goal is to do a fully combined analysis of the data of all three techniques, and in the future even 4 techniques when adding VLBI. In such a combined analysis the strength of each technique may be used to overcome the weaknesses in the other techniques. In this combination of techniques SLR plays a crucial role as it is the only technique that provides (more or less) unbiased range measurements. Furthermore, SLR is the only technique that provides direct access to the orientation and the scale of the terrestrial reference frame. In addition, SLR is extremely important in validating the orbits of both the IGS and the IDS.

Recent Progress and Analysis Center Improvements

In the pilot project for biases the ESOC bias solutions were clearly different from the other ACs. This was investigated and it was found to be caused by an erroneous setting of the troposphere correction. After this problem was resolved the biases became very similar to those of the other ACs. This troposphere bug also affected the routine solutions where after fixing it the scale of the solution changed noticeable and became in better agreement with the other ACs. In general, the quality of the ESOC ILRS contributions seems to be very good.

The space debris office of ESOC was looking for orbits of some of the other SLR cannonball targets as they use them as “calibration” targets. Since we start our processing with a 3-week pre-processing solution we decided to include these targets in this pre-processing step. The satellites we included are: LARES (to be included in the ILRS soon anyway), Ajisai, Stella, Starlette, and Larets.

Technical Challenges

In our GNSS work we always make use of the SLR observations of the GNSS satellites to validate our orbits and the models we are using. For example, we have performed an initial reprocessing of all the IGS data for ITRF2020 and analyzed the quality of the obtained solutions with all the available SLR data of the GNSS targets. Table 7-2 below summarizes the obtained statistics (based on one-way SLR observation residuals).

The table shows the very good agreement between the GNSS based orbits and the SLR observations. Only for Galileo a small mean is still visible. Thanks to the SLR observations we were able to identify this issue and also have the means to validate our solution(s) for it. Our latest results with an improved thermal model for the Galileo FOC satellites no longer show a significant mean offset.

Last but not least the table shows that we have over 1 million (!) of SLR observations with a sigma of around 20 mm which could contribute to the ITRF2020 if we would include them in a combined SLR-GNSS (re)processing. This would tie the SLR and GNSS sites not only through the ground co-location sites but would also tie them "in space". We believe that this would bring a significant benefit for both techniques!

Table 7-2. Quality of SLR solutions of GNSS targets

GNSS	Number of NPT	Mean (mm)	Sigma (mm)	Timeframe
GPS	108871	-4.9	21.5	1995-2020
GLONASS	856094	-1.7	23.7	2009-2020
Galileo	232393	16.9	17.6	2015-2020

Note that BeiDou and QZSS are not included in these statistics as they are not yet included in our IGS (re)processing.

Future Plans

We are currently in the final stages of developing the VLBI capabilities of our NAPEOS software. Ideally we would be able to participate in the ITRF2020 reprocessing for VLBI but that in not very likely at present. We are lacking some operational features to make that (easily) possible. But for the next ITRF (re)processing we are sure to be ready to contribute to all 4 techniques. And ideally we would also generate a "COOL" solution (COOL = Combination On the Observation Level) using all 4 techniques in one single solution.

Personnel

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GFZ (German Research Centre for Geosciences), Germany

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Areas of Interest

Our main focus is to measure the shape and rotation of the Earth, its orientation in space, its surface and its gravitational field. For that purpose, SLR data serve as one of the key observation types in the analysis. Particular interests lie in the prospects of SLR in defining the origin of the Terrestrial Reference Frame (TRF) and its scale together with VLBI. Also, the low degree gravity field and its variations in time are deduced where the time series of C(2,0) values is supplied in support of the GRACE-FO mission.

Therefore, GFZ contributes to the ILRS by running a SLR station in Potsdam and an AC in Oberpfaffenhofen. On a daily and weekly basis, the AC operationally provides weekly global SLR ground station coordinates and daily EOPs from the analysis of SLR observations to the LAGEOS, LAGEOS-2, Etalon-1 and Etalon-2 satellites. On a weekly basis, also the orbits of these satellites are provided. Every few years the AC contributes to the development of the ITRF. The AC also takes part in the pilot projects and in other activities of the ILRS ASC, actually the pilot project “Systematic Station Error Monitoring” (SSEM) is being conducted.

Recent Progress and Analysis Center Improvements

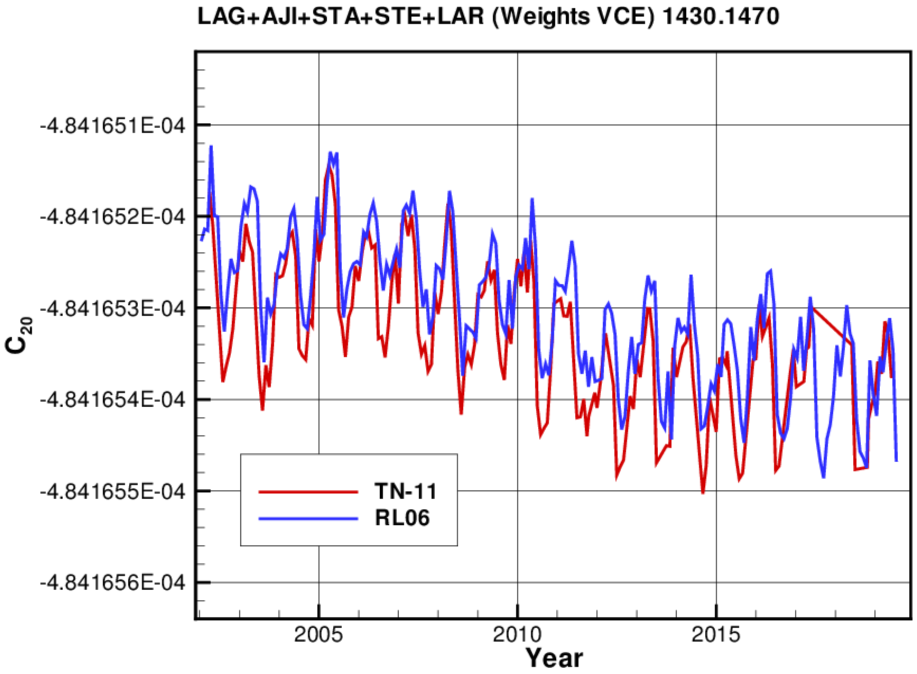

Figure 7-8. The GFZ C(2,0) time series (RL06) versus GRACE Technical Note 11 (TN-11).

In the reporting period the GFZ C(2,0) time series (König et al., 2019[1]) in support of the GRACE and GRACE-FO missions became published, it is maintained online and accessible through the GravIS portal[2]. The solution, fully compatible with GFZ’s GRACE products, is constructed from SLR range observations to the

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[1] König R, Schreiner P, Dahle C: Monthly estimates of C(2,0) generated by GFZ from SLR satellites based on GFZ GRACE/GRACE-FO RL06 background models. V. 1.0. GFZ Data Services, http://doi.org/10.5880/-GFZ.GRAVIS_06_C20_SLR

[2] gravis.gfz-potsdam.de

six geodetic satellites LAGEOS and LAGEOS-2 (spinning off from the AC's operational products), Ajisai, Starlette, Stella, and LARES. The contributions of the individual satellites are combined via variance component estimation. The result is in good agreement with the C(2,0) time series by the GRACE project published in Technical Note 11 as shown in Figure 7-8.

A major focus in the reporting period has been laid on analyzing via simulations the improvement of the terrestrial reference frame by extension of the ground station network and by combination with other space-geodetic techniques and space-geodetic missions. Also, the role of the local ties is studied in detail. The project named GGOS-SIM resulted in a powerful software tool and an impressing ensemble of papers published[3].

Also, in the reporting period we found an operational procedure to include the Etalon satellites in the generation of the AC products. This migration provides a slight improvement of the EOPs, an example is shown in Figure 7-9. For the pilot project SSEM and for future re-processing efforts, the Etalon orbits have been processed back to the year 1993.

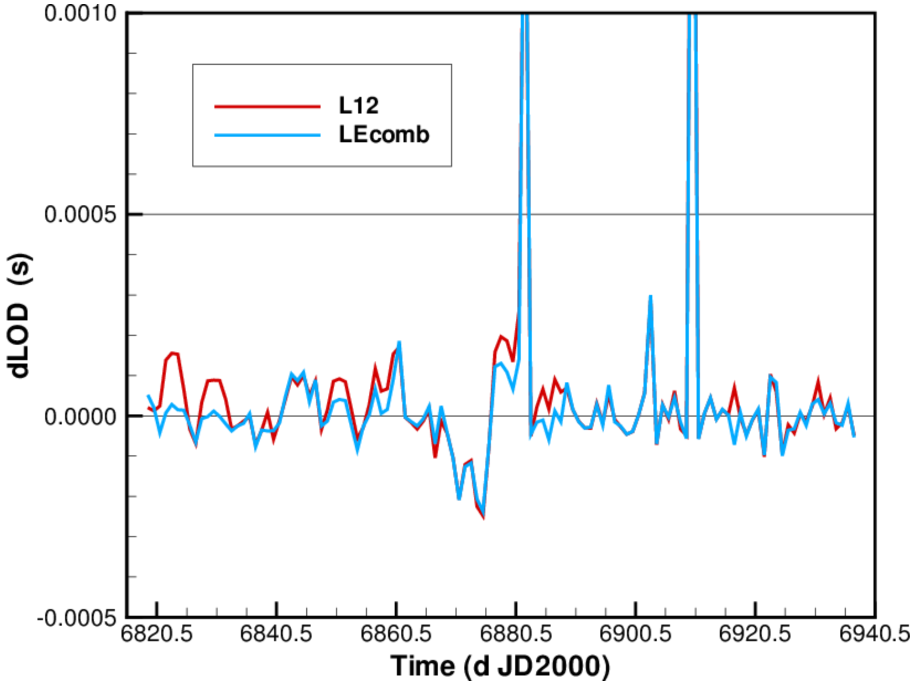

Figure 7-9. Improvement of the LOD estimates (the blue curve is closer to zero) if the Etalon observations are added.

Further, our software has been updated to handle the new linear mean pole convention, the new wavelength dependent center-of-mass corrections for SLR range observations and the new high frequency Earth orientation parameter model. The CRD V2 format is under testing. Our local data archive has been updated, cleaned and prepared for newly released historical data by some stations.

Technical Challenges and Future Plans

The next two years will see the incorporation of the LARES observations into the operational AC products. Also, the augmentation of the AC product list by low degree gravity field parameters will play a major role. Above this, we will focus on the optimal combination of all space geodetic techniques for improved monitoring of the Earth's shape and orientation in space and it's time variable gravity field.

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[3] https://www.earth.tu-berlin.de/menue/forschung/laufende_projekte/ggos_sim/parameter/en/

AC Personnel

- Dr. Rolf König, head, development, AC operations
- Margarita Vei, AC operations, maintenance
- Ingo Meyer, hardware
- Dr. Hans Karl Neumayer, mathematics, software
- Patrick Schreiner, testing, AC operations back up
- Dr. Krzysztof Snopek, data acquisition, archive

Figure 7-10. The team from left to right: P Schreiner, I Meyer, M Vei, K Snopek, HK Neumayer, R König.

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Areas of Interest

Fields of interest at the GRGS include:

- Earth rotation, and its gravity field
- Terrestrial reference frame: station coordinates, Helmert transformation
- Orbit determination and validation

Operational activities: ILRS weekly/daily products: Solutions (orbits + inversion of stacked normal equations) computed on a weekly basis. SINEX files contain EOP (A set per day) and station coordinates (1 set per week). Based on data acquired by the ILRS network on LAGEOS-1 and -2, Etalon-1 and -2 (LARES currently being tested as a future satellite included in the operational products).

Recent Progress and Analysis Center Improvements

The GRGS has been the analysis center of the International Laser Ranging Service since 2008. In 2012, following the transfer of Florent Deleflie from the OCA to the Paris Observatory, and the return to Paris of David Coulot (IGN), the operational SLR processing chains based on GINS/MATLO software, then GINS/LOCOMOTIV are installed on the servers of the Institut de Mécanique Céleste et de Calcul des Éphémérides, on the Paris site of the Paris Observatory. The period 2016-2018 was particularly difficult due to an extremely significant breakdown of the IT resources of the IMCCE which has had a strong impact on the activity of the analysis center since the middle of 2016. A significant part of the time allocated to the tasks of Florent Deleflie was devoted over the period to the re-establishment of an operational IT architecture for the Analysis center, with a backup of the scripts and results now managed directly by the project leaders. In parallel, a duplication of the processing chains is in the implementation phase within the IGN and the CNES to (i) avoid in the future that such events occur again, (ii) bring together the GRGS colleagues involved in the project, using the most up-to-date tools (including GINS) developed in Toulouse and Paris.

From an operational point of view, the situation of the analysis center is now as follows:

- The processing chains installed at the IMCCE are operational, and the period 2017-2018 has been processed; this concerns the four satellites used by ILRS for operational analyses (LAGEOS-1, LAGEOS-2, Etalon-1, Etalon-2).
- The processing now takes place on a server fully allocated to SLR processing (in particular thanks to funding obtained from CNES in 2017), and a clear policy distinguishing backups between production directories and modeling directories has been defined; today it's highly unlikely that a situation like the one we experienced in 2016 will ever happen again.
- The processing chain is entirely duplicated at IGN-LAREG.

Technical Challenges

The evolution of modeling is at the heart of our research, with the aim of achieving ever better precision and accuracy for the next products delivered by ILRS:

- The determination of biases in distance, and their temporal variability according to the technological evolutions of the stations, is at the heart of this research. In parallel with the activities carried out within the ASC, we compared the results obtained by several methods of determination of the biases;

- From the point of view of the search for a better orbitography, an important work was carried out to evaluate the performances of the albedo models already old used in operational calculations; an update of these models has been the subject of several presentations, and this new model built at IMCCE is in the final phase of evaluation before its publication;
- In the same spirit, an in-depth study of the influence of solar events on variations in atmospheric density used, on the one hand, the SLR data processed at the IMCCE, in addition to the accelerometric data from GRACE;
- And we should also mention the work on the modeling of the attitude of the satellites, compared with "full-rate" data obtained by the best kHz stations.

At the same time, research activities that do not depend directly on the operational nature of the analysis center continued. We can cite in particular the end of a new phase of T2L2 data processing. However, due to IT difficulties at the IMCCE, which was recently completed, it was not possible in 2018 to play a central role in identifying all the studies using SLR data;

Future Plans

We now have to show our ability to participate again in all of ASC activities from 2019. This includes:

- The installation in 2020 of a new GRGS service making it possible to detect “jumps” in the distance biases of the network stations, and independently (therefore with an adapted analysis scheme) of the operational solution. This responds to a greater need than in the past for interaction between (French) observers and (French) analysts;
- The inclusion of a fifth satellite, LARES, in the list of satellites whose trajectory is analyzed from an operational point of view; tests must now be extended to the entire period over which LARES data are available (2012);
- The preparation of the preliminary tests with a view to the future realization of the ILRS contribution to the ITRF2020: this includes the restarting of the historical data processing chain (since 1983);
- The improvement in the level of precision of the GRGS Etalon satellite orbits, three times worse on average, for a reason not yet identified, than the LAGEOS orbits, while the other analysis centers do not observe this degradation (even if this proportionally concerns only an extremely small number of data).

Future plans: contribute again as a regular and reliable basis to the ILRS.

1. Contributing with an operational mode again: SP3c orbits of the geodetic satellite constellation, + snx files with EOP and SSCs
2. Contributing again to Pilots Projects of the ASC
3. Return to a full nominal mode as an official ILRS AC hosted @ Paris Obs

Planned developments :

- Solutions based as well as other geodetic satellites
- Optimization of the combination between different dynamical configurations
- Time series of degree 2 gravity field coefficients, on an operational point of view...
- Methodological activities concerning orbit modelling (non gravitational forces), range bias determination :(optimization of the decorrelation between estimated parameters),

AC Personnel

Figure 7-11. GRGS AC personnel (left to right): Florent Deleflie, Arnaud Pollet

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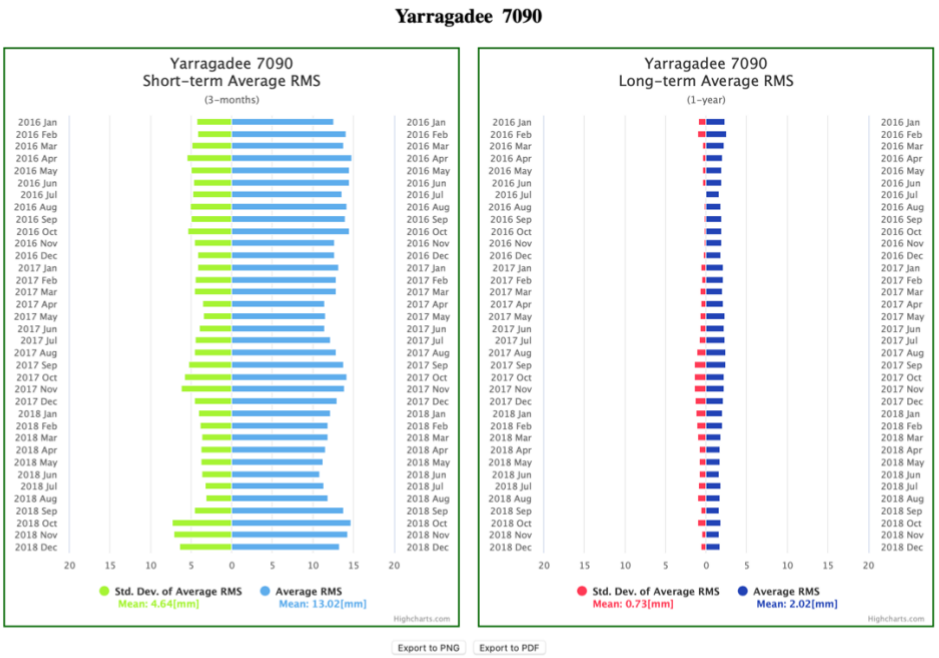
Areas of Interest

The JCET/GSFC AC is presently the coordinating AC for the activities of the ILRS ASC. JCET participated in all ASC-related ILRS activities during the period 2016-19. Our group focuses primarily on the analysis of SLR data from geodetic targets (e.g., the two LAGEOS, Etalons and LARES), to support the official ILRS products contributing to the IERS and ITRS.

Of equal importance though is our interest in controlling the quality of the tracking data and the official products. In that vein we run a quality control (QC) series on a daily basis and deliver online a report that characterizes on a pass-by-pass basis the data quality of all active tracking stations. The results, along with those from similar analyses at other ILRS ACs are available online for further examination and visualization over time, through our "QC Report" web portal (*http://geodesy.jcet.umbc.edu/ILRS_AWG_MONITORING/*). Additional tools, recently developed, will be described in the next section. JCET has a prime interest in the expansion of the geodetic constellation and this was first demonstrated with the joint proposal, design and exploitation of the LARES mission launched in 2012. Our collaboration with the Italian teams at Univ. of Roma "Sapienza", the Univ. of Salento and ASI (Agenzia Spaziale Italiana) resulted in a second accepted proposal for another mission, LARES-2, with a launch date set in the fall of 2020.



Average RMS: It is computed from the input QC RMS's from the individual ACs that contribute to these series
Std. Dev. of Average RMS: The statistical standard deviation of the "above" average RMS.

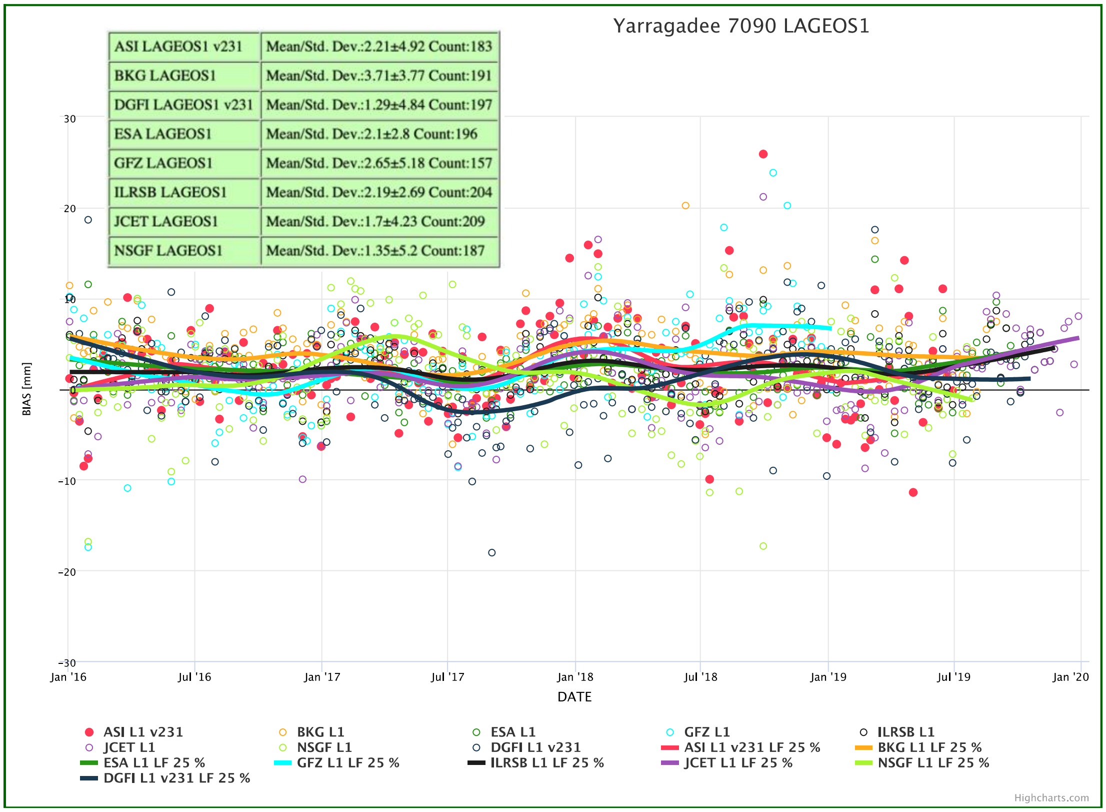
Figure 7-12. A visual display of Yarragadee's (7090) short-term and long-term performance from the corresponding Monthly Report Cards published in the ILRS website (https://ilrs.gsfc.nasa.gov/network/system_performance/global_report_cards/monthly/).

Recent Progress and Analysis Center Improvements

There has been a lot of activity since our last published report (ILRS AR 2009-2010) and given the fact a significant time elapsed between that and the current report, we have decided to provide the state of things as of now rather than at the end of 2019. This we hope will minimize the confusion between what readers will read about as accomplishments of that 4-year period and the information available online today.

During the reporting period, the most significant item that all ACs had worked on was the change in the approach the ASC handled systematic errors in the network. Over these four years a new approach was tested and perfected with numerous repetitions of a complete reanalysis of the SLR data from 1993 to date. During this time, JCET has also developed and implemented several modeling improvements in order to enhance the quality of the operational products of ILRS under the umbrella of the newly established "Quality Control Board—QCB" of the ILRS. One of these is the establishment of a data base with the complete set of ILRS Report Cards (Monthly and Quarterly) with the capability to visualize the results for a specific station over a selected time period (Figure 7-12) on our "ILRS Report Card" web portal (*http://geodesy.jcet.umbc.edu/ILRS_REPORT_CARD/index.php*).This allows to monitor the stability of the system through the average RMS from the contributing ACs and the agreement of these ACs via the Standard Deviation for each month.

MONITORING SYSTEMATIC ERRORS AT ILRS STATIONS

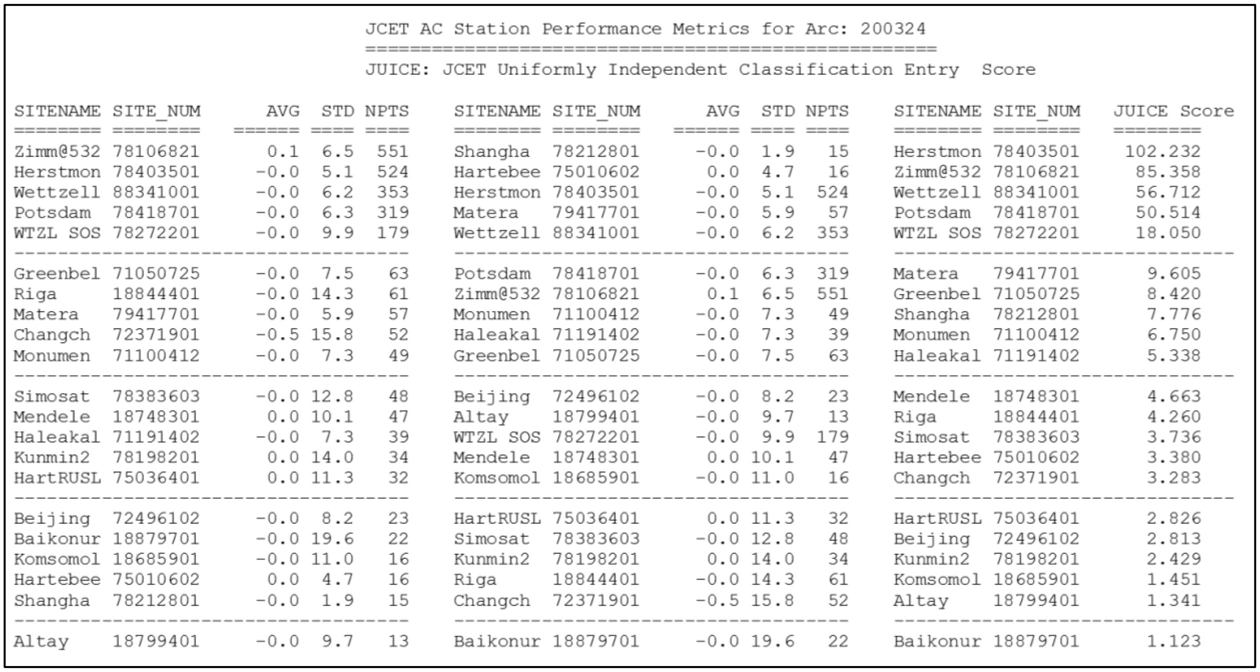


ASI LAGEOS1 v231	Mean/Std. Dev.:2.21±4.92 Count:183
BKG LAGEOS1	Mean/Std. Dev.:3.71±3.77 Count:191
DGFI LAGEOS1 v231	Mean/Std. Dev.:1.29±4.84 Count:197
ESA LAGEOS1	Mean/Std. Dev.:2.1±2.8 Count:196
GFZ LAGEOS1	Mean/Std. Dev.:2.65±5.18 Count:157
ILRSB LAGEOS1	Mean/Std. Dev.:2.19±2.69 Count:204
JCET LAGEOS1	Mean/Std. Dev.:1.7±4.23 Count:209
NSGF LAGEOS1	Mean/Std. Dev.:1.35±5.2 Count:187

Figure 7-13. A visual display of SSEM PP results for Yarragadee (7090) on LAGEOS over the period 2016-2019 from the seven contributing ACs and preliminary ILRS-B combination.

With the newly adopted approach in Station Systematic Error Monitoring—SSEM Pilot Project—PP came the need to be able to quickly examine compared results between the contributing ACs and CCs. We stablished a data base with the results from each cycle of analysis, including the combined series, which can be visualized for any group or single AC and over any period of time specified at *http://geodesy.jcet.umbc.edu/BIAS_v230_EDIT/*, to obtain a graphic with the individual weekly estimates and a smoothed curve for each of the contributing ACs (Figure 7-13). The JCET portal continues to provide access to previously established functions, e.g., the evaluation of the weekly and daily ASC products, that now include a concise table which encapsulates the results of the daily analysis of the previous 7-days' data, in terms of the highest number of collected NPs, the lowest noise level in the data and a JCET-established metric for scoring the system performance: the "JCET Uniformly Independent Classification Entry—JUICE" score (Table 7-3). This index rewards systems with low noise and high yield, the characteristics that matter the most in developing high quality products.

Table 7-3: Daily summary of the active ILRS stations tracking the two LAGEOS and two Etalons.



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                                    JCET AC Station Performance Metrics for Arc: 200324
                                    ===================================================
                                    JUICE: JCET Uniformly Independent Classification Entry  Score

SITENAME SITE_NUM     AVG  STD NPTS     SITENAME SITE_NUM     AVG  STD NPTS     SITENAME SITE_NUM    JUICE Score
======== ========   ====== ==== ====     ======== ========   ====== ==== ====     ======== ========    ========
Zimm@532 78106821     0.1  6.5  551     Shangha  78212801    -0.0  1.9   15     Herstmon 78403501     102.232
Herstmon 78403501    -0.0  5.1  524     Hartebee 75010602     0.0  4.7   16     Zimm@532 78106821      85.358
Wettzell 88341001    -0.0  6.2  353     Herstmon 78403501    -0.0  5.1  524     Wettzell 88341001      56.712
Potsdam  78418701    -0.0  6.3  319     Matera   79417701    -0.0  5.9   57     Potsdam  78418701      50.514
WTZL SOS 78272201    -0.0  9.9  179     Wettzell 88341001    -0.0  6.2  353     WTZL SOS 78272201      18.050
------------------------------------     ------------------------------------     --------------------------------
Greenbel 71050725    -0.0  7.5   63     Potsdam  78418701    -0.0  6.3  319     Matera   79417701       9.605
Riga     18844401    -0.0 14.3   61     Zimm@532 78106821     0.1  6.5  551     Greenbel 71050725       8.420
Matera   79417701    -0.0  5.9   57     Monumen  71100412    -0.0  7.3   49     Shangha  78212801       7.776
Changch  72371901    -0.5 15.8   52     Haleakal 71191402    -0.0  7.3   39     Monumen  71100412       6.750
Monumen  71100412    -0.0  7.3   49     Greenbel 71050725    -0.0  7.5   63     Haleakal 71191402       5.338
------------------------------------     ------------------------------------     --------------------------------
Simosat  78383603    -0.0 12.8   48     Beijing  72496102    -0.0  8.2   23     Mendele  18748301       4.663
Mendele  18748301     0.0 10.1   47     Altay    18799401    -0.0  9.7   13     Riga     18844401       4.260
Haleakal 71191402    -0.0  7.3   39     WTZL SOS 78272201    -0.0  9.9  179     Simosat  78383603       3.736
Kunmin2  78198201     0.0 14.0   34     Mendele  18748301     0.0 10.1   47     Hartebee 75010602       3.380
HartRUSL 75036401     0.0 11.3   32     Komsomol 18685901    -0.0 11.0   16     Changch  72371901       3.283
------------------------------------     ------------------------------------     --------------------------------
Beijing  72496102    -0.0  8.2   23     HartRUSL 75036401     0.0 11.3   32     HartRUSL 75036401       2.826
Baikonur 18879701    -0.0 19.6   22     Simosat  78383603    -0.0 12.8   48     Beijing  72496102       2.813
Komsomol 18685901    -0.0 11.0   16     Kunmin2  78198201     0.0 14.0   34     Kunmin2  78198201       2.429
Hartebee 75010602     0.0  4.7   16     Riga     18844401    -0.0 14.3   61     Komsomol 18685901       1.451
Shangha  78212801    -0.0  1.9   15     Changch  72371901    -0.5 15.8   52     Altay    18799401       1.341
------------------------------------     ------------------------------------     --------------------------------
Altay    18799401    -0.0  9.7   13     Baikonur 18879701    -0.0 19.6   22     Baikonur 18879701       1.123
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Technical Challenges

During the period 2016-2019 the ILRS ASC co-chairs undertook the editorship of a special issue of the Journal of Geodesy dedicated to Laser Ranging. Due to the great interest in the community to publish their work in such an issue, the editorial board was expanded to include two additional members so that the heavy load of the review process could be handled efficiently. The work was to be completed before the end of 2018, however, with several manuscripts still in the review process, an extension till the end of February 2019 was unavoidable. The twenty accepted articles were published online throughout the review process, the finished issue however was physically published in November 2019 [Pavlis, Luceri, Otsubo and Schreiber (eds.), 2019]. This is the second special issue on Laser Ranging, twenty years after the previous one published in 2001.

After receiving from ITRS the call for participation for the development of ITRF2020 in late 2018, we started planning the steps to be followed by the ILRS ASC, based on a timeline that expects the final contribution from all participating IAG Services by the end of February 2021. The challenges we are facing are several, the most important being the successful completion of the SSEM PP since the results will be used for ITRF2020 development. Additionally, we must incorporate the LARES data in the new model, a process that requires increasing the complication of our modeling due to its lower orbital altitude and higher sensitivity to gravitational perturbations. A PP was planned to ensure that all ACs are contributing consistent solutions of comparable accuracy. As a necessary by-product, the ASC will also deliver a weekly-averaged set of low-degree spherical harmonics of the static gravitational field.

Our AC is responsible for the validation and qualification of new SLR systems or existing ones that return to operations after significant down times for various reasons. As the ILRS community is deploying new systems at increasingly faster pace and placing systems in quarantine after more frequent upgrades and modernization, we are facing a task that will require increasing effort and resources. One possible solution is the use of data from additional targets, beyond those contributing to ITRF, to speed up the period of testing. This will require extension of our analysis series to include these low-altitude orbits that require more specialized modeling. We are currently investigating the automation of such analyses on a regular basis.

Future Plans

Based on the ASC plan for participation in the development of ITRF2020, next year (2020) will be devoted in the finalization of the SSEM PP model following the implementation of a new model for the target signature of the geodetic spheres, tailored to each of the active ILRS systems. The need for this improvement became evident after the initial results of the SSEM PP, where it was very clear that the freely estimated biases of the most prolific systems were systematically positive. At this time (early 2020), the implementation of a revised model released in November 2019 resulted in a much more random behavior of the systematics and an overall diminishing of the magnitude of individual stations' biases.

In the coming year the new approach developed under the SSEM PP will become the standard approach in the development of our official products which will require the development of an automated procedure in detecting significant changes in the long-term systematics of each active station in the ILRS network. We have been testing various possibilities and we will implement the one that yields the most reliable results in order to minimize the "false alarms" which can cause confusion in the analysis and undue mitigation efforts at the affected stations. Once we have detected systematics that the stations cannot rationalize and correct, we will include them along with their statistics in the new public version of the ILRS Data Handling file, for users to consider.

The U.S. Naval Observatory hosts IERS' Rapid Service/Prediction Center (RS/PC) for Earth Orientation (NEOS), that in turn uses the ILRS ASC daily EOP products in their forecasting algorithm. They have always required an EOP product that is available as soon as possible and with as high accuracy as possible. We are planning to initiate a series that will include as many SLR targets from LEO to GNSS altitude, to generate such a product on a regular basis. Initial tests with increased Etalon tracking during a 3-month campaign, indicated that this is a viable approach. We are looking at organizing a PP for this service sometime in 2020.

AC Personnel

Figure 7-14. JCET/GSFC AC personnel (left to right): Erricos Pavlis, Magdalena Kuzmicz-Cieslak, and Keith Evans.

Prof. Dr. Erricos C. Pavlis (AC head and ILRS ASC co-chair, member ILRS CB, GB, QCB and MSC), Dr. Magdalena Kuzmicz-Cieslak (AC and ASC member, in charge of daily/weekly data analysis and webmaster), and Mr. Keith Evans (AC and ASC member, in charge of daily/weekly combination of AC solutions and data base management and maintenance).

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NSGF (NERC Space Geodesy Facility), UK

Authors: *José Rodríguez, Graham Appleby*
Responsible Agency: British Geological Survey

Areas of Interest

As required from all official ILRS ACs, NSGF provides orbital dynamics solutions (daily and weekly series), estimating station coordinates at mid-arc epochs, daily EOP (pole coordinates and length of day), dynamic parameters and state vectors. The results are generated in SINEX format and uploaded daily to the two ILRS data centers. Additionally, orbit predictions for a range of satellites tracked by the ILRS network are provided as a backup service to the community.

Beyond the delivery of routine products, NSGF has been involved in two main areas: a) research on the identification and mitigation of systematic errors in the SLR technique; b) the determination of centre of mass corrections (CoM) for SLR geodetic satellites. As a result of these efforts, NSGF has made significant contributions in the field of SLR analysis: prompting the ILRS Analysis Standing Committee to develop a new product based on the estimation of systematic errors along with station coordinates; providing newly computed CoM values for all stations of the network based on models we developed. Results relating to these areas have been published, presented at numerous venues, and made available to the community.

Key results:

- Systematic errors in the SLR technique are responsible for ~50% of the scale difference between the VLBI and SLR networks (~1.37 ppb in ITRF2014)
- Estimation of range biases simultaneously with coordinates for all stations of the network is feasible and offers a bias-free product (long-term, accuracy/noise trade-off)
- Pilot Project on systematic errors prompted from these results nearing completion in 2019 (initial plan devised by NSGF and DGFI). It will be the basis for the ILRS reanalysis for the next realization of the ITRF (planned for 2020)
- New/updated models developed for the computation of CoM offsets for geodetic satellites Starlette, LAGEOS-1/2, Ajisai, Etalon-1/2, and LARES
- Models take into account more aspects of the laser ranging measurement than ever before, modeling explicitly for the first time, stations operating at the multi-photon level of detection
- CoM inaccuracies responsible for some of the range biases estimated for many tracking stations
- New estimation of the geocentric gravitational constant, GM, using state of the art modelling including newest CoM values, agrees with currently established standard with much reduced statistical uncertainty
- New CoM values computed for all stations of the network whose coordinates contribute to the ITRF since 1983. Software provided to interrogate the tables

Recent Progress and Analysis Center Improvements

The software employed to provide routine products has been migrated to the setup employed for the generation of the reanalysis for ITRF2014. This branch was developed in parallel to the stable one, and received many updates to modernize parts of the code, to implement new or more up-to-date models as required, and to introduce new features as these were developed. The code used for the routine products is kept in a frozen state, only receiving updates when strictly necessary (e.g., bugfixes), or when changes do not affect the daily/weekly results (e.g., unrelated features to these solution types). The development version is continuously updated to meet the requirements of the various pilot projects planned within the ILRS ASC, as well as for research purposes.

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AC Personnel

- Graham Appleby (BGS Honorary Research Associate, Herstmonceux, since June 2019)
- José Rodríguez (at Yebes Observatory, Spain, since 2020)

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ILRS Combination Centers

ILRS Combination Centers retrieve the solution files produced by the ILRS Analysis Centers, using them as input to produce the official, and final, ILRS combined products (station positions, velocities, EOP, and orbits). These solutions are designated “ILRS A”, produced by the ILRS primary combination center (Italian Space Agency/ASI, Matera, Italy), and “ILRS B”, produced by the ILRS backup combination center (NASA GSFC/University of Maryland Baltimore County (UMBC) Joint Center for Earth Systems Technology (JCET), Greenbelt MD, USA).

Table 7-4. ILRS Combination Centers (CCs)

Code	AC Title and Supporting Agency
ILRSA	ILRS primary Combination Center, Italian Space Agency, Centro di Geodesia Spaziale "G. Colombo" (ASI/CGS), Italy
ILRSB	ILRS backup Combination Center, Joint Center for Earth Systems Technology/Goddard Space Flight Center (JCET/GSFC), USA

ASI/CGS (Agenzia Spaziale Italiana, Centro di Geodesia Spaziale "G. Colombo") ILRS Primary Combination Center

Authors: *G. Bianco (ASI), V. Luceri (e-GEOS S.p.A.)*
Responsible Agency: Italian Space Agency/Space Geodesy Center “G. Colombo”

Areas of Interest

The ASI Space Geodesy Center "G. Colombo" (ASI/CGS) is the Primary ILRS Combination Center since 2004 when it was selected for the combination of the ILRS products, currently: station coordinates, Earth Orientation Parameters, satellite orbits, station range biases. ASI/CGS is a Fundamental Station of the geodetic network, hosting three permanent Space Geodetic systems (SLR, VLBI, GNSS, absolute gravimeter) and, due to the multi-technique nature of the CGS mission, space geodetic technique combination methods and applications are a top priority objective of the data analysis activities. Besides the single-technique data analysis as Analysis Center (AC), ASI/CGS is involved in combination activities aiming to provide specific products and as well as to test combination methodologies.

The ILRS combined solutions for coordinates and EOPs are obtained using the SW COGEOS developed internally and routinely maintained in order to address the requirements of the ILRS Analysis Standing Committee (ASC). The combination methodology relies on the direct combination of loosely constrained solutions; this straightforward method (e.g., “Methodology for global geodetic time series estimation: A new tool for geodynamics”, P. Davies and G. Blewitt, JGR, vol. 105, no. B5, pages 11083–11100, May 10, 2000) allows handling input solutions easily. The reference frame is defined stochastically and is unknown; no relative rotation between the reference frames is estimated and removed.

Information on the CGS and some of the analysis results are available at the CGS website GeoDAF (Geodetic Data Archiving Facility, *http://geodaf.mt.asi.it*).

Recent Progress and Analysis Center Improvements

In the 4 years 2016-2019, the ASI/CGS has been deeply involved in the ILRS activities, mainly in support of the reference frame maintenance and under the coordination of the ILRS ASC. The ASI CC contributions as ILRS Combination Center are listed hereafter:

- ILRS Routine Products:
    - daily submission of the ILRS official solution (ILRSA) computed using the individual AC parameter estimates based on the analysis of observations to LAGEOS-1, -2 and Etalon-1, -2 satellites over a 7-day arc. The ILRSA solutions contain weekly coordinates of the worldwide SLR tracking network and daily EOPs (x-pole, y-pole, LOD) and it is loosely constrained. A separate daily EOP product is derived from the previous one and constrained to ITRF, it is the ILRS contribution to EOPC04.
    - weekly submission of the combined coordinate/EOP solutions computed using the individual AC contribution based on the observations to LAGEOS-1, -2 and Etalon-1, -2 satellites. This product is similar to the daily official product but has a larger latency and is often used as benchmark.
    - weekly orbits obtained combining the state vectors of the four satellites, LAGEOS and Etalon, estimated by the ILRS ACs. They are available in the ITRF reference frame.
    - Periodic evaluation of the submitted official products are presented at the ILRS ASC meetings to support ACs data analysis activities. The CC is always ready to support the ACs whenever anomalies arise in the submitted solutions or new models are implemented.
    - Geocenter motion: the ILRS SLR time series plays a fundamental role in the definition of the ITRF origin. The geocenter motion is routinely computed applying the Helmert transformation

from the loosely constrained solutions to the ITRF. The figure below is an example of the X translation to ITRF2014.

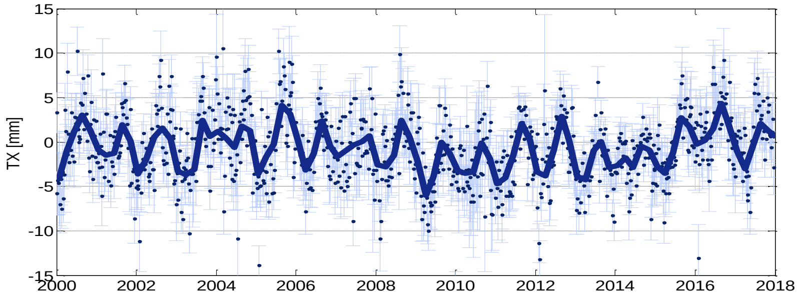

Figure 7-15. X component of the geocenter motion.

- IITRF realization
  The ILRS CC has a fundamental role in the realization of a new ITRF. It is in charge of the delivery of the official ILRS contribution to the reference frame and works on the verification of the ITRF once it is delivered. ITRF2014 was delivered at the beginning of 2016 and tests were performed before adopting the ITRF in the official products mostly due to the implementation of the new post seismic deformation model. Preparation of the next ITRF2020 is underway.
- ILRS Systematic error Pilot Project
  The ILRS ASC established in 2016 a pilot project on the station systematic errors with the aim to recover potential bias directly from the data. The single AC solutions, now including site coordinates, EOP and biases, were combined to obtain a time series of range bias for each single station. The SW COGEOS was modified to include the new parameters into a rigorous combination process. The pilot project proved that this analysis strategy can recover real biases and the agreement among the ACs is generally within the uncertainty of the estimates, except in a few cases usually involving stations with poor or sparse data records. The impact of the approach on the reference frame was investigated by looking at the translations and scale of the loosely constrained combined time series with respect to ITRF2014. More details on the argument are described in the ASC report in this volume and in the paper “Systematic errors in SLR data and their impact on the ILRS products” (V. Luceri et al.) of the special SLR issue Journal of Geodesy (2019).

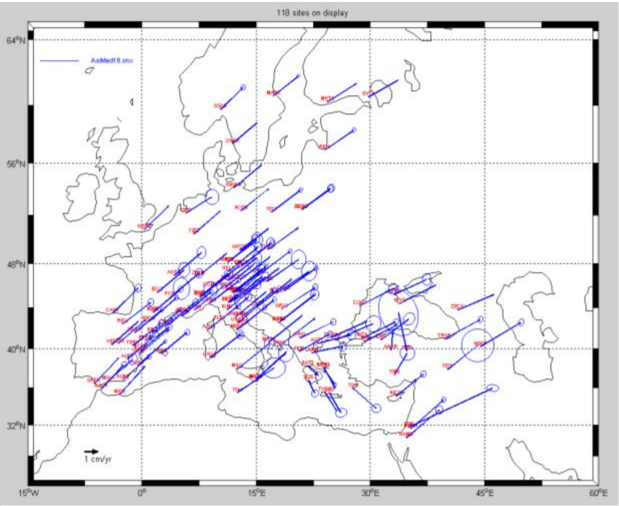

Figure 7-16. The ASIMed velocity field.

Moreover, ASI/CGS in involved in geodetic solution combination: realization, implementation and testing of combination algorithms for the optimal merging of global inter- and intra-technique solutions and of regional (e.g., Mediterranean) solutions to densify tectonic information in crucial areas.

Once a year, ASI/CGS produces a combined velocity solution for the Mediterranean area using its original single-technique velocity solutions (SLR, VLBI and GPS) that cover the whole data span acquired by the three co-located systems from the beginning of acquisitions in Matera. The ASIMed solution gives a detailed picture of the velocity field in the area, profiting of the dense permanent GPS coverage.

Technical Challenges and Future Plans

The next two years will be mainly focused in the preparation of ITRF2020. Work is already in progress and the first step will be the completion of the pilot project on station systematic errors. ASI/CGS is in charge to compute the output of the PP that will be a new error model, i.e., a new data handling file with the list of bias to be used by the ACs to prepare their solution time series.

After the conclusion of the PP, the ASI/CGS combination activities will continue with the evaluation of each loosely constrained solutions provided by the official ILRS ACs (ASI, BKG, DGFI, ESA, GFZ, GRGS, JCET, NSGF) and then their direct combination.

Some of the goals for the work to be done in the near future are the same of the ILRS ASC since all the new features in the solutions are new features to address in the combined product:

- Estimation of low-degree SH of the gravity field
- Inclusion of LARES as a 5th satellite in the operational product
- Plan for the expansion of the target used in operational products
- Pilot project on NT Atm. Loading and Gravity.

CC/AC/AAC/LAAC Personnel

The Italian Space Agency is the owner of the Space Geodesy Center and is the decision-making body, Giuseppe Bianco, director of the ASI/CGS, is the ASI manager of the Combination Center. The activities of the Combination Center are performed by e-GEOS S.p.A. (formerly Telespazio) since the very beginning in the 80's. The team is composed by six people involved in SLR, VLBI and GNSS data analysis. The SLR data analysis is coordinated by Vincenza Luceri.

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JCET/GSFC (Joint Center for Earth Systems Technology/Goddard Space Flight Center) ILRS Backup Combination Center (ILRSB)

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Areas of Interest

JCET hosts the back-up ILRS Combination Center (CC) since December 2010. The purpose of the back-up CC is to ensure that there is always a combined product generated and available online; furthermore, the comparison of the official and back-up combinations can verify the quality and consistency of the ILRS products. Although both CCs use the same AC-provided solutions as input, the combination approach followed by each CC is independent and slightly different in practice. The official product ILRS-A uses directly the solution vectors from each AC product and through a weighted approach that is based on the AC-provided covariances, the combined solution ILRS-A is generated as their weighted mean. In contrast, the back-up combined solution ILRS-B is obtained from a formal Least Squares adjustment, where the input is the Normal Equations (NEQs) obtained from the loosely constrained covariances after their inversion and subtraction of the known loose *a priori* constraints. In both cases the weighting of the input solutions is based on Variance Component Estimation (VCE).

Over the period covered in this report the seven ACs that actively contributed to the ILRS combined products were: ASI, BKG, DGFI, ESA, GFZ, JCET and NSGF. In general, the contributions were received on time daily, as Figure 7-17 attests.

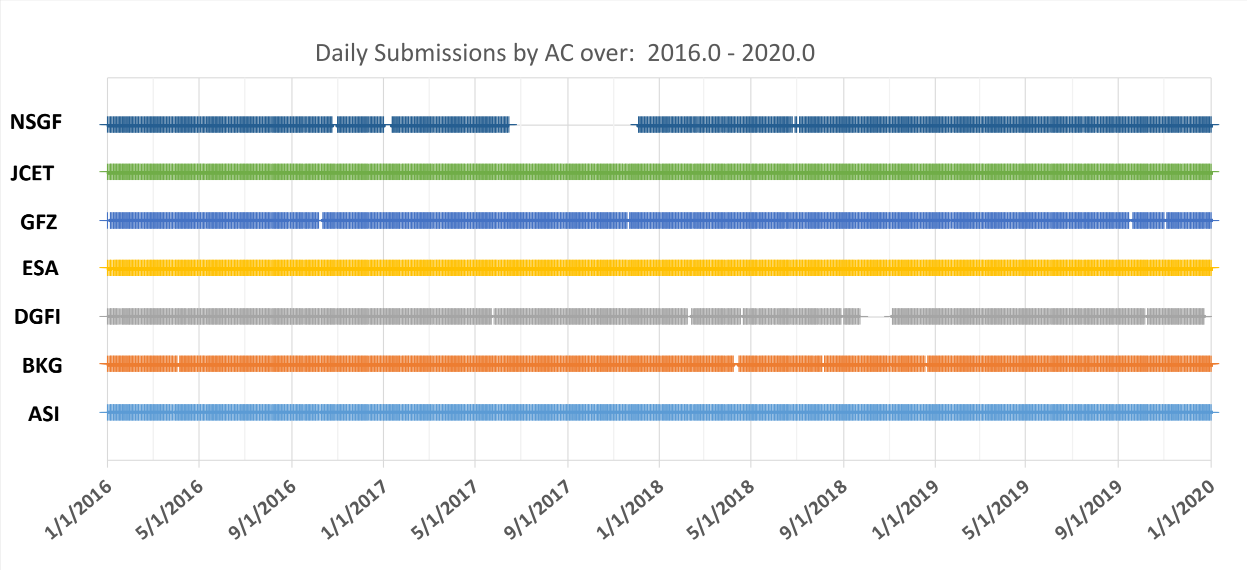

Figure 7-17. Record of the daily AC submissions to be combined at JCET CC over the reporting period.

The results of the ILRSB combination (as well as those of the official ILRSA combination) are uploaded daily online for further examination and intercomparison via our JCET Portal (*http://geodesy.jcet.umbc.edu/ILRS_AWG_MONITORING/*). If you select the 1st option “Weekly Station Positions & Daily EOP Series”, then you can access and graph the evolution of any station’s position component in Cartesian or local coordinates from ITRF2014/SLRF2014 and the daily EOP offsets from IERS Bulletin A series. Selecting the 3rd option “Evaluation of Weekly ASC Products” you can access and graph the results of the official (Daily) and previous version (Weekly) combinations, including the individual AC contributions to these combinations.

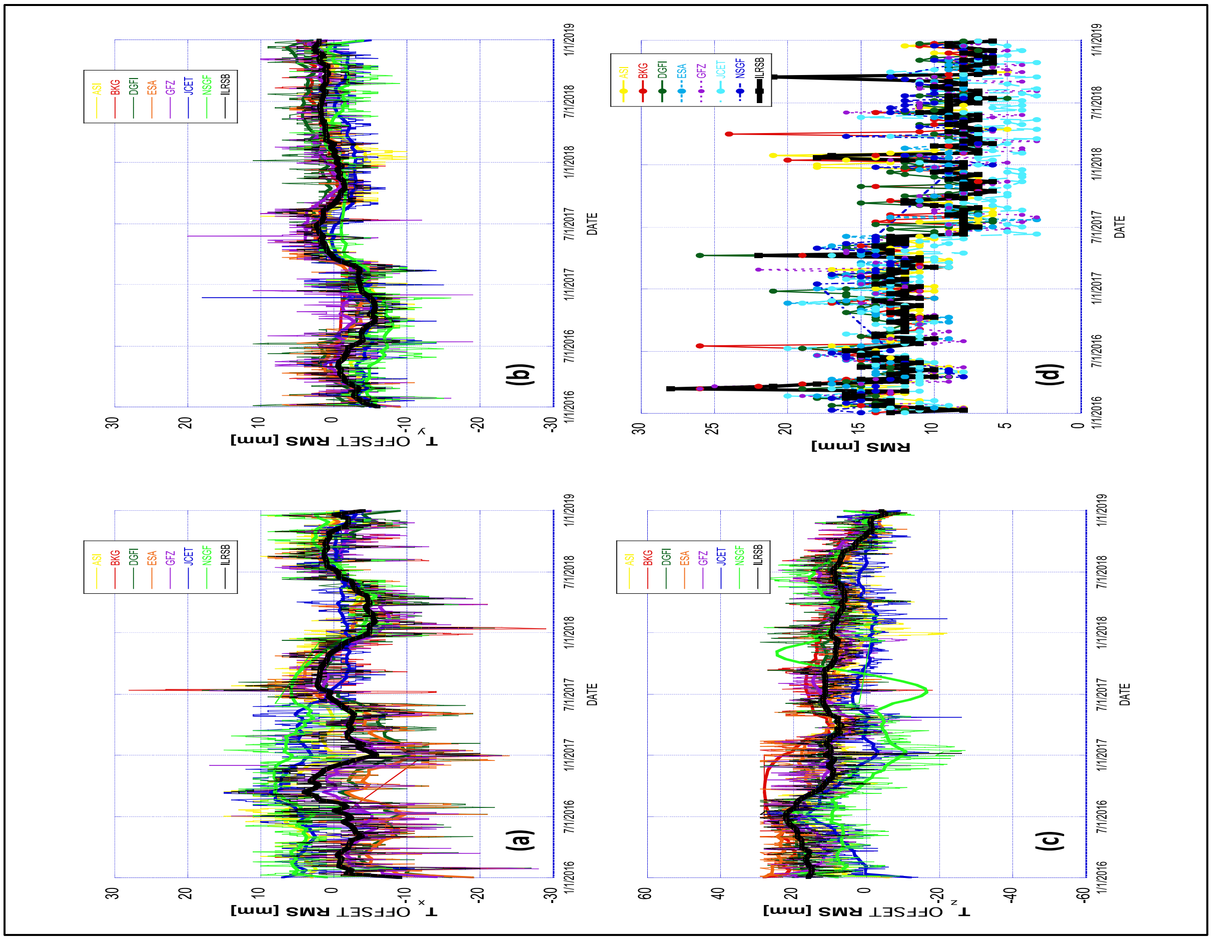

Figure 7-18. Daily TRF origin offsets from that of ITRF2014/SLRF2014 for each AC submission and the JCET CC combination ILRSB (a through c), and the Core Site RMS after the combination (d) over 2016-2019. Note the significant drop in RMS after the adoption of ITRF2014 (07/01/17).

Recent Progress and CC Improvements

The completion of the ITRF2014 model in late 2015 required the subsequent adoption of the new model as the a priori standard for all official ILRS applications. This step was delayed considerably due to the delayed release of the associated EOP series, IERS 14 C04, which for consistency, would have to be used in association with ITRF2014. The ILRS ASC switched to ITRF2014 on July 1, 2017, following the resolution of frequent and undocumented updates of the public version of the IERS C04 series. By that time, we had created an extension of ITRF2014, including a number of SLR sites that were not present in the official release in a similar fashion as it was done with ITRF2008. The resulting expanded model is called SLRF2014 and it is in the ITRF2014 frame by construction.

Related to the IERS EOP series delayed release was also the confusing situation with the IERS Mean Pole (MP) that was to be used by all Services. In 2015 IERS had released a Fortran routine (IERS_CMP_2015.f) that generated the MP position on a requested date. To overcome the unavailability of the extended MP series we generated an extension of the original routine using a linear prediction up to 2021 and delivered the new routine (ILRS_CMP_2016.f) to the ASC for use. Eventually, at the 2017 Unified Analysis Workshop the proper MP definition and modeling was addressed, and an entirely new and simplified model was adopted by the IERS at the end of the year. The old MP terminology was replaced with the "linear mean pole" and linear formula that will be valid for several decades, based on a linear fit to IERS C01. The new model will be used in the development of ITRF2020.

Technical Challenges

The ILRS ASC decision to change the approach of treating systematic errors at the tracking stations in late 2015 resulted in a cycle of repeated reanalyzes of the SLR data for 1993 to present. Initially as a test over a 4-year period (2005-2008) was performed. Based on the results of this PP the ILRS ASC embarked on tests to perfect the new approach. Eventually, it was agreed that a separate bias would be solved for each of the two LAGEOS, but for the Etalons only a combined one due to the poorer and sparser NP data set. The adoption of the new approach caused several reanalysis cycles due to numerous concurrent modifications of the "target signature model" (aka CoM model). Each of these reanalyzes required a subsequent combination of the individual AC series to produce the combined official and back-up product. In order to facilitate a quick and easy comparison of the results, JCET uploaded the individual AC-estimated biases as well as the combined results on an online data base accessed through the JCET Portal from the "Systematic Error Monitoring Project" (*http://geodesy.jcet.umbc.edu/ILRS_AWG_MONITORING/*) option.

The combination results for the two LAGEOS satellites were used to form the weighted mean for each site, over its period of contribution to the combination. This long-term mean bias is not for use in modeling the systematics at the stations but rather to quickly categorize the stations according to how serious or not their systematics are. We arbitrarily set ±10 mm as a boundary of the two predominant groups of stations, with the majority of the strong stations having bias magnitudes of less than 10 mm and the less capable sites significantly larger than 10 mm.

When this graphic categorization was first done with the 2018 combination, it became apparent that the preponderance of biases was positive, with very little difference between the two LAGEOS targets for most systems. This systematic behavior of the biases in a network of very diverse technology, mode of operations, observing crews, etc., could only be explained by a common model error for the majority of the stations: the adopted CoM model that was several years old and based on system information that were by that time fairly old and inaccurate due to the constant system upgrades and changes in the network, which do not usually get recorded in the stations' site log at the same time as they occur. This actually proved to be very true and in 2017 a revision of the model was undertaken by the group of experts led by the NERC AC. This eventually resulted in a new model which was since updated several times, the last one being November of 2019 (*public version*). The differences of the two models are reflected in the change of behavior of the long-term biases of the network, as displayed in Figures 7-19(a) and 3(b).

The next step to complete the SSEM PP is the identification of the change of persistent biases at each site and the computation of the mean value over each period, along with its accuracy estimate. Once this is accomplished the mean biases can be used *a priori* in the re-analysis for the development of ITRF2020. Over the other periods with less systematic bias behavior or stations with completely erratic bias behavior, can be still included in the analysis, however, a weekly bias estimation will be necessary to avoid the introduction of systematics in the product.

Future Plans

The plans for the 2020-2021 period are very much set in stone after our acceptance to participate in the development of ITRF2020. The first year 2020 will be devoted to the finalization of the SSEM bias model and the tests for the introduction of LARES in the final combined product. During 2020 the remaining ancillary models will also be finalized and distributed to the ACs for use in the re-analysis for the ITRF2020. The majority of the ILRS contribution can be completed within 2020, including the combination of the individual AC contributions. It is anticipated that the ASC will switch in 2020 their mode of production to the same standards as those adopted for the re-analysis. This will result in a seamless transition from the reprocessing to the operational products which will at that point be perfectly compatible with the re-analyzed version.

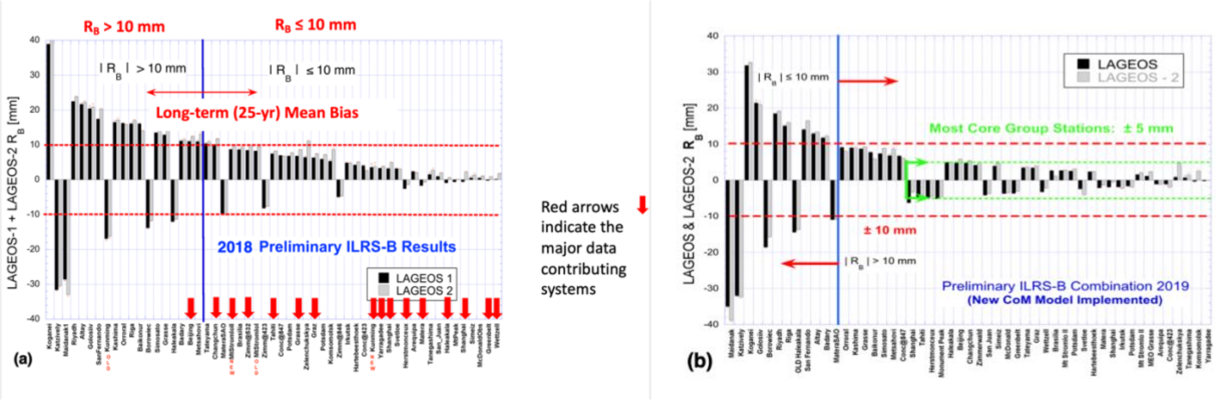

Figure 7-19. Results of the SSEM PP: Long-term bias estimates for the ILRS network (25-yr averages) based on the old CoM model (a) and after the recent adoption of the new CoM model (b). The Core sites now have biases bound by ±5 mm; the increasingly random behavior of these estimates is of note. Overall, large biases are associated with the less capable and low yield systems.

As we approach the end of 2020, the entire 2020 SLR data set will need to be re-analyzed one last time, to benefit from improved ("final") values of the IERS C04 EOP series, and this version will comprise the products to be submitted for generation of ITRF2020. The last couple of months of 2020 should be redone just before the submission to ITRS for the same reason, since IERS C04 is about two months in arears in finalizing its values. Once the entire set of weekly SINEXs is submitted to ITRS, we will work in coordination with the ASI CC (ILRSA) and ITRS to address issues that they will likely encounter with the ILRS submission and ensure the full resolution of each one of them. Upon release of ITRF2020, the ILRS CCs will organize and coordinate the evaluation of the new model, and eventually its implementation within the ILRS.

CC Personnel

Prof. Dr. Erricos C. Pavlis (CC head and ILRS ASC co-chair, member ILRS CB, GB, QCB and MSC), Dr. Magdalena Kuzmicz-Cieslak (CC and ASC member, in charge of daily/weekly data analysis and webmaster), and Mr. Keith Evans (CC and ASC member, in charge of daily/weekly combination of AC solutions and data base management and maintenance).

Figure 7-20. JCET/GSFC CC personnel (left to right): Erricos Pavlis, Magdalena Kuzmicz-Cieslak, and Keith Evans.

Publications

Please refer to the Presentations and Publications under the JCET AC Section.

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ILRS Associate Analysis Centers

Associate Analysis Centers are organizations that produce special products, such as satellite predictions, time bias information, precise orbits for special-purpose satellites, station coordinates and velocities within a certain geographic region, or scientific data products of a mission-specific nature. Table 7-5 lists the current ILRS AACs.

Table 7-5. ILRS Associate Analysis Centers (AACs)

AAC Title and Supporting Agency
Austrian Academy of Sciences, Austria
Center for Orbit Determination in Europe (CODE) Switzerland
Center for Space Research (CSR), University of Texas, Texas, USA
Central Laboratory for Geodesy (CLG), Bulgaria
Delft Institute for Earth Oriented Space Research (DEOS), The Netherlands
Groupe de Recherche en Géodésie Spatiale (GRGS), France
Hitotsubashi University, Japan
Institute of Applied Astronomy, Russian Academy of Sciences, Russia
Institute of Astronomy, Moscow, Russia
Institute for Space Astrophysics and Planetology (IAPS)/National Institute for Astrophysics (INAF) and INFN-Roma2, Italy
Korea Astronomy and Space Science Institute (KASI), South Korea
Main Astronomical Observatory of the National Academy of Sciences of Ukraine (GAOUA), Ukraine
Newcastle University, United Kingdom
Norwegian Mapping Authority (Kartverket), Norway
Pulkovo EOP and Reference Systems Analysis Center (PERSAC), Russia
Russian Metrological Institute of Technical Physics and Radio Engineering (VNIIFTRI), Russia
Russian Mission Control Centre, Russia
Shanghai Astronomical Observatory (SHAO), China
Tsukuba Space Center/JAXA, Japan
Wroclaw University of Environmental and Life Sciences (WUELS), Institute of Geodesy and Geoinformatics (IGG), Poland

CODE (Center for Orbit Determination in Europe), Switzerland

Author: Ulrich Meyer
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Areas of Interest in the frame of ILRS

The Center for Orbit Determination in Europe (CODE) is a joint venture of the Astronomical Institute of the University of Bern (AIUB), the Swiss Federal Office of Topography (swisstopo), the Federal Agency of Cartography and Geodesy of Germany (BKG) and the Institute of Astronomical and Physical Geodesy of the Technische Universität München (IAPG/TUM). The activities as an Associated Analysis Center of the ILRS are located at AIUB.

CODE acts as an Analysis Center of the International GNSS Service (IGS; Johnston et al, 2017)). Since 2003, a rigorous combined analysis of the GPS and GLONASS microwave measurements is carried out for the final, rapid and ultra-rapid product line of the IGS. From the combined GPS/GLONASS rapid orbits predictions for those satellites tracked by the ILRS are derived and provided to the ILRS.

The IGS is running the MGEX (multi-GNSS extension; Montenbruck et al, 2017) as a pilot project in order to incorporate the new GNSS (like Galileo, BeiDou, QZSS, and NAVIC) and new signals from the established systems into the operational processing. CODE is contributing to this initiative with a five-system solution containing GPS, GLONASS, Galileo, BeiDou, and QZSS for orbits, clocks and related biases (Prange et al, 2016).

CODE provides daily SLR quick-look reports based on all SLR observations to all GNSS satellites carrying retroreflectors from the last six days. Residuals to the SLR observations are computed based on the GNSS microwave–derived orbits and Earth rotation parameters (ERPs) determined at CODE for the IGS. The reports contain the mean, RMS and number of and are distributed daily via e-mail.

Further SLR-based analysis activities

AIUB has also been involved in the orbit determination of a number of Earth observation satellites in low Earth orbits (LEOs) like CHAMP, GRACE, GOCE and Swarm, and has derived static or monthly gravity field solutions that are determined in an extended orbit determination procedure applying the Celestial Mechanics Approach (CMA) developed at AIUB. In recent years the gravity field determination has been extended to the LAGEOS satellites and the SLR-LEOs Starlette, Stella, AJISAI, Larets, LARES and Beacon-C (Sośnica et al, 2015).

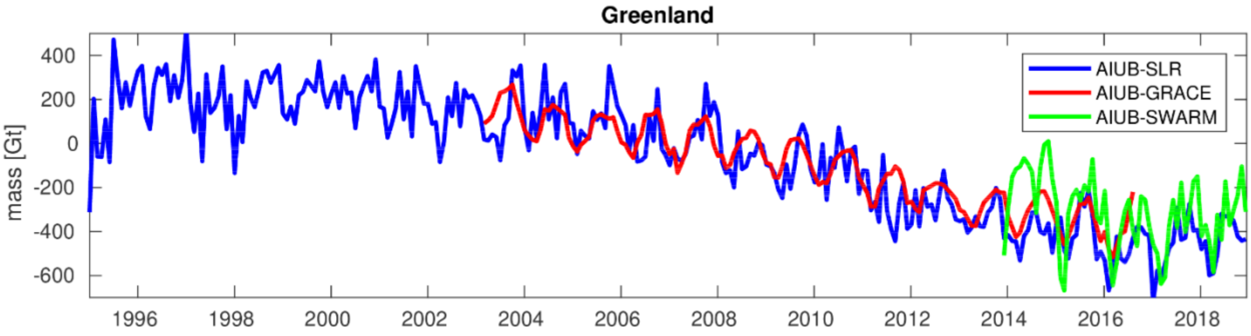

Figure 7-21. Mass change in Greenland derived from monthly SLR, GRACE or Swarm gravity fields (truncated at spherical harmonics degree and order 6).

AIUB had the leading role in the Horizon 2020 project European gravity field service for improved emergency management (EGSIEM; Jäggi et al, 2019). In the frame of this project a prototype scientific combination service for monthly GRACE gravity fields has been developed. Weighted combinations were performed on the solution (Jean et al, 2018) and on the normal equation level (Meyer et al, 2019a) and the latter approach was extended to combinations with SLR-derived gravity field models. The combination service is continued as COST-G, a product center of the International Gravity Field Service (IGFS) under the umbrella of the International Association of Geodesy (IAG).

Recent Progress and Analysis Center Improvements

Lately, SLR and Swarm gravity field combinations on the normal equation level have been studied to derive mass change estimates in areas of major ice melt in Greenland and Antarctica with the goal of bridging the gap between the GRACE and GRACE-FO missions (Meyer et al, 2019b).

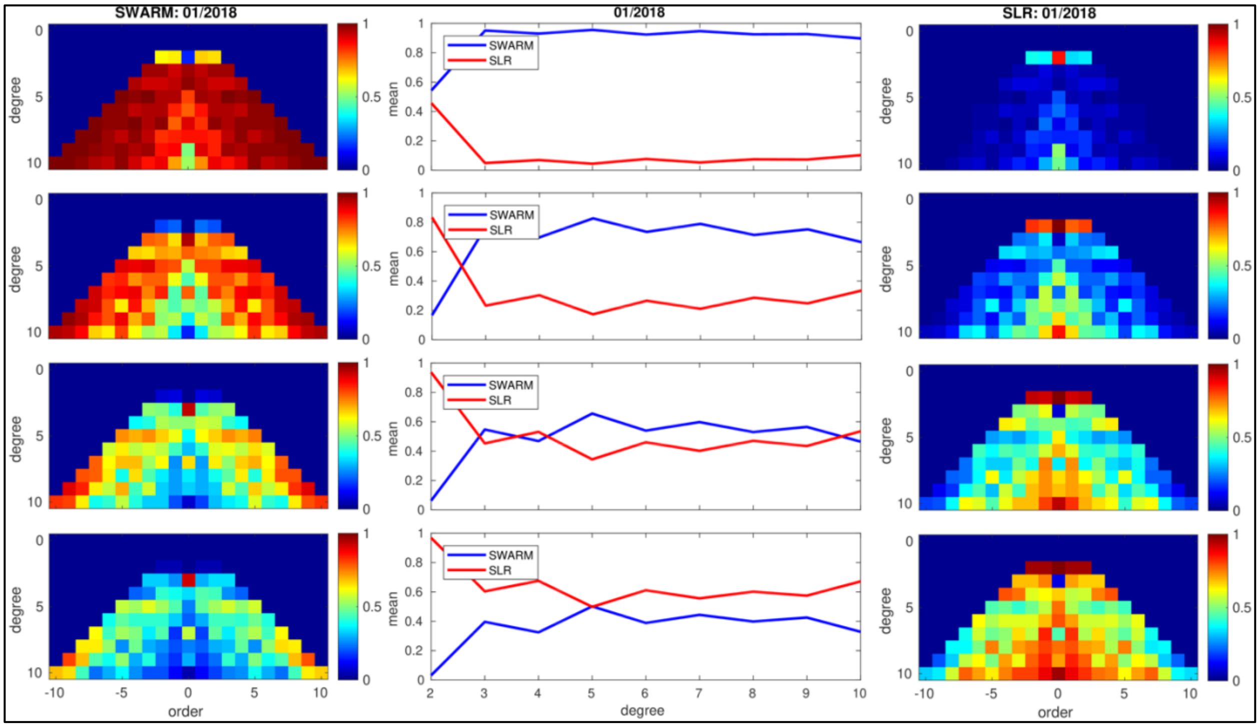

Figure 7-22. Contribution per spherical harmonic coefficient of Swarm (left) or SLR (right) in case of relative weights 100:1 (top), 10:1, 4:1, or 1:1 (bottom) of the Swarm or SLR normal equations in the combination.

In collaboration with BKG it is further planned to extend the COST-G combination service to SLR derived monthly gravity fields of different Analysis Centers (ACs).

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Introduction

In addition to contributing to the SLR data acquisition through its operations at the McDonald Laser Ranging Station (MLRS), the Center for Space Research routinely analyzes the tracking data for several geodetic satellites in support of reference frame evaluation, geodetic conventional model investigations, tests of General Relativity, and monitoring long-wavelength geopotential variations and geocenter motion.

Geocenter Motion

We have been particularly interested in the determination of seasonal geocenter motion with SLR data, since this represents both possible systematic drifts in the terrestrial frame as well as seasonal mass transport within the Earth system at the longest length scale. In this analysis, geocenter motion is defined consistently with the IERS Conventions as the vector from the origin of the ITRF network to the instantaneous center of mass of the entire Earth. In Figure 7-24, we show an estimate of the geocenter motion obtained from SLR tracking to LAGEOS-1/-2 from late 2002 through 2018, using a new approach that attempts to accommodate the higher-degree site loading that affects the SLR estimates of geocenter motion. The network is held fixed to SLRF2014, and the geocenter motion vector is estimated every 60 days.

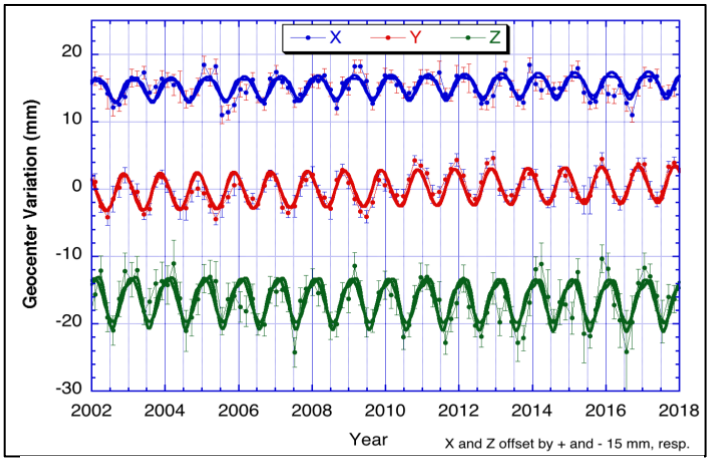

Figure 7-24. Geocenter variations estimated every 60 days from LAGEOS-1/-2. The fit curve is a linear, annual and semi-annual term. A small slope of +0.1 mm/y is observed in Y.

The annual variations determined from the CSR series agree well in both amplitude and phase with other observations from GPS global inversion, a number of geophysical model predictions and combinations of GRACE and ocean bottom pressure models, as seen in Table 7-6 (for more details, see Ries, 2016). The only significant discrepancy is with SCW for the amplitude and phase of the seasonal variation in Z. The SCW technique relies on a global ocean model and GRACE to determine the degree-1 terms. It may be that the ocean model is not fully capturing the seasonal mass variations at high latitudes.

Long-period Variations of the Earth's Gravity Field and the Mean Pole

A few papers published in 2014 and 2015 explained that the IERS conventional model for the mean pole, which at the time was the filtered mean pole (annual and Chandler variations removed), was incorrect for the computation of rotational deformation (aka the pole tide). Instead, the mean pole should be a strictly linear model, which presumably would be driven by GIA. In 2017, we explored the ramifications of changing the mean pole model to a linear model and proposed a linear pole model that was a fit to the entire filtered mean pole time series from 1900 to 2015. One of the effects of this new mean pole model, which dominantly affects C21 and S21, appeared to make the estimates of C21 from LAGEOS-1 and -2 agree better with the prediction from the filtered mean pole (see Figure 7-25). The agreement for S21 was also slightly improved though not as significantly as for C21. This suggests that the rotational deformation model was more correct using the linear mean pole (see Ries and Desai, 2017 for more detail). Based on these results, the linear mean pole model was adopted for computing rotational deformation in the IERS Conventions.

Table 7-6. Estimates of annual amplitude (mm) and phase (deg) from CSR compared to several geodetic and geophysical model estimates. The amplitude and phase are defined by amp*cos(ωt-phase), where t is years past January 1 and ω is the annual frequency. (SCW refers to Swenson, Chambers and Wahr, 2009).

Comparison	X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)	
SLR (L1/L2)	1.9	50	2.8	321	3.9	28	This study (mean of 4 SLR solutions using ITRF2005 and 2014)
GPS loading + GRACE + OBP	1.9	41	2.9	329	3.7	25	Mean of GPS global inversion results
New 'Climatological model'	1.9	45	2.9	325	3.8	26	Average of SLR and GPS results
Geophysical models	2.3	31	2.2	333	3.1	33	Mean of 8 geophysical models
GRACE+Ocean Model	2.2	43	3.0	333	2.7	42	SCW, 2008 (updated 2012, AOD restored)
AOD	1.3	9	1.6	350	0.9	364	AOD1b (RL05, 2002-2014) (GAC)
Climatological model wo AOD	1.3	86	1.5	293	3.3	34	Degree-1 with AOD removed (GSM)
GRACE+Ocean Model	1.3	92	1.4	282	1.8	87	SCW, 2008 (updated 2012, AOD not restored)

As part of our investigation into this issue, it became clear that the drift in C21/S21 is entirely predictable from the filtered mean pole. This suggests that the trend in C21/S21 is not a mass trend signal at all, but rather simply reflects the drift in the Earth's principal axis as it follows the mean rotation axis (the filtered mean pole) (see Wahr, 1987). In other words, the trend in C21/S21 should be ignored when computing mass redistribution from GRACE. As an experiment, the effect of the linear mean pole was also forward-modeled in the analysis. As is apparent in Figure 7-25 (light blue line), the trend in C21 can be entirely explained by the drift in the mean pole. More study is required to verify if this conclusion is correct and should be considered when computing mass trends from GRACE.

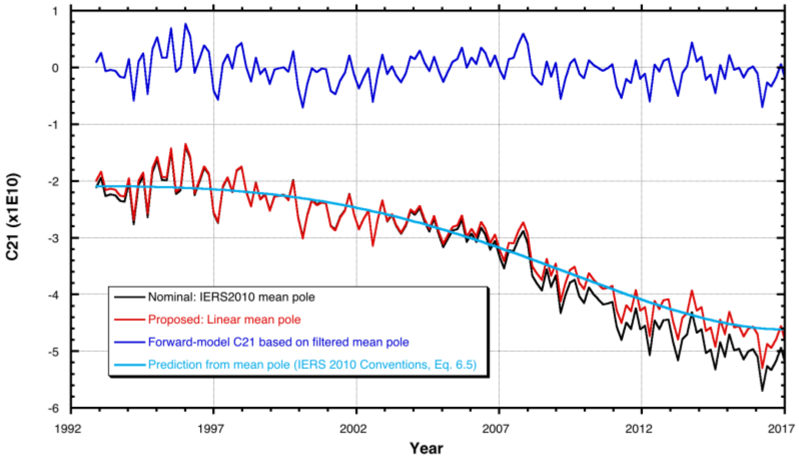

Figure 7-25. Estimates of C21 from LAGEOS-1 and -2, based on various modeling choices.

Analysis of the four-decade time series of C20 from SLR data was found to show a significant variation related to the strong El Niño-Southern Oscillation events with periods of 2-6 years. In particular, the variation related to the powerful 2015-2016 El Niño that peaked during November-December of 2015 was one of the strongest on record (see Cheng and Ries, 2018).

Future Plans

We plan to continue the analysis of the low-degree gravity variations and geocenter from SLR as well as investigate the possible sources of the scale difference between SLR and VLBI. We are particularly interested in the estimation of GM from targets other than LAGEOS-1 and -2.

AAC Personnel

Figure 7-26. Analysis working group members at the University of Texas at Austin (left to right) : John Ries, Minkang Cheng.

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Areas of Interest

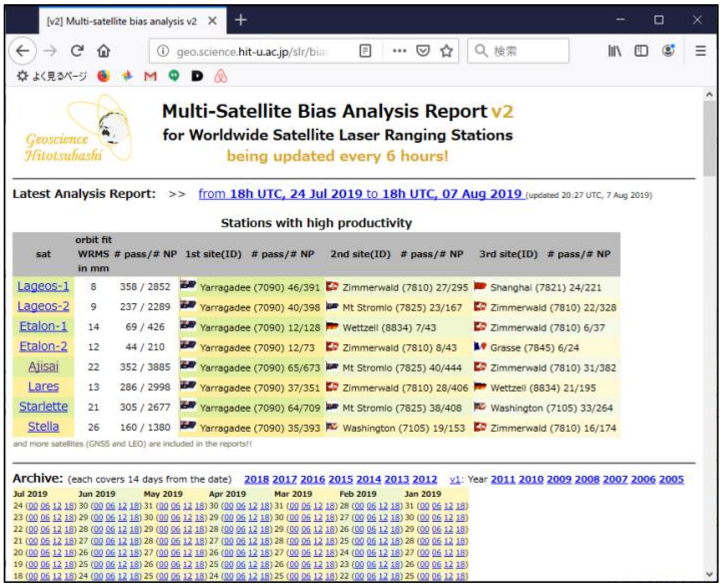
We always seek to make full use of the high precision measurement of satellite laser ranging and look into various aspects ranging from satellite dynamics to reflector optical responses. We also routinely provide quality control information to the ILRS stations.

Recent Progress and Analysis Center Improvements

We have developed our analysis package "c5++" since 2010. It is being used not only by Japanese institutes but also by several institutes in Europe.

The rapid quality check reports are being updated every 6 hours on our website: *http://geo.science.hit-u.ac.jp/slr/bias/* (also shown in Figure 7-27)

where a number of new satellites have been added to the analysis in the past few years. The international quality control activities including ours are published largely helped by 9 coauthors worldwide (Otsubo et al., 2018). We also presented a longer-term, more precise assessment at the consecutive three workshops in Potsdam, Riga and Canberra which is available at the ILRS NESC Forum (*http://sgf.rgo.ac.uk/forumNESC/index.php?board=15.0*).



Multi-Satellite Bias Analysis Report v2
for Worldwide Satellite Laser Ranging Stations
being updated every 6 hours!

Latest Analysis Report: >> from 18h UTC, 24 Jul 2019 to 18h UTC, 07 Aug 2019 (updated 20:27 UTC, 7 Aug 2019)

Stations with high productivity

sat	orbit fit WRMS in mm	# pass/# NP	1st site(ID)	# pass/# NP	2nd site(ID)	# pass/# NP	3rd site(ID)	# pass/# NP
Lageos-1	8	358 / 2852	Yarragadee (7090)	46/391	Zimmerwald (7810)	27/295	Shanghai (7821)	24/221
Lageos-2	9	237 / 2289	Yarragadee (7090)	40/398	Mt Stromlo (7825)	23/167	Zimmerwald (7810)	22/328
Etalon-1	14	69 / 426	Yarragadee (7090)	12/128	Wettzell (8834)	7/43	Zimmerwald (7810)	6/37
Etalon-2	12	44 / 210	Yarragadee (7090)	12/73	Zimmerwald (7810)	8/43	Grasse (7845)	6/24
Ajisai	22	352 / 3885	Yarragadee (7090)	65/673	Mt Stromlo (7825)	40/444	Zimmerwald (7810)	31/382
Lares	13	286 / 2998	Yarragadee (7090)	37/351	Zimmerwald (7810)	28/406	Wettzell (8834)	21/195
Starlette	21	305 / 2677	Yarragadee (7090)	64/709	Mt Stromlo (7825)	38/408	Washington (7105)	33/264
Stella	26	160 / 1380	Yarragadee (7090)	35/393	Washington (7105)	19/153	Zimmerwald (7810)	16/174

and more satellites (GNSS and LEO) are included in the reports!!

Archive: (each covers 14 days from the date) 2018 2017 2016 2015 2014 2013 2012 v1: Year 2011 2010 2009 2008 2007 2006 2005

Jul 2019	Jun 2019	May 2019	Apr 2019	Mar 2019	Feb 2019	Jan 2019
24 (00 06 12 18)	30 (00 06 12 18)	31 (00 06 12 18)	30 (00 06 12 18)	31 (00 06 12 18)	28 (00 06 12 18)	31 (00 06 12 18)
23 (00 06 12 18)	29 (00 06 12 18)	30 (00 06 12 18)	29 (00 06 12 18)	30 (00 06 12 18)	27 (00 06 12 18)	30 (00 06 12 18)
22 (00 06 12 18)	28 (00 06 12 18)	29 (00 06 12 18)	28 (00 06 12 18)	29 (00 06 12 18)	26 (00 06 12 18)	29 (00 06 12 18)
21 (00 06 12 18)	27 (00 06 12 18)	28 (00 06 12 18)	27 (00 06 12 18)	28 (00 06 12 18)	25 (00 06 12 18)	28 (00 06 12 18)
20 (00 06 12 18)	26 (00 06 12 18)	27 (00 06 12 18)	26 (00 06 12 18)	27 (00 06 12 18)	24 (00 06 12 18)	27 (00 06 12 18)
19 (00 06 12 18)	25 (00 06 12 18)	26 (00 06 12 18)	25 (00 06 12 18)	26 (00 06 12 18)	23 (00 06 12 18)	26 (00 06 12 18)
18 (00 06 12 18)	24 (00 06 12 18)	25 (00 06 12 18)	24 (00 06 12 18)	25 (00 06 12 18)	22 (00 06 12 18)	25 (00 06 12 18)

Figure 7-27. Six-hourly quality control reporting service at Hitotsubashi University.

We detected interesting features in the estimates of solar radiation pressure coefficients (C_R) of LAGEOS and Ajisai. LAGEOS-1 C_R is always larger than LAGEOS-2 C_R due to unknown reasons, but the reason why Ajisai's C_R is even smaller with a periodic wobble can be well explained with the optical property of Ajisai (Hattori and Otsubo, 2019).

A simulation study was conducted with Japanese colleagues to find an effective way to expand the SLR tracking network. The best place depends on the geodetic parameters, but in general, our study showed the weakness of the existing ILRS network lies in the high latitude area of the southern hemisphere

(Otsubo et al, 2016). Later, Otsubo served as a PI of a feasible study of Syowa (Antarctica) SLR and an on-site site survey was conducted by the National Institute of Polar Research in 2018.

During a sabbatical year, Otsubo stayed with NERC/BGS Space Geodesy Facility, UK (May-August 2016), GeoForschungsZentrum, Germany (September-December 2016), and Chalmers tekniska högskola, Sweden (January-March 2017).

Otsubo served as a guest professor of National Astronomical Observatory of Japan (2016-2019) and will serve as a guest professor of Institute of Space and Astronautical Science, JAXA (2019-). Our software "c5++" is being applied to a deep space mission Hayabusa-2, in particular its laser altimeter data.

Technical Challenges and Future Plans

Precise force modeling for earth radiation pressure is ongoing, and we plan to test various atmospheric delay models. We would like to learn precise attitude modeling of non-spherical satellites from the DORIS community.

AAC Personnel

Hitotsubashi AAC work has mostly been done by T Otsubo, who is helped by assistant Ms. Mihoko Kobayashi and collaborated with his current and past students.

Figure 7-28. T. Otsubo in front of our quality control computer.

References

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Areas of Interest

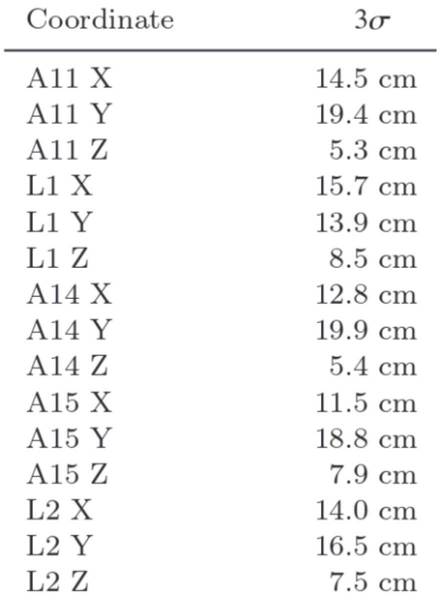
IAA RAS routinely produces lunar and planetary ephemeris EPM. The lunar part of EPM is important for different theoretical and applied studies, including modeling of the lunar interior, building lunar and Earth-lunar reference frames, and planning future lunar missions. The lunar part of EPM relies solely on LLR observations made since late 1969 at different observatories. IAA RAS has received status of an ILRS Lunar AC in 2018. IAA RAS works closely with other analysis centers and LLR observatories, in the joint effort to improve the lunar dynamical model and provide the best lunar reference frame.

Recent Progress and Analysis Center Improvements

Since version EPM2015, the dynamical model of the Moon in EPM is based on DE430 model and includes:

- perturbations of the orbit of the Moon in the gravitational potential of the Earth;
- torque due to the gravitational potential of the Moon;
- perturbations of the orbit of the Moon due to lunar and solar tides on the Earth;
- distortion of the Moon's figure as a result of its rotation and Earth's gravity;
- torque due to the interaction between the lunar crust and the liquid core.

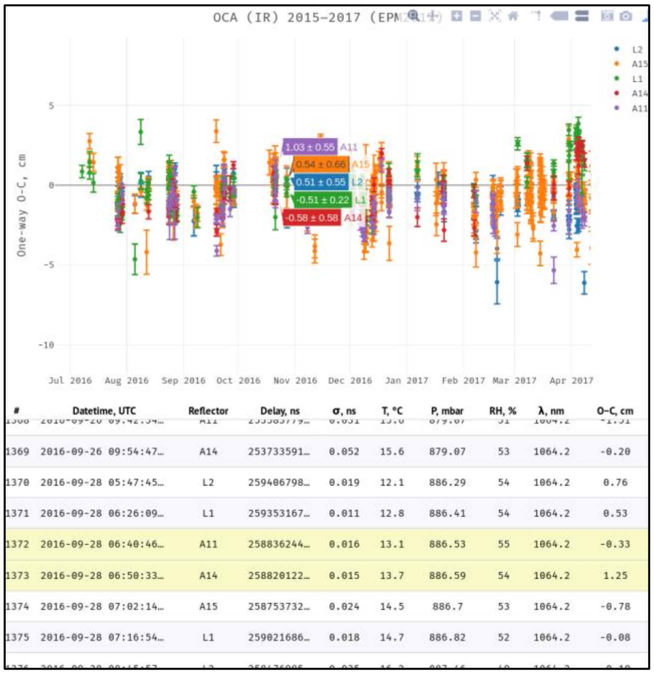
In the lunar part of EPM2017, more recent LLR observations (until the end of 2016) were used. New infrared observations that are now regularly performed at Grasse have dramatically improved the accuracy of the ephemeris. Unfortunately, no LLR observations were provided from Apache Point Observatory since the end of 2016. Historical data from Crimean Astrophysical Observatory (1982–1984) was processed and its accuracy confirmed. Figure 7-29 gives an estimate of the accuracy of the lunar frame in EPM ephemeris.



Coordinate	3σ
A11 X	14.5 cm
A11 Y	19.4 cm
A11 Z	5.3 cm
L1 X	15.7 cm
L1 Y	13.9 cm
L1 Z	8.5 cm
A14 X	12.8 cm
A14 Y	19.9 cm
A14 Z	5.4 cm
A15 X	11.5 cm
A15 Y	18.8 cm
A15 Z	7.9 cm
L2 X	14.0 cm
L2 Y	16.5 cm
L2 Z	7.5 cm

Figure 7-29. Uncertainties of the lunar coordinates of the five retroreflectors basing on LLR observations of 1970–2017.

Three web applications have been developed that provide free ephemeris and LLR-related service to users worldwide. The online ephemeris service (*http://iaaras.ru/en/dept/ephemeris/online/*) provides, among other things, geocentric position and physical libration of the Moon. LLR pointing service (*http://iaaras.ru/en/dept/ephemeris/llr-pointing/*) provides important data for planning LLR observations in an arbitrary observatory. The LLR O-C web service (*http://iaaras.ru/en/dept/ephemeris/llr-oc/*, Figure 7-30) allows to view the residuals (O−C) of past LLR observations and also of observations uploaded by the user.



#	Datetime, UTC	Reflector	Delay, ns	σ, ns	T, °C	P, mbar	RH, %	λ, nm	O−C, cm
1369	2016-09-26 09:54:47…	A14	253733591…	0.052	15.6	879.07	53	1064.2	-0.20
1370	2016-09-28 05:47:45…	L2	259406798…	0.019	12.1	886.29	54	1064.2	0.76
1371	2016-09-28 06:26:09…	L1	259353167…	0.011	12.8	886.41	54	1064.2	0.53
1372	2016-09-28 06:40:46…	A11	258836244…	0.016	13.1	886.53	55	1064.2	-0.33
1373	2016-09-28 06:50:33…	A14	258820122…	0.015	13.7	886.59	54	1064.2	1.25
1374	2016-09-28 07:02:14…	A15	258753732…	0.024	14.5	886.7	53	1064.2	-0.78
1375	2016-09-28 07:16:54…	L1	259021686…	0.018	14.7	886.82	52	1064.2	-0.08

Figure 7-30. LLR O−C webpage made by IAA RAS.

Technical Challenges

A number of developments were undertaken to support the planned new Russian LLR station; however, the construction is being delayed, mainly due to the optical part of the station.

Future Plans

The routine processing of the LLR observations should continue. The next, improved version of EPM, including improved lunar ephemeris, is scheduled for release in 2020.

Research must continue in the areas of:

- Finding the cause of nonzero S21 gravity coefficient in the lunar solution. It is linked to the lunar model, which does not quite represent reality. Mathematically, if the Moon behaved according to the model, the S21 must be zero. There are two possible directions towards the improvement of the model: the first one is the model of the lunar core, and the second one is the model of the tidal response of lunar gravity field.
- Exploration of the possibility of Ephemeris-ICRF tie via LLR.
- Testing general relativity with LLR.

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- Dmitry Pavlov (*dpavlov@iaaras.ru*): responsible for implementation of the lunar part of EPM, and also for the online ephemeris service (*http://iaaras.ru/en/dept/ephemeris/online/*) and the online LLR pointing service (*http://iaaras.ru/en/dept/ephemeris/llr-pointing/*).
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LARASE (LAser RAnged Satellites Experiment), Italy

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Areas of Interest

LARASE is an experiment funded by the Italian National Institute for Nuclear Physics (INFN), National Scientific Commission II (CSN2) on Astroparticle Physics Experiment. We perform measurements of relativistic effects with laser-ranged satellites (LAGEOS, LAGEOS-2, and LARES) in the weak-field and slow-motion limit of Einstein's theory of General Relativity (Lucchesi et al., 2015 and Lucchesi et al., 2017).

Furthermore, we develop new models for the non-conservative forces acting on the cited satellites.

Products:

- State vector of the satellites
- Components of the spin vector of the satellites
- Accelerations on LARES due to the neutral drag with several atmospheric models

Recent Progress and Analysis Center Improvements

Concerning the models, in the last years we developed a new model for the spin evolution of the considered satellites named LASSOS (LArase Satellites Spin mOdel Solutions), based on the solution of the full set of Euler equations (Visco and Luccesi, 2018). The neutral drag perturbation on LARES has been handled in synergy by computing the drag acceleration with SATRAP and performing the POD with GEODYN (Pardini, et al, 2017 and Pardini et al, 2018). Concerning the solid and ocean tides models, we considered their errors (on the basis of IERS Conventions) in relation to the Lense-Thirring effect measurement (Pucacco and Lucchesi, 2018).

Recent improvements concern a model for the Earth gravity field even zonal harmonics based on linear fits to GRACE monthly solutions in relation to the Lense-Thirrimg effect measurement. Finally, we performed a new precise and accurate measurement of the Lense-Thirring effect on the combined orbits of LAGEOS, LAGEOS-2, and LARES (Lucchesi et al., 2019).

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Technical Challenges and Future Plans

We plan to include LARES-2 in our analyses after its launch, and to outline a dedicated dynamical model for the non-conservative forces acting on it. The thermal trust accelerations will be computed for the two LAGEOS and LARES satellites. We also plan to perform new measurements of gravitational effects with the aim to test the predictions of General Relativity with respect to those of other metric theories of gravitation.

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Areas of Interest

As an AAC, JAXA is providing CPF files of Ajisai, LAGEOS-1, and -2 on a daily basis. Also, as an operator of Tanegashima SLR station, we are interested in the accuracy of the CPF files of Ajisai. We always check the number of observation data of Ajisai available from the CDDIS server.

Recent Progress and Analysis Center Improvements

We evaluated the accuracy of Ajisai's CPF files. A summary of the accuracy of the CPF files assessed by using the overlapping method (Figure 7-31). As conclusions (Figure 7-29):

(1) the positioning accuracy of the CPF files is 0.1 to 0.8 [m]. Since the diameter of Ajisai is 2.15 [m], it is enough for tracking Ajisai.

(2) when the number of observation data decreased, the accuracy of CPF files also decreased.

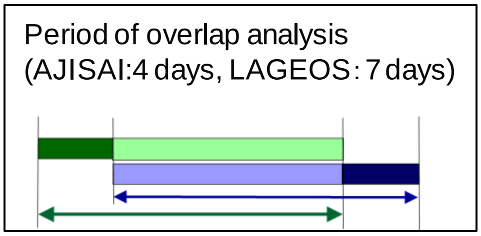

Figure 7-31. Overlap analysis for Ajisai CPF files.

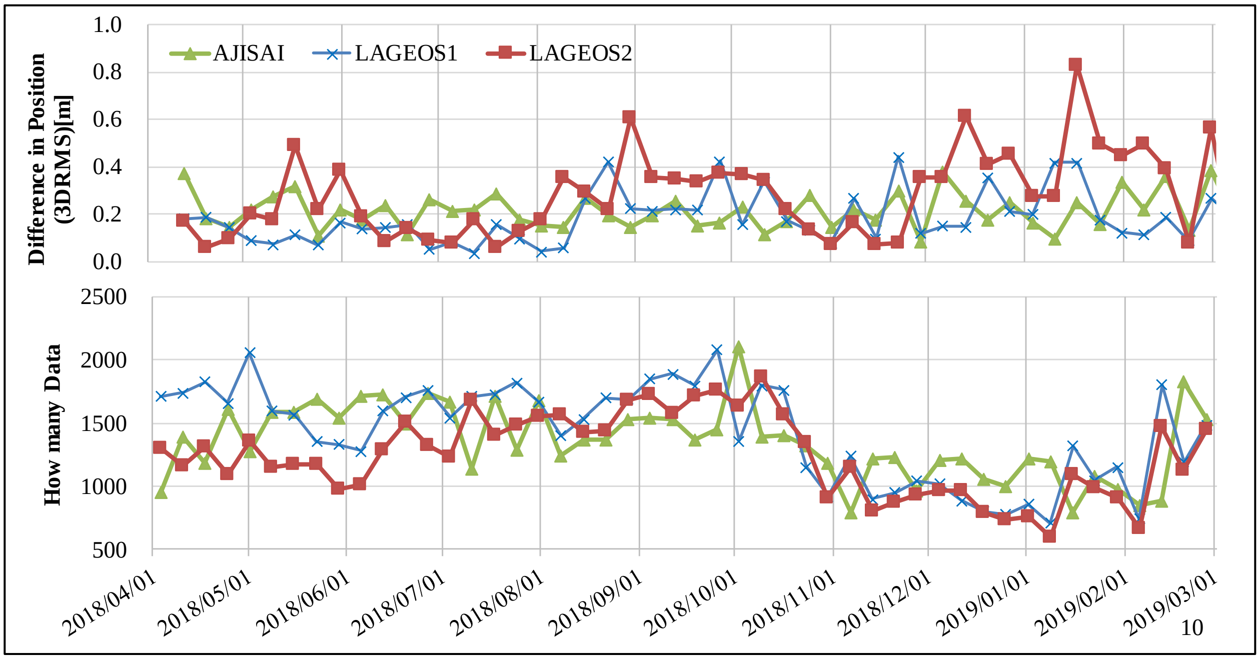

Figure 7-32. Summary of the accuracy of CPF files generated by the JAXA AAC for Ajisai and LAGEOS-1 and -2.

We regard providing CPF files as an obligation for us as the owner agency of Ajisai. We will make an effort to provide its CPF files continuously.

Technical Challenges and Future Plans

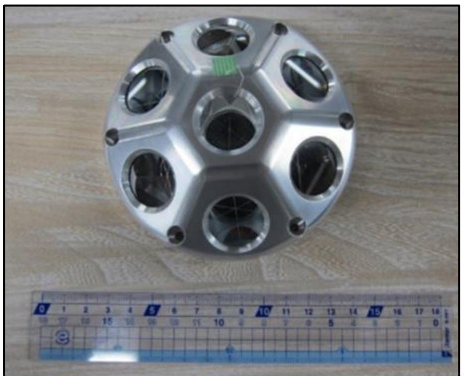

Figure 7-33. Mt. FUJI retroreflector array.

In 2020, JAXA will launch a satellite, ALOS-4, in which LRA will be mounted; JAXA will start distributing the CPF files of ALOS-4 as well. Since ALOS-4 will operate in LEO, we have to keep it in our mind to generate accurate CPF files.

Moreover, JAXA is developing a small, cost-effective, and general-purpose LRA called Mt. FUJI (MulTiple reFlector Unit from Jaxa Investigation). The purpose of this device is not limited to orbit determination. By attaching the Mt. FUJI, all objects change from non-cooperative to cooporative. So, after the operation of spacecraft is over and the object falls into a category of space debris, it becomes easier to track it. We are negotiating with future rocket project teams and satellite missions concerning the usage of Mt. FUJI. Now, we do not have a solution to make accurate CPF files, but we will improve our method by the launch of the first object which mounts Mt. FUJI.

AAC Personnel

Figure 7-24. Staff at JAXA Tsukuba Space Center: left to right) Takushi Sakamoto, Takehiro Matsumoto, Yuki Akiyama, Shinichi Nakamura, and Kazuhiro Yoshikawa.

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Areas of Interest

The ILRS Associated Analysis Center (AAC) at the Institute of Geodesy and Geoinformatics, Wroclaw University Of Environmental and Life Sciences (IGG WUELS) was established in March 2017 providing a service called as multi-GNSS Orbit Validation Visualizer Using SLR (GOVUS) as its main component.

At a time of growing demand for the multi-GNSS constellation, civil and scientific users need intuitive and real-time information about the quality of available multi-GNSS products. Processing of GNSS data for all satellite navigation systems is complicated due to several satellite structural aspects such as various frequencies of transmitted signals or differences in the shape of satellites' bus and solar panels. Satellite Laser Ranging (SLR) technique can be used as an independent validation for the orbit products.

Moreover, the research team, which contribute to the IGG ILRS AAC, focuses on the processing of SLR observations. Three main branches of interest in the research activities are: (1) precise orbit determination of GNSS satellites using SLR observations; (2) troposphere delay modeling for SLR measurements, (3) estimation of global geodetic parameters using SLR observations to geodetic, GNSS, and LEO satellites i.e., Earth rotation parameters (ERPs), geocenter coordinates (GCC), scale of the reference frame, station coordinates and gravity field.

Recent Progress and Analysis Center Improvements

The GOVUS service (Zajdel et al., 2017) is addressed to users of multi-Global Navigation Satellite System (multi-GNSS) orbit products and SLR stations belonging to the ILRS, which track GNSS satellites. The main tasks of the developed service are to (1) store archival and current information about the ILRS laser stations and multi-GNSS satellites; (2) store the multi-GNSS microwave orbit validation results using SLR; (3) allow for fast and advanced online analyses on the stored dataset; (4) provide an autonomous computing center; and (5) generate up-to-date dataset and reports. Among all the current providers of multi-GNSS orbits, only the products delivered by the Center for Orbit Determination in Europe (CODE) are currently being validated as a representative example of 5-system orbit products delivered in the framework of MGEX. CODE multi-GNSS orbit includes particular types of satellites: GPS, GLONASS of type M and K, Galileo of type IOV and FOC, BeiDou-2 of type MEO and IGSO and QZSS.

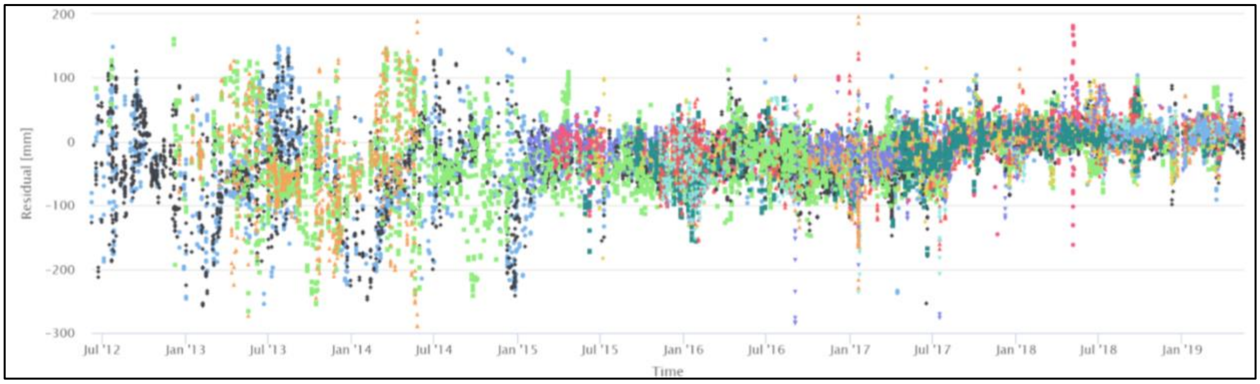

Figure 7-35. Example of the plot from the GOVUS service; Time series of SLR residuals for Galileo satellites in the period 2012-2019.

GOVUS is available at *http://www.govus.pl*. Daily reports of SLR validation are available at *https://www.govus.pl/slr/daily*.

Most of the functions of the GOVUS service were presented at the consecutive ILRS workshops in Riga and Canberra at the Clinic Session. Moreover, the GOVUS service has been presented to the GNSS community at the 6th Galileo Science Colloquium 2017 in Valencia.

The publication effort of the research group at the IGG ILRS AAC for the period 2016-2019 covers 12 articles in the key international journals.

Bury et. al (2019a) summarized the GNSS-intensive tracking campaigns conducted by the International Laser Ranging Service and provides results from multi-GNSS orbit determination using solely SLR observations.

Bury et. al (2019b) described the inconsistency between solutions based on the microwave (GNSS) and optical (SLR) observations which may arise from the omission of the impact of atmospheric pressure loading, especially the nontidal loading (ANTL) part. The systematic shift of the estimated SLR station coordinates, which arises from the ANTL omission, is called the Blue-Sky effect. The offset is related to the long-term averaging of ANTL for SLR observations which are provided in sparse intervals, unlike GNSS, which observes continuously.

Drożdżewski et al. (2018) presented the sensitivity and capability of the SLR observations for the recovery of azimuthal asymmetry of the atmosphere delay above the SLR stations, which can be described as horizontal gradients of the troposphere delay. They concluded that SLR can be employed as a tool for the recovery of the atmospheric parameters with a major sensitivity to the hydrostatic part of the delay. Moreover, the so-called Potsdam Mapping Function (PMF) dedicated to SLR observations has been developed (Drożdżewski et al. 2019) and troposphere effects in global geodetic parameters were tested.

Sośnica et al. (2018a) showed a solution strategy with estimating satellite orbits, SLR station coordinates, geocenter coordinates, and Earth rotation parameters (ERP) using SLR observations to 2 Laser Geodynamics Satellites (LAGEOS) and 55 GNSS satellites. Integration of SLR measurements to GNSS and LAGEOS satellites leads to a substantial increase in the number of weekly solutions and improves the consistency of ERP estimates w.r.t. the GNSS microwave-based results. Sośnica et al. (2019) described also the corresponding results using SLR observations to GNSS satellites only.

Sośnica et al. (2018b) used SLR observations to Galileo satellites for the validation of different orbit empirical models with a special focus put on Galileo satellites in eccentric orbits. The SLR satellite signature effect was analyzed for single-photon and multi-photon. Kaźmierski et al (2018) and Katsigianni et al. (2019) used SLR observations to GLONASS, Galileo, and BeiDou for the validation of the quality of real-time and final orbits provided by the French Space Agency CNES.

Strugarek et al., (2019) used SLR observations to GOCE satellite for the quality assessment of kinematic and reduced-dynamic orbits as well as for the assessment of the impact of the solar and geomagnetic activities on different types of GOCE orbits.

Zajdel et al. (2019) compared the results of the geocenter coordinates delivered in the SLR solution based on LAGEOS satellites and the multi-GNSS solution, which include GPS, GLONASS and Galileo satellites. They concluded that the geocenter offset in the solution with the inhomogeneous distribution of multi-GNSS stations, which is a similar situation to the core SLR network, is generally closer to the SLR time series, which may indicate the network effect in the GCC estimates.

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Technical Challenges and Future Plans

Covering more satellites: LAGEOS, LARES, and selected LEOs: GRACE, GRACE-FO, Swarm, Sentinel-3A/B.

AAC Personnel

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Lunar Associate Analysis Centers

Lunar Associate Analysis Centers process normal point data from the Lunar Laser Ranging (LLR) stations and generate a variety of scientific products including precise lunar ephemerides, librations, and orientation parameters which provide insights into the composition and internal makeup of the Moon, its interaction with the Earth, tests of General Relativity, and Solar System ties to the International Celestial Reference Frame.

LLR has shown a strong capability to put Einstein's relativity theory to the test and to improve the limits for a number of relativistic parameters. In addition, lunar science and many quantities of the Earth-Moon dynamics could widely be studied. LLR data analysis within the ILRS is carried out by few major analysis centers. Current Lunar Associate Analysis Centers within the ILRS are listed in Table 7-7.

Table 7-7. ILRS Lunar Associate Analysis Centers (LAACs)

LAAC Title and Supporting Agency
Institute of Applied Astronomy, Russian Academy of Sciences (IAA RAS), Russia
Institut für Erdmessung/Forschungseinrichtung Satellitengeodäsie (IFE/FESG), Germany
Istituto Naz. di Fisica Nucleare - Laboratori Naz. di Frascati (INFN-LNF), Italy
Jet Propulsion Laboratory (JPL), Pasadena, California, USA
Paris Observatory Lunar Analysis Center (POLAC), France
University of Texas Analysis Center for LLR, Austin, Texas, USA

IAA RAS (Institute of Applied Astronomy Russian Academy of Sciences), Russia

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Responsible Agency: Russian Ministry of Science and Higher Education

Areas of Interest

Lunar activities at the IAA RAS are summarized in their AAC report found previously in this section.

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IFE/FESG (Institut für Erdmessung/Forschungseinrichtung Satellitengeodäsie), Germany

Authors: *Jürgen Müller, Franz Hofmann, Liliane Biskupek, Ulrich Schreiber*

Responsible Agency: Institute of Geodesy, Leibniz University Hannover and Forschungseinrichtung Satellitengeodäsie, Munich, Germany

Areas of Interest

IfE/FESG analyzes LLR data to carry out dedicated research in the following fields: relativity, reference frames, earth rotation, selenophysics.

Recent Progress and Analysis Center Improvements

The modelling of the Earth-Moon dynamics – as a central element of the IfE LLR analysis tool – has been updated in several points.

In the ephemeris computation, the model of the gravitational effects on the Moon was extended. The interaction of the Sun with the lunar gravity field up to degree and order 3 and the interaction of the planets with the lunar gravity field up to degree and order 2 are used to reduce the specific modelling inaccuracy well below the 1 mm threshold. To reach the same ephemeris precision for the Earth-Moon system, the interaction between the point-mass Earth (Moon) with the gravity field up do degree and order 6 for the Moon (Earth, just zonal parts) was included. The figure-figure interaction between Earth and Moon can now be computed up to any degree and order of the gravitational field of both bodies. The effects are added to the equations for translational and rotational motion. The gravitational coupling of the complete degree-2 field of the Earth with the degree-3 field of the Moon has to be considered to get an ephemeris precision below 1 mm.

A further large improvement was the update of the modelled solid Earth tides and the implementation of the consistent rotational model of the Moon as a two-layered body with a solid mantle and fluid core according to the DE430 ephemeris [Folkner et al., 2014]. The tide-induced variations of the selenocentric reflector coordinates are now modelled according to the degree-2 variations in Petit and Luzum (2010) which were adapted to the Moon.

The overall improvement of the IfE-analysis model is reflected in the reduction of the post-fit residuals of about 30 % compared to the previous solution (Figure 7-36). Since 2006 the weighted rms reaches a value of about 1-2 cm. Nevertheless, some un-modelled effects in the longitude libration remain at this stage and have to be investigated in future studies.

The accuracies of the estimated parameters also benefitted from the updated modelling [Biskupek, 2015; Hofmann, 2017]. Hofmann et al. (2018) give the recent results for station and reflector coordinates, nutation coefficients and Earth rotation corrections. The validity of Einstein's theory of gravitation has been studied using various test parameters. Within the achieved accuracy of our LLR analysis, no deviations from Einstein's theory were detected. The most important results include the estimation of improved limits for a possible temporal variation of the gravitational constant with $\dot{G}/G_0 = (7 \pm 8) \times 10^{-14}\,\mathrm{yr}^{-1}$ and a possible violation of the equivalence principle with $\Delta(m_g/m_i)_{EM} = (3 \pm 5) \times 10^{-14}$ [Hofmann/Müller, 2018]. Further studies with more LLR NP in infrared show the benefit of that observations for relativistic investigations. Special analysis of the LLR residuals was performed to study a possible equivalence principle violation due to assumed dark matter in the center of our Galaxy. Here, the amplitude of a possible anomalous range oscillation with a sidereal period was determined. Again, no violation within a realistic error limit of 1 - 2 mm was found [Zhang et al., 2020].

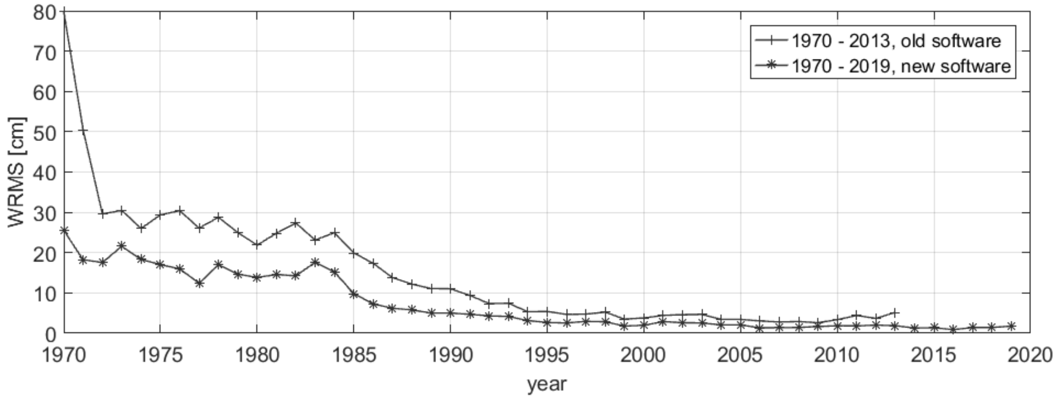

Figure 7-36: Comparison of the annual weighted rms (wrms) of the one-way post-fit residuals: NP between 1970 and 2013 analysed with the old software and NP between 1970 and 2019 analysed with new software.

In a simulation study, Hofmann (2017) investigated the impact of new observatories on the Earth and reflectors on the Moon for the determination of different parameters. Even a single corner cube reflector [Currie et al., 2013] in a position close to the edge of the visible lunar disk at medium selenocentric latitude would well support the modelling of the rotational motion and therefore would improve the results of the LLR analysis.

Technical Challenges and Future Plans

Further plans comprise the improved modelling of the lunar interior, ephemeris calculation and analysis of novel differential LLR data.

LAAC Personnel

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- Mingyue Zhang/Institut für Erdmessung
- Vishwa Vijay Singh/Institut für Erdmessung
- Ulrich Schreiber/Forschungseinrichtung Satellitengeodäsie

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Areas of Interest (Lunar Science Activities in a Nutshell)

Current understanding of our Universe passes through the spinous issue of constraining the most suitable theory of gravity that explains the motion at large scales of universe's expansion history. Einstein's theory is actually passing several tests and commonly one assumes that its validity lies on four different typologies of tests, although more recently new developments have been made in the field of black hole and gravitational wave physics. Among all, the Lunar Laser Ranging technique, hereafter LLR, is one relevant possibility in which through direct measurements of time of flight from the Earth to the Moon and back one can find out possible deviations of Einstein's gravity within the Solar System scale. In so doing, optical passive instrumentations can be adopted and for the sake of completeness, this technique is clearly included within weak field approaches to test gravitational theories. Hence its refinement has reached utmost importance, being particularly relevant to cosmologists, in order to distinguish standard gravity from any possible extensions or modified scenarios of Einstein's theory, e.g., for example f(R) theories, modified teleparallel gravity, Gauss-Bonnet corrections to Einstein-Hilbert's action and so forth.

Unfortunately, and quite unpleasantly, the importance of LLR is jeopardized by underestimated data points so far available by means of Earth stations placed all around the world. The sensibility of such data surveys is often not enough to guarantee direct evidences/predictions that open new insights toward non-negligible corrections to gravity. Consequently, the task of simulating LLR data by means of powerful software based on Monte Carlo techniques has increased its importance and is currently one of the most suitable benchmark for forecasting our expectations together with more modern treatments based on statistical learning codes.

Among all, the Planetary Ephemeris Program, hereafter PEP, represents a free available code that aims at understanding the physics of gravitation using LLR data points and simulating either more data or alternative configurations by means of internal Monte Carlo procedures commonly based on Metropolis-Hastings algorithm. The architecture of the code has been firstly developed at Harvard-Smithsonian Center for Astrophysics at Harvard, USA, and aims at generating ephemerides of planets and, above all, of the Moon and particularly it acts as a direct comparison between data and expectations. In fact, the code is thought to simulate LLR and satellite laser ranging data in order to test extended models of gravity, and/or standard gravity, directly with numerical outcomes. In this respect the code verifies possible deviations from Einstein's theory of gravity by taking general relativity and expanding it at low energy domains, obtaining the Post Parameterized Newtonian parameters, hereafter PPN parameters, and confronting them with Monte Carlo simulations previously implemented via heavy Markov chains computed within the code itself.

The comparison has the advantage of being predictive as one assumes the geometry and the placing of laser retroreflectors, i.e., the principal passive instrumentations used for the LLR technique, on the Moon changing the principal properties of these passive optical objects and analyzing how this fact can lead to observable results over PPN parameters. The corresponding bounds are also compared with an evolving Newtonian gravitational constant, G. This perspective may be true since possible variations of G with respect to cosmic time are allowed as effective gravitational constants are assumed as byproduct of the coupling between extra terms coming from new theories of gravitation and the previous version of G, i.e., the one developed by Newton.

Indeed, the idea of checking whether G varies with respect to time turns out to be a direct consequence of assuming an extended theory of gravity in which geometrical additional terms naturally couple with the strength of gravity.

Thus, this prerogative is inferred from the code as consequence of the numerical simulations provided during computations and so far viable constraints have been bounded up to a part over 10^{-16} showing up no relevant differences, at least in the framework of weak field, with standard gravity.

Since currently several evidences, such as dark matter and inflationary epochs, seem to indicate that extended theories of gravity may be used as alternatives to explain the unknown constituents of the universe, it appears clear that future efforts based on LLR will complement the cosmological probes. Further new developments using LLR techniques can be made in order to focus and to refine the sensibility prompted in PEP and in simulations got from analogous theoretical and experimental treatments. The idea is to check any possible deviations from our standard knowledge about gravity and, above all, to understand if, combining more than one data survey can actually be considered as a relevant indication for a more appropriate comprehension of gravity. For example, looking at the dark side of the Moon, in future missions, it would be possible to match cosmological data with the ones provided in PEP and with simulations that will employ other data sources. The idea is to provide contour plots, based on 68% and 95% confidence levels, of PPN parameters that are intertwined with hierarchical data set analyses in order to fix tighter and stringent limits over the whole picture of our universe.

Recent Progress, Analysis Center Improvements, and Technical Challenges for the Future (Establishment and Activities of the Joint Lab between ASI-CGS and INFN-LNF)

INFN-LNF (Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali di Frascati), in the framework of the activities of its Joint Lab with ASI-Matera (Agenzia Spaziale Italiana - Centro di Geodesia Spaziale 'Giuseppe Colombo', aka ASI-CGS) [1], delivered to ASI, ESA, and NASA-JPL several miniaturized laser retroreflector payloads designed for the Moon, Mars, and other planetary missions. Moreover, INFN-LNF's flagship experiment, MoonLIGHT (Moon Laser Instrumentation for General relativity High accuracy test), the single, solid, large lunar laser retroreflector, was selected by ESA for flight on board on one of the first upcoming Missions of Opportunity in 2021-22; for a very brief introduction to the science of MoonLIGHT, see previous Section, or the following.

Specifically, the *microreflector* payloads designed for the Moon, Mars, and other planetary missions, are, amongst the other, INRRI[4], LaRRI[5], and LaRA[6] (see Figures 7-37, 7-38, and 7-39). [2, 3, 4]:

- Family of laser microreflectors for planetary geology measurements, object of strategic missions of NASA (InSight 2018, Mars 2020) and ESA (ExoMars).
- Two such payloads were launched in 2016: INRRI (Figure 7-37) and LaRRI (Figures 7-37 and 7-40), respectively with the ESA ExoMars 2016 mission, and in 2018 with the NASA InSight 2018 mission; two more will be launched in 2020: INRRI (Figures 7-38 and 7-41), and LaRA (Figure 7-39), respectively with the ESA ExoMars 2020 mission, and with the NASA Mars 2020 mission.

These instruments are positioned by measuring the time-of-flight of short laser pulses, the so-called *laser ranging* technique (for details on satellite/lunar laser ranging and altimetry see the ILRS website *https://ilrs.gsfc.nasa.gov*), which is notionally pictured in Figure 7-42. The goals of the microreflectors and their role as the passive, maintenance-free, long-lived instrument component of a future MGN (Mars

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[4] INstrument for landing-Roving laser Retroreflector Investigations.

[5] Laser RetroReflector for InSight.

[6] Laser Retroreflector Array.

Geophysical Network) were solidly proofed thanks to the success of InSight, which will always be the first, *core node* of such an MGN [5, 6, 7, 8].

Figure 7-37. Left: microreflector payload for ESA ExoMars 2016. Right: microreflector payload for NASA InSight 2018.

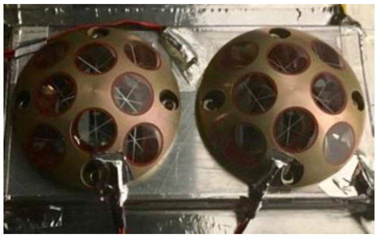

Figure 7-38. Left: microreflector payload for ESA ExoMars 2020. Right: identical spare available at INFN for other international mission opportunities.

Figure 7-39. Microreflector payloads for NASA Mars 2020.

Moreover, science applications of microreflectors include surface geodesy, geophysics (when combined with seismometers, heat flow probes, etc., like the instrument suites of InSight [2] and Apollo[7] [9, 10]) and the test of fundamental relativistic gravity. We performed test physics simulations of the contribution of a 5-microreflector MGN to test General Relativity with the Planetary Ephemeris Program developed by I. Shapiro et al (see for example [11]). Under specific and conservative assumptions (about laser observations from orbit, tracking of the orbiter, etc.) the contribution of this MGN is found to improve the measurements of Gdot/G (possible time changes of the gravitational constant) and of ⍰⍰ the Parametrized Post Newtonian constant related to gravitational self-energy and to possible violations of the strong equivalence principle. This test will be complementary to (and with experimental errors independent of) the one performed with large-size lunar laser retroreflectors (Apollo 11, 14, 15; Lunokhod 1, 2) observed by lunar laser ranging from Earth since 1969 [12, 13].

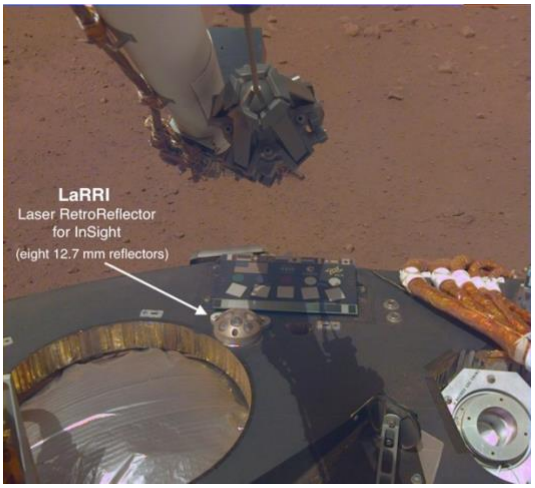

Figure 7-40. LaRRI, on Mars, on the top deck of the InSight lander, in front of the camera calibration targets.

Figure 7-41. INRRI for ExoMars 2020 already installed on the top deck of the landing platform.

Since its very establishment, the main goal of the INFN-LNF's SCF_Lab has been the deployment on the Moon of MoonLIGHT (Figure 7-43): a retroreflector for lunar laser ranging measurements, which will fly in the years 2021-2022. This 100 mm single, solid, large reflector is intended for direct lunar laser ranging

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[7] EASEP and ALSEP = Early Apollo Scientific Experiment Package/Payload (Apollo 11) and Apollo Lunar Surface Experiments Package (≥ Apollo 12).

from stations in USA, Italy (ASI-CGS) and France (Grasse). Its main applications are the LGN (Lunar Geophysical Network), and precision tests of General Relativity and new theories of fundamental relativistic gravity. MoonLIGHT was selected by ESA for flight on board one of the first upcoming Missions of Opportunity in 2021-22 (Figure 7-44).

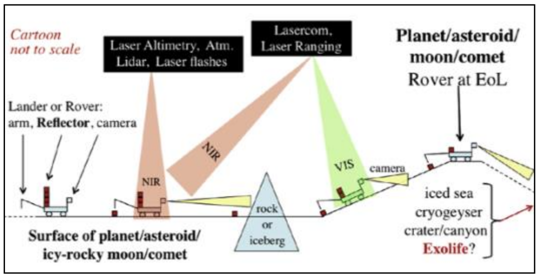


Figure 7-42. Notional concept of microreflectors for solar system exploration research.

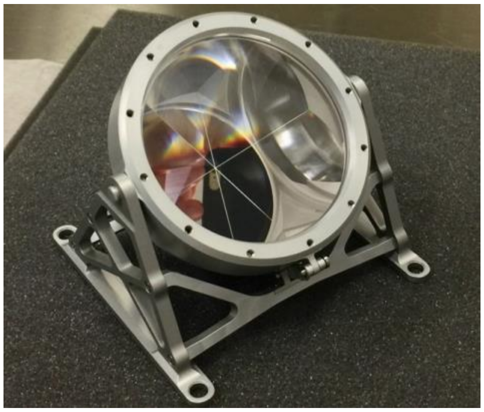
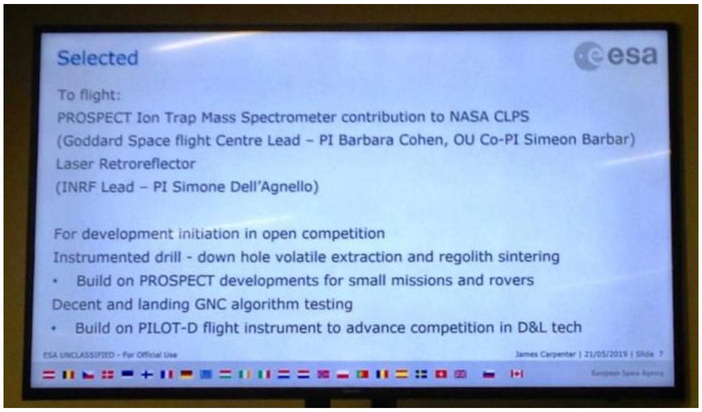


Figure 7-43. MoonLIGHT, retroreflector for lunar laser ranging measurements.



Selected

To flight:
PROSPECT Ion Trap Mass Spectrometer contribution to NASA CLPS
(Goddard Space flight Centre Lead – PI Barbara Cohen, OU Co-PI Simeon Barbar)
Laser Retroreflector
(INRF Lead – PI Simone Dell'Agnello)

For development initiation in open competition
Instrumented drill - down hole volatile extraction and regolith sintering
- Build on PROSPECT developments for small missions and rovers

Decent and landing GNC algorithm testing
- Build on PILOT-D flight instrument to advance competition in D&L tech

ESA UNCLASSIFIED - For Official Use
James Carpenter | 21/05/2019 | Slide 7

Figure 7-44. Public announcement of MoonLIGHT selection for flight on an ESA Mission of Opportunity at the European Lunar Symposium 2019 by James Carpenter (ESA).

Concerning the experimental importance of MoonLIGHT, one reminds that Einstein's theory of General Relativity (GR) provides a comprehensive description of space, time, gravity and matter at the macroscopic level. Classical tests of GR (e.g., perihelion precession of Mercury, deflection of light, and gravitational redshift) confirmed that the theory is well founded. But they are valid essentially in a weak field. In the last thirty years, several shortcomings of Einstein's theory were found, and scientists began wondering whether GR is the only fundamental theory capable of successfully explaining the gravitational interaction, at all scales. This new point of view comes mainly from the study of cosmology, and of quantum field theory. Therefore, various alternative gravitational theories were proposed which attempt to formulate at least a semiclassical scheme in which GR can be replicated [14]. There are many possible experiments for testing GR and its extensions but most of them are complex (i.e., involvement of atomic clocks, interferometers, etc.). Thus, it is very important to work with the best possible theoretical framework to compare models with observations. An example is the Parametrized Post Newtonian (PPN) formalism [15]. Solar System experiments, like lunar laser ranging, allow us to measure some of these PPN parameters, and thereby to determine which theory of gravity best describes the observed physical phenomena (GR, scalar tensor theories, f(R), or something else).

Future Plans (The European Lunar Symposium 2020 (…and 2021!))

The European Lunar Symposium (ELS), a meeting that soon became annual, is held every year, since 2012, in a different city in Europe. ELS is a meeting and interaction point for scientists and engineers, academics and industry, from Europe and all over the world. Lunar exploration is undergoing a new global surge, and many are the current interests in the exploration of the Moon: astronomical, astrophysical, geological, commercial, resource utilization, and strategic considerations, to its use as an outpost for future human exploration of the Solar System. ELS brings together the European scientific and technical communities interested in various aspects of lunar exploration. In addition, lunar experts from countries engaged in launching lunar missions are also invited to attend this meeting.

Figure 7-45. The original logo of the 'in-person' ELS 2020 (https://els2020.arc.nasa.gov/).

Figure 7-46. The present logo of the 'virtual' ELS 2020 (https://els2020.arc.nasa.gov/).

INFN, for the second time (on eight editions overall - there was no 2013 symposium), is leading the SOC/LOC of the event. As a reference, together with the 2020 website (*https://els2020.arc.nasa.gov/*), one reports also the 2015 website (*https://els2015.arc.nasa.gov/*). The first definition meeting for the event was held in May 2018, during that year symposium.

As of 2nd March 2020, following the disruptions generated by the worldwide outbreak of COVID-19, the Padua 2020 'in-person' ELS went 'virtual'. The perspective attendees were duly communicated by e-mail the change in content fruition for this year ELS. Main (*https://els2020.arc.nasa.gov/*) and local (*https://agenda.infn.it/event/21149/*) websites of the event were correspondently updated to reflect the new state of things. As a consequence, the LOC was suppressed. Despite the unforeseeable and unprecedented calamity, and thanks to the collaboration of the participants, the SOC was able to assemble a 'remarkable' program (available for downloads, together with the collection of the abstracts, from the event websites). As of today (16th April 2020), one counts 198 participants, 80 talks, 40 posters. Finally, as per the 'breaking news' dated 9th April 2020, the board of the conference decided to reassign to INFN the leadership of the 2021 symposium. INFN, for the third time out of nine editions in 2021, will be in charge of the event organization.

LAAC Personnel

The two following lists (one for Scientific Profile, the other one for Technological Profile) are in alphabetic order - they report only the SCF_Lab Team members involved in lunar activities:

- Scientific Profile:
  1. Bellettini Giovanni (Associate) - Full Professor
  2. Casini Stefano (Employee) - Fellowship Holder
  3. Di Paolo Emilio Maurizio (Employee) - Staff Researcher
  4. Filomena Luciana (Employee) - Postdoc
  5. Ioppi Luca (Employee) - Fellowship Holder
  6. Luongo Orlando (Employee) - Staff Researcher

7. Maiello Mauro (Associate) - High School Teacher
8. March Riccardo (Associate) - Senior Researcher
9. Mauro Lorenza (Associate) - PhD Student
10. Muccino Marco (Employee) - Staff Technologist
11. Rubino Laura (Associate) - PhD Student
12. Vittori Roberto (Associate) - Executive Researcher

- Technological Profile:
  13. Bianco Giuseppe (Associate) - Executive Technologist
  14. Dell'Agnello Simone (Employee) - Executive Technologist
  15. Delle Monache Giovanni Ottavio (Employee) - Staff Technologist
  16. Porcelli Luca (Employee) - Staff Technologist

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Areas of Interest

We fit lunar laser ranges from 1970 to the present. The fits determine the lunar orbit including tidal acceleration, orientation of the Moon in space, geocentric station positions and motions, orientation of the Earth in space, Moon-centered retroreflector positions, lunar tidal displacement Love number h_2, tidal dissipation associated with potential Love number k_2 at several periods, dissipation at the lunar fluid-core solid-mantle boundary, and *GM*(Earth+Moon).

The tidal acceleration of the Moon is mainly caused by dissipation due to ocean tides, but tidally induced eccentricity rate has a significant additional contribution from tidal dissipation within the Moon. The orientation of the Earth in space includes precession, obliquity rate, and nutations. The orientation of the lunar body in space over time, the physical librations, and also tidal displacements provide geophysical information on the lunar interior. Tidal dissipation in the Moon is strong in the lowest mantle above the core. The physical librations also give information on dissipation at and flattening of the lunar core-mantle boundary (CMB). One lunar free libration mode is similar to the terrestrial Chandler wobble, but with a 75-year period, while another is a 2.9-year oscillation in longitude. Free libration amplitudes should damp out with time so the two observed sizable lunar free librations require a geologically recent stimulus. The lunar orbit provides a very good test of the equivalence principle, an assumption of general relativity. The orbit is also sensitive to relativity-caused geodetic precession.

Renewed interest in missions to the Moon provides an opportunity to place new retroreflectors on the Moon.

Post-fit and rms residuals are provided to the lunar ranging stations at Observatoire de la Côte d'Azur, France; Apache Point Observatory, New Mexico; Matera, Italy; and Wettzell, Germany.

Publications:

Williams, J. G., and D. H. Boggs (2016), Secular tidal changes in lunar orbit and Earth rotation, Celest. Mech. Dyn. Astron. 126, 89–129. doi:10.1007/s10569-016-9702-3

Pavlov, D., J. G. Williams, and V. V. Suvorkin (2016), Determining parameters of Moon's orbital and rotational motion from LLR observations using GRAIL and IERS-recommended models, Celest. Mech. Dyn. Astron. 126, 61–88, doi:10.1007/s10569-016-9712-1

Matsuyama, I., F. Nimmo, J. T. Keane, N. H. Chan, G. J. Taylor, M. A. Wieczorek, W. S. Kiefer, and J. G. Williams (2016), GRAIL, LLR, and LOLA constraints on the interior structure of the Moon, Geophys. Res. Lett. 43, doi:10.1002/2016GL069952

Williams, J. G. (2018), Insight-Building Models for Lunar Range and Range Rate, Celest. Mech. Dyn. Astron. 130:63. *https://doi.org/10.1007/s10569-018-9857-1*

Müller, J., T. W. Murphy, Jr., U. Schreiber, P. J. Shelus, J.-M. Torre, J. G. Williams, D. H. Boggs, S. Bouquillon, A. Bourgoin, and F. Hofmann (2019), Lunar laser ranging – a tool for general relativity, lunar geophysics and earth science, J. Geod. 93 (issue 11), 2195–2210, doi:10.1007/s00190-019-01296-0

Recent Progress and Analysis Center Improvements

Over the years 2016–2019 we have improved the modeling of lunar ranges. Dynamical model improvements include updating the orientation of the Earth for figure perturbations, relativistic geodetic precession affecting lunar physical librations, and solar radiation pressure on the lunar orbit. In the range model we added separate biases for ranges at 1064 ns and 532 ns, refraction delay in the corner cubes, monthly thermal expansion of reflector arrays, atmospheric pressure loading at stations, and seasonal terrestrial center-of-mass vs. center-of-figure effects. All have very small effects on the rms residuals. Thermal expansion and solar radiation pressure are few millimeter systematic effects for tests of the equivalence principle.

Tidal dissipation causes the Moon to recede from the Earth by 38.2 mm/yr, corresponding to an acceleration in orbital longitude of –25.9 "/cent^2. Tide-caused eccentricity rate affects perigee and apogee by –6 and +6 mm/yr, respectively, so that the perigee recedes by 30 mm/yr and the apogee recedes by 46 mm/yr.

The tidal *Q* of the Moon is around 40–45 at 1 month and 1-year periods, but larger at 3 and 6 years. The strong tidal dissipation is thought to come from a zone of partial melting in the deepest part of the mantle.

The Moon centered positions of the 5 retroreflecting arrays are known to better than 1 m. The arrays have been photographed by the Lunar Reconnaissance Orbiter and their positions are useful for global cartography.

We support an effort to place Next Generation Lunar Retroreflectors on the Moon. The University of Maryland NGLRs would be single solid corner cubes that are 10 cm in diameter. Single corner cubes do not spread the photon arrival times of the return pulse.

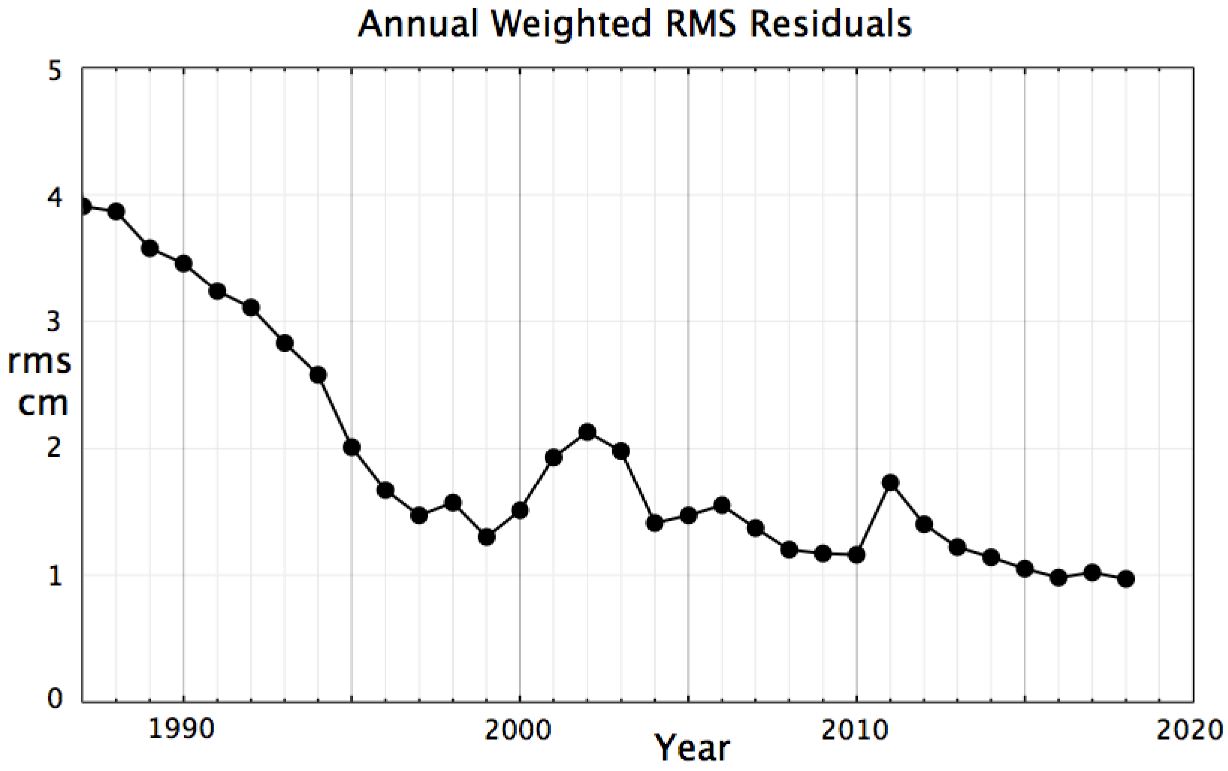

Figure 7-47. Annual weighted RMS residual over the last 3 decades.

The weighted rms residual over the 2016–2019 span is 0.065 ns or 1.0 cm. The four smaller reflectors are fit somewhat better than the larger Apollo 15 array. The figure shows the four-fold improvement in the annual weighted RMS residual over the last 3 decades. Over the recent 4 years there are 4819 ranges to

5 lunar retroreflectors at the Apollo 11, 14, 15 and Lunokhod 1 and 2 sites. The number of observations to the smaller reflectors increased in 2017, 2018, and 2019, which benefits the lunar science results.

Technical Challenges and Future Plans

We will be providing a new numerically integrated lunar ephemeris with physical librations for public use. This will be available to space missions and to the tracking stations for their predictions.

We will examine the model looking for improvements. We will attempt to find the cause of an unexplained contribution to eccentricity rate. We will also study the slightly different alignments of the principal axes of the moment of inertia matrices of the mantle and whole Moon.

A new trigonometric analysis of the numerically integrated physical librations is planned.

We will aid the effort to place Next Generation Lunar Retroreflectors on the Moon. These single corner cubes would be larger than the individual corner cubes used in the Apollo and Lunokhod arrays.

LAAC Personnel

- James G. Williams (*James.G.Williams@jpl.caltech.edu*) does model formulation, development of theory, and data analysis.
- Dale H. Boggs (*Dale.H.Boggs@jpl.caltech.edu*) performs software development and data analysis.
- J. Todd Ratcliff performs Earth rotation analysis, combining LLR results with other techniques.
- Slava G. Turyshev participates in tests of gravitational physics.

Figure 7-48. JPL Lunar Analysis Center staff, left to right: James Williams, Slava Turyshev, Dale Boggs, and Todd Ratcliff.

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Responsible Agency: Observatoire de Paris (SyRTE), Paris, France

Areas of Interest

POLAC (Paris Observatory Lunar Analysis Center) is an ILRS Lunar analysis center founded by J. Chapront, M. Chapront−Touzé and G. Francou in 1996. The original purpose of POLAC was the analysis of the lunar laser ranging observations (LLR) based on the adjustment of their semi-analytical solution of the lunar motion named ELP (Ephémérides lunaires Parisienne) to LLR data. These LLR analyses have allowed us to improve the determination of fundamental astronomical parameters, such as the free modes of lunar physical librations, the tidal secular acceleration of the lunar longitude, or the transformation between celestial reference systems. Since 2010, POLAC also provides the accurate predictions required to achieve Lunar laser ranging observations. From the very beginning, POLAC has always worked in close collaboration with the team of the laser ranging station of Grasse (MéO).

Recent Progress and Analysis Center Improvements

Between 2016 and 2018, the two main activities of POLAC – LLR predictions and LLR analysis – have significantly evolved.

Firstly, concerning the LLR predictions, with the ending of lunar observations at MLRS (McDonald Observatory) at the beginning of 2016, Randall Ricklefs, in charge of calculating LLR predictions for the "International Laser Ranging Service" (ILRS), decided to end this responsibility and it is now POLAC who takes on this task for the LLR community. This increases the international service loads of POLAC which already produced LLR predictions for a small group of stations involved in LLR via a dedicated web interface (*http://polac.obspm.fr/PaV/index.html*). Each day, POLAC now produces LLR predictions for all the five retro-reflectors on Moon under CPF formats (version 1 and version 2) and distributes them to the CDDIS and EDC database systems allowing their use by all the ILRS members and their storage for normal point post-analysis.

Secondly, in an experimental mode, POLAC provides predictions for allowing MeO Grasse station to achieve two-way laser ranging with the retro-reflectors array on board of the lunar satellite LRO (Lunar Reconnaissance Orbiter). The LRO ephemeris we use to compute laser ranging predictions are the ones produced by the LRO navigation team for the observation day in the SPICE SPK format. With this, POLAC computes a Grasse-specific light-time and azimuth/elevation prediction file in the Topocentric Prediction Format (TPF), accounting for the latest Earth Orientation Parameters provided by the International Earth Rotation and Reference Systems Service (IERS). With the help of one of these TPF files, MeO station has succeeded for the first time ever a 2-way ranging with LRO on September 4, 2018. Later two other successful passes have definitively validated the correctness of POLAC LRO-LR predictions.

Thirdly, concerning the LLR analysis, POLAC has upgraded its Lunar solution by substituting to ELP a new lunar ephemeris called ELPN (Ephéméride lunaire Parisienne Numérique). This new ephemeris has been developed by Adrien Bourgoin in the framework of his thesis (Bourgoin, 2016) by numerical integration of the differential equations governing the orbital and rotational motion of bodies in the Solar System and the difference between the Terrestrial Time (TT) and the Barycentric Dynamical Time (TDB) to make the ephemeris self-consistent. Special attention has been paid to the computation of partial derivatives integrated numerically from the variational equations.

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One of the achievements of ELPN has been to allow POLAC to take part to the long legacy of testing fundamental Physics with lunar laser ranging. Indeed, even if ELPN was built originally in the General Relativity (GR) framework, it allows for GR alternative theories of gravity as well. One of particular interest is the Standard Model Extension (SME) which parametrizes Lorentz symmetry violations, notably in the pure gravity sector (Bailey et al, 2006) and in the matter sector (Kostelecký et al, 2011) of the formalism. By fitting ELPN in the SME framework to the 50 years of collected data, we have been able to provide stringent and realistic estimates on possible Lorentz symmetry violations arising at the level of the weak and the strong Einstein equivalence principles. These results have been published in two articles in Physical Review Letters (Bourgoin et al., 2016 and Bourgoin et al., 2017). We give in Table 7-8 below the determination of six combinations of SME parameters for which the current best constrain has been achieved by this last study.

Table 7-8. SME Parameters

	SME[9]	Constraints
$\bar{s}^1$	$\bar{s}^{XY}$	$(-0.5 \pm 3.6) \times 10^{-12}$
$\bar{s}^2$	$\bar{s}^{XZ}$	$(+2.1 \pm 3.0) \times 10^{-12}$
$\bar{s}^3$	$\bar{s}^{XX} - \bar{s}^{YY}$	$(+0.2 \pm 1.1) \times 10^{-11}$
$\bar{s}^4$	$0.35\,\bar{s}^{XX} + 0.35\,\bar{s}^{YY} - 0.70\,\bar{s}^{ZZ} - 0.94\,\bar{s}^{YZ}$	$(+3.0 \pm 3.1) \times 10^{-12}$
$\bar{s}^5$	$-0.62\,\bar{s}^{TX} + 0.78\,\alpha(\bar{a}_{\mathrm{eff}}^{e+p})^X + 0.79\,\alpha(\bar{a}_{\mathrm{eff}}^{n})^X$	$(-1.4 \pm 1.7) \times 10^{-8}$
$\bar{s}^6$	$0.93\,\bar{s}^{TY} + 0.34\,\bar{s}^{TZ} - 0.10\,\alpha(\bar{a}_{\mathrm{eff}}^{e+p})^Y - 0.10\,\alpha(\bar{a}_{\mathrm{eff}}^{n})^Y$ $- 0.044\,\alpha(\bar{a}_{\mathrm{eff}}^{e+p})^Z - 0.044\,\alpha(\bar{a}_{\mathrm{eff}}^{n})^Z$	$(-6.6 \pm 9.4) \times 10^{-9}$

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Bourgoin, A., Hees, A., Bouquillon, S., Le Poncin-Lafitte, C., Francou, G., Angonin, M.-C., 2016, "Testing Lorentz Symmetry with Lunar Laser Ranging", Physical Review Letters 117, 241301.

Bourgoin, A., Le Poncin-Lafitte, C., Hees, A., Bouquillon, S., Francou, G., Angonin, M.-C., 2017, "Lorentz Symmetry Violations from Matter-Gravity Couplings with Lunar Laser Ranging", Physical Review Letters 119, 201102.

Kostelecký, V. A., Tasson, J. D., 2011. "Matter-gravity couplings and Lorentz violation", Physical Review D 83, 016013.

LAAC Personnel

- S. Bouquillon (coordinator)
- A. Bourgoin, A. Hees & C. Le Poncin-Lafitte (LLR analysis and tests of fundamental physics)
- G. Francou (LLR analysis and data collection)
- T. Carlucci (LLR and LRO-LR predictions)

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[9] Red parameters ($\bar{s}^{XY}$,$\bar{s}^{XZ}$, etc.) are from the pure gravity sector of the SME (Bailey et al, 2006) while the green parameters ($\alpha(\bar{a}_{\mathrm{eff}}^{n})^X$,$\alpha(\bar{a}_{\mathrm{eff}}^{n})^Y$, etc.) are from the pure matter sector (Kostelecký et al, 2011).

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