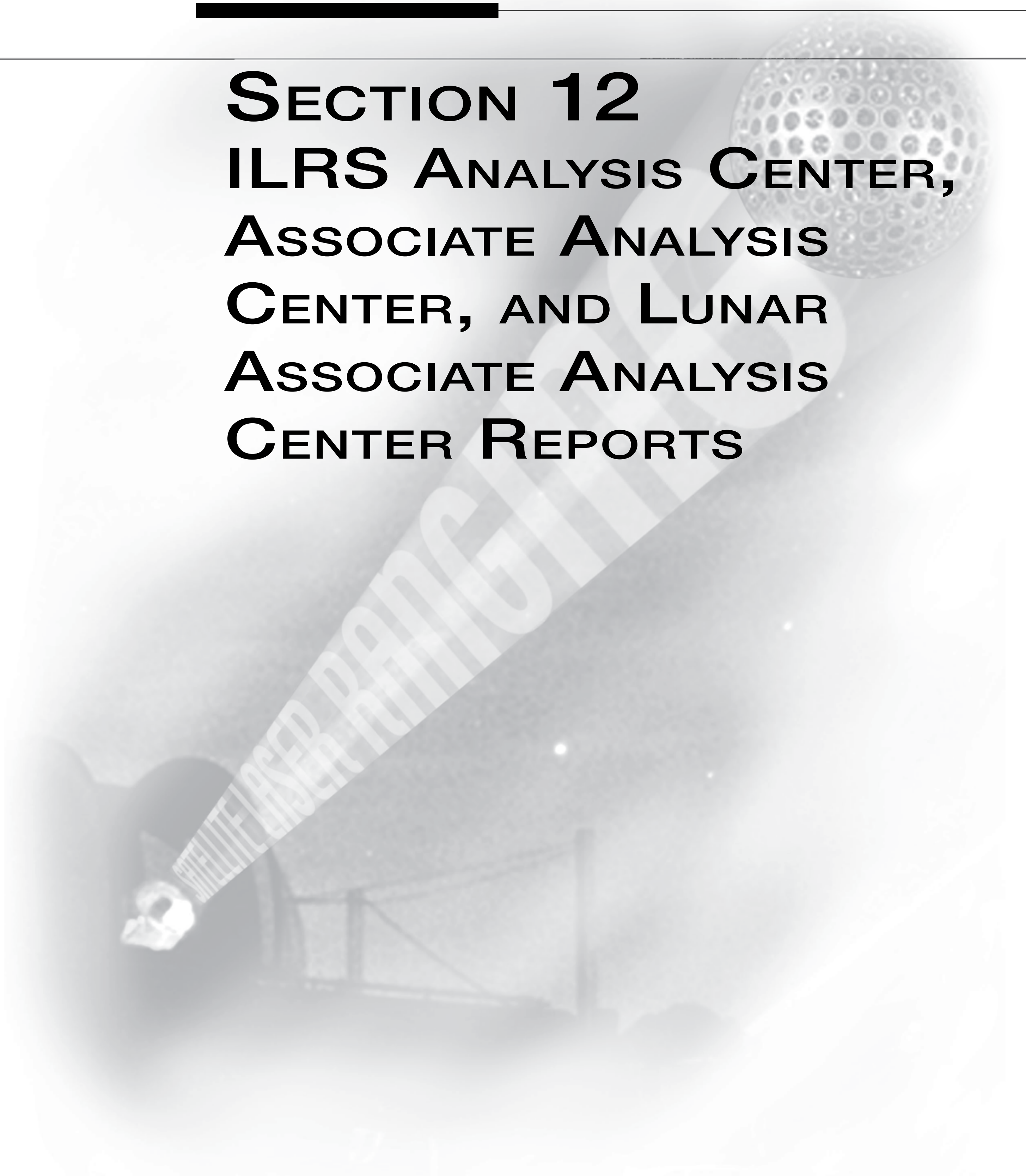
Section 12
ILRS Analysis Center, Associate Analysis Center, and Lunar Associate Analysis Center Reports



SECTION 12

ANALYSIS CENTER REPORTS

ILRS ANALYSIS CENTER REPORTS

Eight centers have been qualified as ILRS Analysis Centers. These centers are required to provide weekly submissions of Earth orientation parameters and station coordinates 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.

Italian Space Agency/Space Geodesy Center "G. Colombo" (ASI/CGS)

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Introduction

The ASI Space Geodesy Center "G. Colombo" (CGS) has contributed to the ILRS since the beginning of the service activities both in its role of fundamental station and analysis center. The SLR data analysis activities at the ASI/CGS started in the 1980's and, since then, have been focused primarily on global, extended solutions in support of the reference frame maintenance. Due to the multi-technique nature of the CGS mission, geodetic technique combination methods and applications are a top priority objective of the data analysis activities performed at the center.

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 (ACs) when the ILRS AC structure was finalized (2004). In June 2004, the center was selected by the ILRS as its primary official Combination Center (CC) for station coordinates and Earth Orientation Parameters (EOPs).

Information on the CGS and some of the analysis results are available at the CGS web server GeoDAF (Geodetical Data Archive Facility, *http://geodaf.mt.asi.it*).

ILRS Analysis Center

During 2007-2008, the ASI/CGS was deeply involved in the ILRS activities, mainly in support of the reference frame maintenance under the coordination of the Analysis Working Group (AWG). The center's main contributions were:

- Pos+EOP Products:
  - ♦ Weekly submission of loose coordinate/EOP solutions estimated using LAGEOS and Etalon data and following the ILRS product requirements. These solutions are the ASI/CGS input to the official ILRS combined SSC/EOP product.
  - ♦ Daily submission of loose coordinate/EOP solutions estimated using LAGEOS and Etalon data and following the AWG requirements. The daily product is the ASI/CGS input to the official ILRS combined EOP product, which continues in a testing phase.

- Weekly orbits: Satellite ephemerides for LAGEOS and Etalon using the solutions of the ILRS ACs will become a future ILRS product. The ASI/CGS estimated state vectors of the four LAGEOS and Etalon satellites are distributed weekly, as requested by the AWG, in the same loose reference frame of the SSC/EOPs as input to the combination.
- SLRF2005: The latest reference frame ITRF2005 was constructed using the time series of station positions and EOPs provided to the IERS by the IAG Services. The ILRS time series contribution covered the years from 1993 to 2005. This short time span had two main effects on the ITRF2005 calculation: the lack of the older SLR stations and bad estimates for those stations no longer operational in the early 1990's. To overcome these problems, a new TRF was generated from the combination of ITRF2000, ITRF2005, and those new stations starting operations following the development of ITRF2005. This TRF is considered a temporary solution to be used by the AWG until a new ILRS reference frame is constructed from the official ILRS combined weekly solutions.
- Next ITRF solution: Great effort was devoted to the definition of the AWG guidelines for the ILRS contribution to the next ITRF, mainly regarding the site biases and the core sites for the EOP referencing of the combined weekly product. The main ILRS standard product is a weekly estimate of site coordinates and EOPs over a seven-day arc; the presence of a range bias is immediately mapped in the station coordinates, mainly in the up component. A time series obtained from biased measurements can produce a scale inconsistency with respect to other geodetic techniques and SLR is very sensitive in this sense. On the other hand, the contemporary adjustment of biases and coordinates weakens the solution, causing a large scatter in the coordinate time series, and can absorb geodetic signatures. A good solution seems to be the application of known biases and biases computed with a long arc solution over decades. A bias analysis was performed on LAGEOS data for all the sites of the network for the definition of the bias to be applied in the generation of the next ILRS time series including the information taken from the CDDIS database and the site engineering reports. Different time series of solutions, covering the period 1993-2007, have been produced to test both the a priori SLRF2005 and the adopted biases.
- Station qualification: ASI/CGS is one of the ACs designated by the AWG to validate the data from new sites. The first two stations undergoing the validation were Golosiiv and Altay.

ILRS Primary Combination Center

In 2007, the ASI-CGS combination activities, within the ILRS frame, were focused on the continuous production of the ILRS official combined weekly solution and its further analysis to prepare the new long term contribution to the ITRF, as well on the preparation of new evolved ILRS combined products, serving future needs of the SLR community, as a more frequent EOP product and a continuous generation of combined SLR orbits for the main geodetic satellites. The center's main contributions as an ILRS Combination Center in 2007-2008 were:

- Pos+EOP Products:
  - Weekly submission of the ILRS official solution (ILRSA) derived from the combination of individual contributing SLR solutions based on the observations of the LAGEOS-1/-2 and Etalon-1/-2 satellites. The ILRSA solutions contain weekly coordinates of the worldwide SLR tracking network and daily EOPs (X-pole, Y-pole, LOD), ITRF-framed for IERS Bulletin B and EOPC04.
  - Daily submission of the combined coordinate/EOP solutions computed using the individual AC contributions. The final product will contain daily EOPs, ITRF-framed with a constant, minimum latency of two days. The generation of these daily solutions continues in a testing and evaluation phase.

- ♦ Weekly orbits: the experimental ILRS combined orbit consists of a combined set of state vectors for the LAGEOS-1/-2 and Etalon-1/-2 satellites, aligned to the EOP/SSC weekly product. The ILRS CCs are tasked to develop a combination procedure that will provide an optimal ILRS product from the individual AC orbital solutions. The initial study phase started with the analysis of the available SP3 test files from the ILRS ACs.

Other Activities in 2007-2008

The ASI/CGS analysis activities extended beyond the accomplishment of its role within the 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 contribution to the operational EOP series to assure the CGS contribution to the reference frames establishment. The CGS routinely provides one-day estimated EOP, from LAGEOS and Etalon data, to the IERS.
  - ♦ Generation of the multi-year solution ASI07L01, from LAGEOS-1 and -2 data (1983-2007). Global network SSC/SSV, daily EOP (x, y, LOD), and geocenter (C10, S11, C11) are the main parameters estimated in this solution and available by request.
  - ♦ Tests of the ITRF datum. In the last geodetic reference system, ITRF2005, the SLR time series was not considered in the scale definition mainly for its discontinuity in the time series. Investigations have been carried out to find a possible explanation in the unbalance of the SLR network geometry.
- IERS CPP Pilot Project: Participation to the project in a consortium (ASI, PoliMi, INGV) with the aim to design, implement and maintain the procedures for the rigorous combination of geodetic solution.
- EOP excitation functions: Pre-operational production of the geodetic excitation functions from the ASI/CGS estimated EOP values for the IERS (at present SLR only; the current use of CGS VLBI and GPS EOP is also under testing) to make them available on the ASI geodetic web site (*http://geodaf.mt.asi.it*). The daily geodetic excitation functions are produced every Tuesday along with the operational weekly SLR solution, compared whenever possible with the atmospheric excitation functions from the IERS SBAAM, under the IB and non-IB assumption, including the "wind" term.
- 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.
  - ♦ Twice 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 (*http://geodaf.mt.asi.it/html_old/ASImed/ASImed_06.html*) gives a detailed picture of the residual velocity field in the area, benefiting from the dense, permanent GPS coverage. The semiannual updating provides improvements in the velocity field information as geodetic sites become stable in terms of their data acquisition history.

Future Plans

Most of the current activities will continue, with particular attention to the ILRS- and IERS-oriented products. Deeper investigations will be directed toward the analysis of the geocenter time series and to the new time series of low degree geopotential zonals.

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Bundesamt für Kartographie und Geodäsie (BKG)

Maria Mareyen, Bernd Richter/BKG

The BKG SLR analysis center is one of the eight ILRS analysis centers that provide weekly and daily solutions from the analysis of LAGEOS-1/-2 and Etalon-1/-2 SLR data. BKG uses the Utopia (CSR Texas) software for this analysis. The satellite combinations are done at the observation level after fitting the orbits (BKG Solve). The provided products consist of a set of improved station coordinates, polar motion coordinates and LOD and their variance-covariance matrices in SINEX format according to the ILRS requirements. In addition, the weekly solution is accompanied by the sets of satellite's positions in time in the SP3c format.

To compare the performance of the SLR-ACs the combined solution from DGFI for week 071110 to 080927 is selected as a reference. Among others, the scale factor is chosen as an example (Figure 12-1).

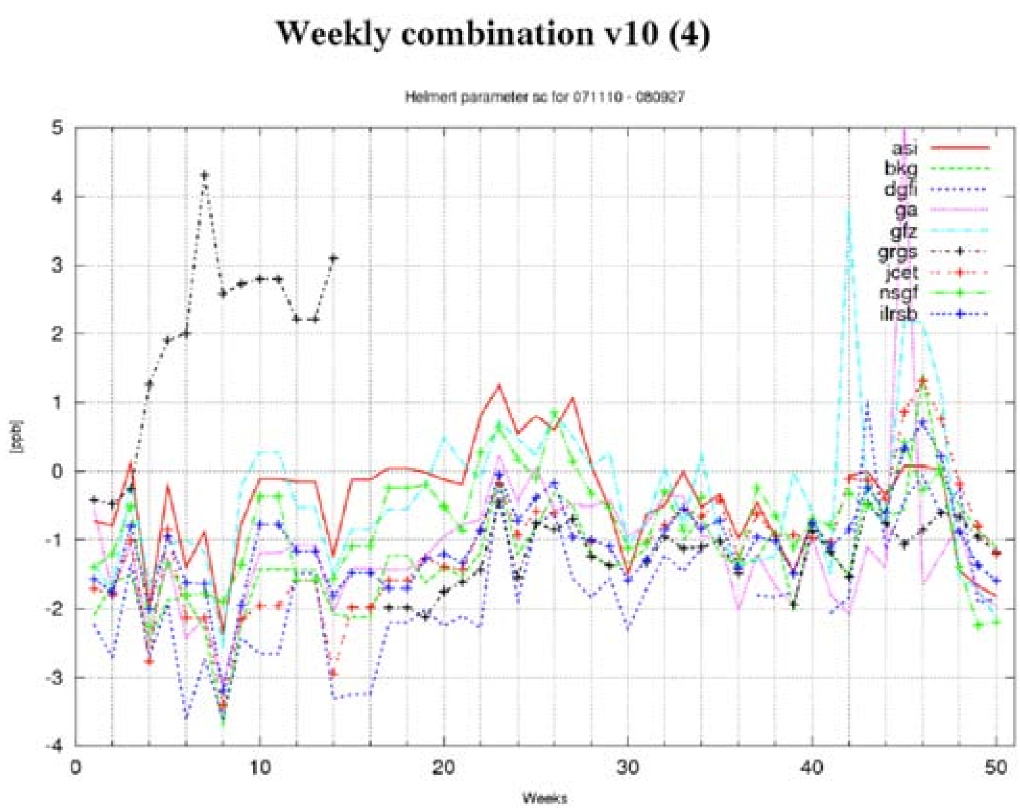

Figure 12-1. Weekly time series of the scale factor (ppb) provided by courtesy of DGFI Germany.

The BKG SLR AC supported development at AIUB to augment the Bernese software (BSW) with SLR capabilities for LAGEOS-1 and -2 data processing. Taking the SLR benchmark data set, solutions calculated with Utopia were compared with the solutions derived by the SLR component of the BSW. As a demonstration, the results of daily time series of orbit differences (AIUB versus BKG solution D) are presented in Figure 12-2. In the figure the difference between the two orbit solutions is shown in three components (light color). The darker line shows the mean value per revolution.

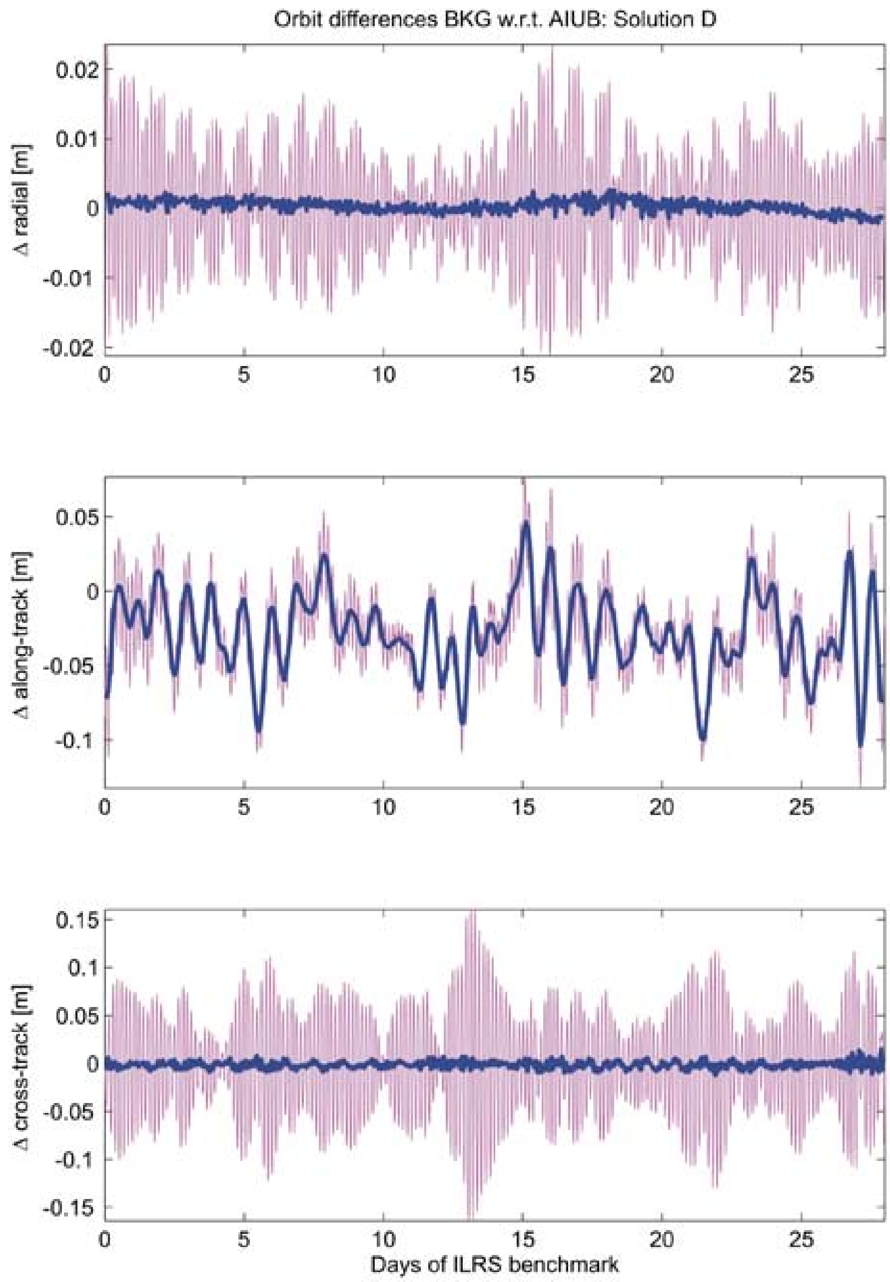

Figure 12-2. Daily time series of orbit differences (AIUB versus BKG solution D).

BKG must new develop the necessary scripts for the routine work to match the requirements and the environment of the SLR-BSW installation at BKG.

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Deutsches Geodätisches Forschungsinstitute (DGFI)

Horst Müller, Rainer Kelm, Detlef Angermann/DGFI

Introduction

As one of the ILRS Analysis Centers, DGFI was, besides the routine weekly processing of SLR station positions and Earth orientation parameters (EOP) and LAGEOS orbits, heavily involved in the processing required for the SLR time series for the new ITRF2008 reference frame. Furthermore, the backup solution for the combined SLR time series was computed at the DGFI ILRS Backup Combination Center. Other activities include the daily processing of a bias report for all SLR stations, using the LAGEOS and Etalon observations, and the qualification of new or returning SLR stations. The activities in the GGOS-D project concluded in 2008 with the final combined solution.

ILRS Analysis Center

As an ILRS Analysis Center, DGFI processes (on a weekly operational basis) SLR data to LAGEOS-1/2 and Etalon-1/2 and provides loosely constrained solutions (SINEX files) with station positions and Earth orientation parameters (X-pole, Y-pole and length of day) to the ILRS data centers at CDDIS and EDC. This processing is accomplished with the DGFI software package DOGS version 5.0. Additionally, orbits to these satellites are routinely processed and delivered.

During the automated processing, a number of quality checks are performed; one of these checks is the computation of pass-wise range and significant time biases. The weekly solutions and the results of the bias analysis sorted by satellite and week are available from the DGFI web server, *http://ilrsac.dgfi.badw.de/quality/index.html*. We provide the biases with respect to SLRF2005 coordinates for all stations and passes, but presently for the LAGEOS satellites only.

DGFI has agreed to maintain a list of station discontinuities and data handling, which will be distributed to all analysts through the data centers at CDDIS and EDC. Together with ASI and GRGS, DGFI performs the station qualification testing for new and returning tracking stations.

ILRS Combination Center

DGFI, as the official ILRS Backup Combination Center, uses the same procedures and constraints as the ILRS Primary Combination Center, which is performed by ASI, Italy. Both centers are obliged to compute, on a weekly basis, a combined SLR solution as an official product of the ILRS. The products are stored at the ILRS data centers. Both Combination Centers use software versions for automated processing.

The official weekly products are:

- Combined solution for station coordinates and EOP. DGFI delivers a SINEX file with a minimal constraints solution and with an unconstrained normal equation system.
- Combined solution for EOP aligned to SLRF2005. DGFI takes the EOP part of the above combined solution arguing that the minimal constraints solution is indirectly an alignment to SLRF2005, because the a priori coordinate values are taken from SLRF2005.

The combination of SP3c orbits is in a testing phase. When the AWG decides on the final product, combined LAGEOS-1/2 and Etalon-1/2 orbits, can be processed and provided to users.

More information on the analysis and Combination Center at DGFI is available from our homepage: *http://ilrsac.dgfi.badw.de/*.

Contribution to ITRF2008

After long discussions on ITRF2005, the generation of the next ITRF (ITRF2008) is now in process. DGFI is involved in the reprocessing. The reprocessed series of 15-days resp. weekly SINEX files with station positions and EOPs ranging from 1983 to 2008 were processed and sent to the data centers. The DGFI Combination Center combines all contributions from the eight Analysis Centers into the combined backup product, which will be used for validation. Figure 12-3 shows the transformation parameters from the similarity transformation between the new DGFI series for ITRF2008 and SLRF2005. There is a small drift, though data before 1993 are significantly worse than later periods. The figure shows a small offset and drift of scale and origin.

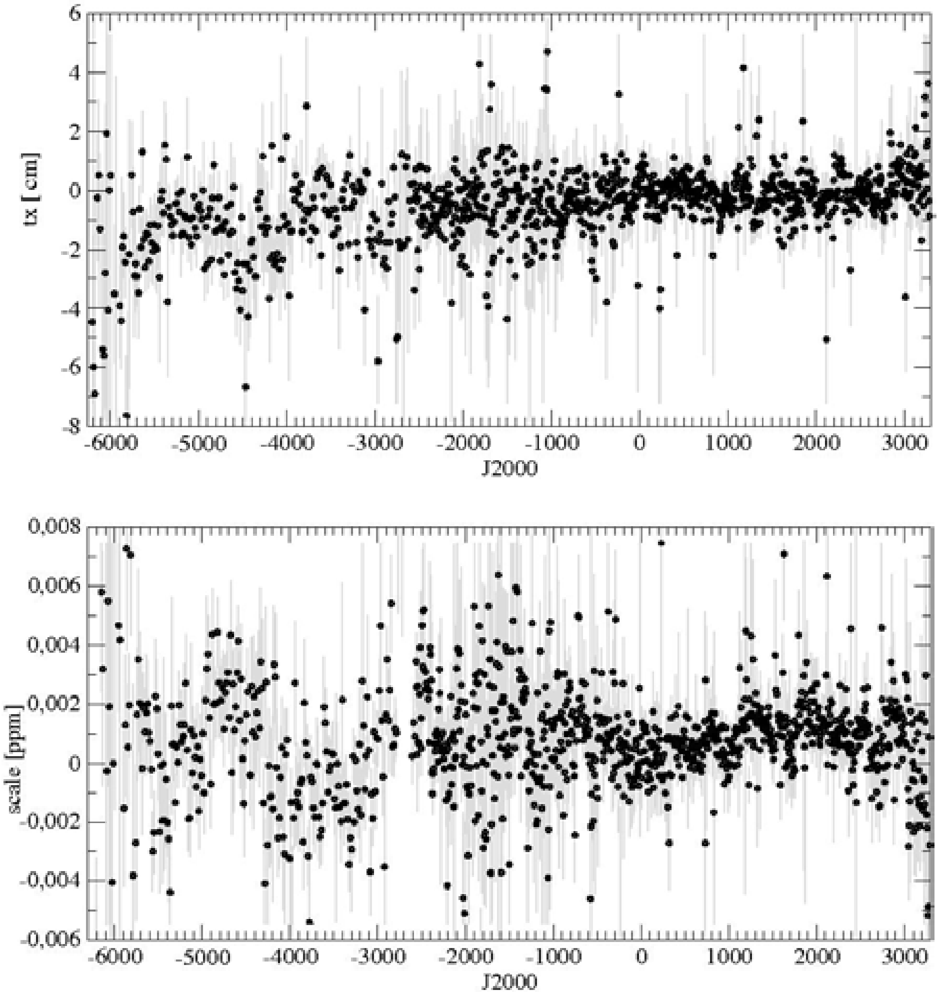

Figure 12-3a and -3b: Transformation parameters between DGFI solution and SLRF2005 with error bars.

Future Plans

Since the problems with the EOP interpolation and the LOD variations seem to be solved in the DGFI software, participation in the daily processing activity is foreseen. A still pending project is the routine processing of Starlette and Ajisai data, which should be resolved in 2009.

References

Angermann D., Drewes H., Gerstl M., Krügel M., Meisel B.: ITRS Combination Centre at DGFI.. ITRS Combination Centre at DGFI., IERS Annual Report 2006, Bundesamt fuer Kartographie und Geodaesie, Frankfurt a.M. , 2008

Angermann D., Müller H.: On the strength of SLR observations to realize the scale and origin of the terrestrial reference frame. IAG Symposia, Vol.133,3-9, Springer 2009.

Angermann D., Drewes H., Gerstl M., Krügel M., Meisel B.: DGFI combination methodology for ITRF2005 computation, Proceedings of the IAG Symposium Geodetic Reference Frames GRF 2006 Munich, Springer, 2009, in press.

Krügel, M, Angermann, D., Drewes, H., Gerstl, M., Meisel, B., Tesmer, V., Thaller, D.: GGOS-D Reference Frame Computations. GEOTECHNOLOGIEN Science Report, No. 11, ISSN 1619-7399, 2007a.

Müller H., Angermann D.: Some Aspects Concerning the SLR Part of ITRF2005. In: Luck J., Moore Ch., Wilson P. (Hrsg.): Proceedings of the 15th International Workshop on Laser Ranging, EOS Space Systems PTY Limited, Canberra, 2008

Müller H.: Analysis of Multi-Wavelength SLR Tracking Using Precise Orbits. In: Luck J., Moore Ch., Wilson P. (Hrsg.): Proceedings of the 15th International Workshop on Laser Ranging, EOS Space Systems PTY Limited, Canberra, 2008

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Geoscience Australia (GA)

Ramesh Govind/Geoscience Australia

Introduction

Geoscience Australia (GA) was accepted as an ILRS Analysis Center in April 2007 after successfully completing and fulfilling all the benchmark requirements. During the period 2007-2008, focus has been on the weekly ILRS SINEX submissions and contribution to the ITRF2008. These results have been reported by the AWG Combination Centers. The GA Analysis Center routinely processes LAGEOS-1/-2, Etalon-1/-2, Stella, Starlette, GIOVE-A and GLONASS data for satellite orbit determination, station coordinates, Earth Orientation Parameters, station performance monitoring and developing a long-term time series of the low-degree and order spherical harmonic coefficients of the Earth's gravity field.

Facilities/Systems

The GA processing system uses NASA's GEODYN and SOLVE set of programs for orbit determination, geodetic parameter estimation, and combination solutions. A suite of programs has been developed in-house for analysis, re-formatting, and producing SINEX files.

Analysis Activities during 2007-2008

- Weekly solutions consisting of LAGEOS-1, LAGEOS-2, Etalon-1 and Etalon-2 data for the ILRS weekly product.
- As a contribution to the definition of the ITRF2008, weekly SINEX solutions were provided for the period 1983-2008, as per the requirements of the ILRS AWG.
- Stella and Starlette data for the period beginning 1996 through the end of 2008 were processed to study the contribution of these satellites to the definition of the ITRF. This work was reported at the 2007 Fall AGU in San Francisco (see below).
- In terms of GNSS, the potential for SLR observations to contribute to the definition of the ITRF and determination of other geodetic products (such as EOPs), the following SLR data were processed and the preliminary results were reported at the International GNSS Symposium in Sydney, 2007 (see Table 12-1 below).

Table 12-1. SLR Data from GNSS Satellites Processed for Geodetic Products

Satellite	Start Date	End Date
GLONASS -80	991024	020224
GLONASS -84	010701	050828
GLONASS -86	020303	021229
GLONASS -87	020303	070128
GLONASS -89	030323	070429
GLONASS -95	050904	070527
GLONASS -99	070121	070520
GIOVE-A	060528	071230

- SLR data to the Jason-1 and Envisat satellites were used to quality check their DORIS-determined orbits and to also compare the satellite orbits determined from the two observation types. These results were routinely presented at the International DORIS Service (IDS) AWG meetings. The Jason-1 and Envisat SLR data processed for this study are shown below:

Table 12-2. SLR (and DORIS) Data Processed for Orbit Comparison Studies

Satellite	Start Date	End Date
Jason-1	020120	080817
Envisat	020616	081231

Current Activities

Since the completion of the ITRF2008 submissions, focus is now on:

- Evaluating the potential contribution of SLR GNSS data to ILRS geodetic products
- Evaluating the contribution of Starlette and Stella to the ITRF definition
- Continuing quality checks of DORIS orbit products using SLR observations for Jason-1, Jason-2, and Envisat.

Related Publications

During the period 2007-2008 the following presentations were made:

Govind, R., F.G. Lemoine, N. Zelensky, S. Luthcke: "Evaluation the effect of atmospheric gravity and annual gravity field variation on LAGEOS orbits", ILRS Fall Workshop, Grasse, September 2007.

Govind, R., F.G. Lemoine, Z. Altamimi, K. Le Bail, D. Chin: "The contribution of Starlette/Stella SLR to Terrestrial Reference Frame definition, American Geophysical Union Fall Meeting, December 2007.

Govind, R. "The value of SLR observations to GNSS: The potential for Terrestrial Reference Frame Definition", International GNSS Symposium, Sydney, December 2007.

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Helmholtz Centre Potsdam GeoForschungsZentrum German Research Centre for Geosciences (GFZ)

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Activities in Support of the ILRS

Submission of orbit predictions for CHAMP, GRACE-A and -B and TerraSAR-X

For CHAMP, orbit predictions were updated three times per day prior to September 1, 2007, afterwards four times per day. For GRACE the update frequency was twice per day. Since its launch on June 15, 2007, TerraSAR-X orbit predictions are also produced. The update frequency for this satellite depends on the availability of the on-board data and has been twice per day in most cases so far.

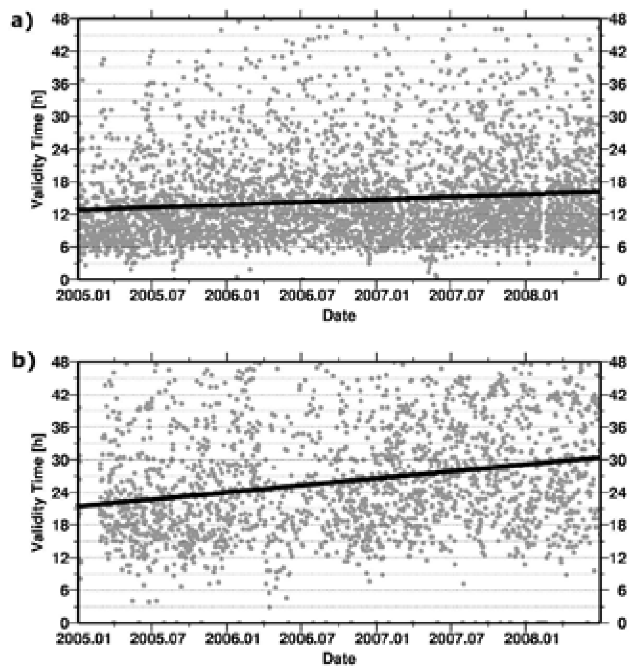

Figure 12-4. Validity times for all GFZ orbit predictions since 2005 for a) CHAMP and b) GRACE-A.

The accuracy of the orbit predictions is continuously monitored in order to allow for daylight ranging for what we assume is an error margin of 10 ms in time bias. Due to decreasing orbital altitudes and increasing solar activity, a faster degradation of the orbit prediction accuracy can be expected. The degradation can be avoided by enhancing the orbit prediction update frequency presumably if new input data become available to allow an update. For this reason GFZ operates the polar satellite receiving station at Ny lesund (Spitzbergen), which enables download of the on-board data of the missions mentioned above nearly once per revolution, i.e., approximately every 1.5 hours. Figure 12-4 shows the validity time for all orbit predictions generated for CHAMP and GRACE-A since January 2005. The validity time is defined as the time in the predicted part of the orbit in which the time bias stays below 10 ms. The analysis shows that the majority of the orbit predictions is valid for more than six hours for CHAMP and for more than 12 hours for GRACE. These results justify the update frequency adopted thus far. The analysis also shows a trend towards increased validity times, which might be due to the concurrent low solar activity period.

GFZ's orbit prediction products consist of IRVs with drag functions, SAO elements, two-line elements, and the CPF format. The generation of IRVs with drag functions and SAO elements was terminated in December 2008. The orbit prediction generation system experienced no major downtimes and therefore has an operational readiness of nearly 100%.

Production of position and Earth orientation parameters from LAGEOS-1 and -2 analyses

GFZ continued its ILRS analysis center activities concerning the Pos+EOP project. Loosely constrained station position estimates with weekly resolution and Earth orientation parameters (polar motion and length-of-day) with daily resolution from LAGEOS analyses were submitted each week with three days latency in the form of SINEX files within the full reporting period. Since February 17, 2008, GFZ is additionally providing similar solutions on a daily basis with a one-day latency.

In support of the ITRF2008 development, historical LAGEOS data from 1983 up to the present were processed and supplied to the ILRS combination centers.

Production of LAGEOS-1 and -2 orbits in SP3 format

Since December 2, 2008, GFZ has delivered orbit solutions for LAGEOS-1 and -2 to the ILRS data centers. These orbit solutions correspond to the weekly Pos+EOP product and are provided in the SP3 orbit format.

Other Activities Involving SLR Data

- Regular computation of ERS-2 preliminary and precise orbits using SLR observations under ESA contract.
- New precise, consistent EIGEN-GRACE04S orbits of the radar altimetry satellites ERS-1, TOPE Poseidon, and ERS-2 with recent models.
- Monitoring of CHAMP, GRACE, and TerraSAR-X operational POD
- Generation of dedicated CHAMP, GRACE, LAGEOS, and general purpose satellite-only gravity field models and combined gravity field models from satellite and surface gravity data: the EIGEN series.
- Generation of an SLR reference frame solution for a rigorous combination with other space-geodetic solutions under common, up-to-date standards within the GGOS-D project
- Combined adjustment of GPS and Low Earth Orbiting (LEO) satellites on the observation level with GPS, SLR and mission-specific observations for reference frame and gravity field resolution (integrated approach).

Future Plans

- Adopt CRD format for observation data
- Processing and analysis of historical LAGEOS tracking data from 1976 to 1982
- Processing of LAGEOS long arcs
- Generation of Pos+EOP QC reports
- Consistent reprocessing of radar altimetry satellite orbits in ITRF2008 using up-to-date models
- Rigorous combination of space-geodetic data on the observation level for geodynamic applications

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Operational Activities

1. ILRS weekly products: solution sent to ILRS data centers on a weekly basis. SINEX files contain EOP, station coordinates. Based on LAGEOS-1 and -2 orbital arcs (Etalon-1 and -2 currently being tested).
2. ILRS daily products: solution sent to ILRS data centers on a daily basis. SINEX files contain EOP, station coordinates.
3. Planned developments: solutions based on Etalon-1 and -2 orbits, as well. Optimization of the combination between different dynamical configurations, time series of degree 2 gravity field coefficients, on an operational basis.
4. References: EGU 2009, EGU 2008, COSPAR 2008, SF2A 2008, SF2A 2007

Analysis/Reanalysis Activities

1. Analysis/reanalysis for ILRS: comparison between the so-called “GRGS v11 solution” and “GRGS v20 solution”, over the period 1993-present. Reanalysis of historic data (before 1993) under investigation.
2. Analysis for GRGS (combination center): GRGS-OCA is in charge of a complete reanalysis of SLR data (2005-present), for all geodetic satellites (especially LAGEOS-1 and -2, but other satellites as well, Starlette and Stella in particular), with a force model accounting for all loading effects. GRGS aims at providing a global solution for EOP, and station coordinates, thanks to a combination of individual solutions based on SLR, GNSS, VLBI, or DORIS data.
3. Daily analysis of T2L2 (Time Transfer by Laser Link) data.
4. Other activities: orbit determination and validation for various satellites: Jason-1, Jason-2, GPS-35, GPS-36, GIOVE-A, GIOVE-B.
5. Planned developments: time series of gravity field coefficients, on an operational point of view (degree 2 to degree 5), on a weekly basis.

Methodological Activities:

1. Methodological activities concerning orbit modeling: empirical forces modeling, non-gravitational forces modeling (LAGEOS-1 and -2), correlation with gravity field and EOP coefficients.
2. Methodological activities concerning time and range bias: optimization of the de-correlation of the parameters.
3. Methodological activities concerning statistics and estimation methods: optimization of the combination between different dynamical configurations, comparisons of results obtained from merely “geometrical” approaches, and merely “dynamical” approaches.
4. Planned developments: time transfer equations.

Fields of Interest

- Earth rotation, and its gravity field
- Station coordinates, range bias, terrestrial reference frame
- Fundamental physics
- Orbit determination and validation
- Motion of the Moon

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Joint Center for Earth Systems Technology/Goddard Space Flight Center (JCET/GSFC)

Erricos C. Pavlis, Magdalena Kuzmicz-Cieslak, and Peter Hinkey/JCET

Introduction

The JCET/GSFC AC participated in all AWG-related ILRS activities during the period 2007-08. In addition this AC presently coordinates the overall activities of the AWG. Since April 2001, we routinely analyze LAGEOS-1 and -2, and Etalon-1 and -2 data for the generation of the weekly operational products. In 2007 we investigated the development of an additional daily operational product to address the needs of IERS' NEOS service for as "fresh" EOP estimates as possible. After a test-period of some months, the procedure was presented to the AWG and it was decided to run a pilot project that would give the opportunity to other ACs to contribute to this product and give the CCs the opportunity to merge them into a combined product with similar attributes to the weekly one. This was formally installed as a pilot project in late 2008 with initially three ACs contributing to the product. Upon evaluation of the results by NEOS, the AWG will decide whether to continue or abandon this effort. The JCET-developed web-based process to generate a summary, visualizations and statistical analysis product of the official weekly ILRS products has been further improved, extended to include the contributions from the additional ACs that joined the AWG during this period (GA and GRGS). The web pages can be accessed from: *http://geodesy.jcet.umbc.edu/ILRS_QCQA*. Figure 12-5 shows the initial page.

Figure 12-5. Front page of JCET's "Evaluation, Validation and Monitoring of ILRS combination products".

The entire process has been revisited during 2008 and a new one has been designed which will be far more flexible, allowing the user to select the period of time and the type of products to be plotted, a choice of the plot scale and access to the data used to generate the plots. This new system is expected to be functional for a test-period in 2009 and soon after released for public access.

Since JCET is also coordinating the AWG, it is also conducting the software benchmarking process for all new candidate ACs for the ILRS. During 2008 we had initial submissions from ESA/ESOC and an existing AC (BKG) since they are in the process of exchanging the currently used software (Utopia) with a new version of the Bernese software that was extended to handle laser range data.

The collaborative work with the Italian groups at the University of Lecce and University of Rome ("La Sapienza"), resulted in the approval of the LARES mission by ASI and initiation of the construction of the satellite. In support of the LARES mission design group, JCET prepared several targeted studies tailored to address questions associated with the optimization of the spacecraft design.

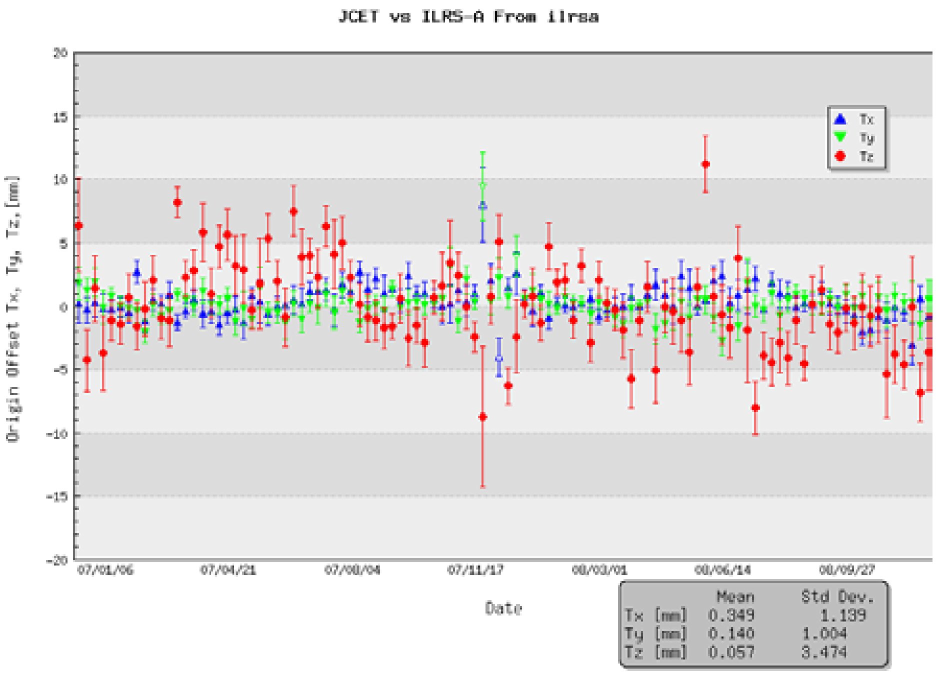


Figure 12-6. Time series of origin shifts of the JCET contribution with respect to the ILRS combination product for 2007 - 2008.

Background

The activities of JCET are primarily focused on the analysis of SLR data from LAGEOS -1/-2 and Etalon-1/-2, as required for the generation of ILRS products. The products supported are weekly station positions (and velocities for the multi-year solutions) and the Earth Orientation Parameters, xp, yp, and LOD at daily intervals. In anticipation of a future ILRS product, we also form on a weekly basis a cumulative solution that is based on the entire set of analyzed data from 1993 to present. The weekly sets of normal equations are also used to derive a weekly resolution series of "*geocenter*" offsets from the adopted origin of the reference frame, defined by the multi-year solution.

Facilities/Systems

The operational products are now developed on a Linux cluster with eight processors. Over a period of six months in 2008, the processes were run in parallel on the Sun workstation and the Linux cluster to ensure that the processes were delivering identical results. Once the consistency was assured, the old line of production was switched off and the new line replaced it.

Current Activities

The generation of weekly solutions as a contribution to the IERS/ITRF and the monitoring of episodic and seasonal variations in the definition of the geocenter with respect to the origin of the conventional reference frame continues in a routine manner (Figure 12-6).

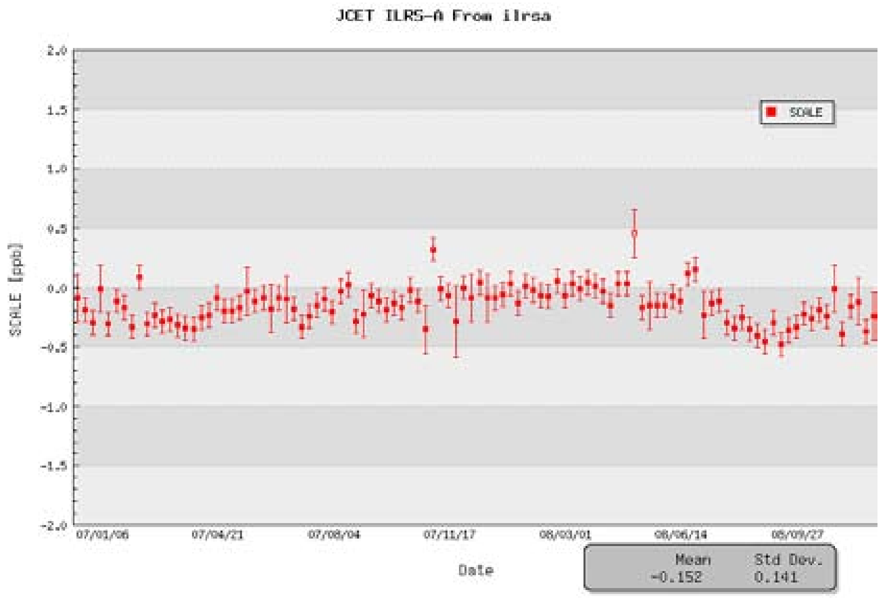


Figure 12-7. Time series of scale of the JCET weekly contribution with respect to the ILRS combination product for 2007-2008. The 0.141 ppb standard deviation corresponds to less than 1 mm in length.

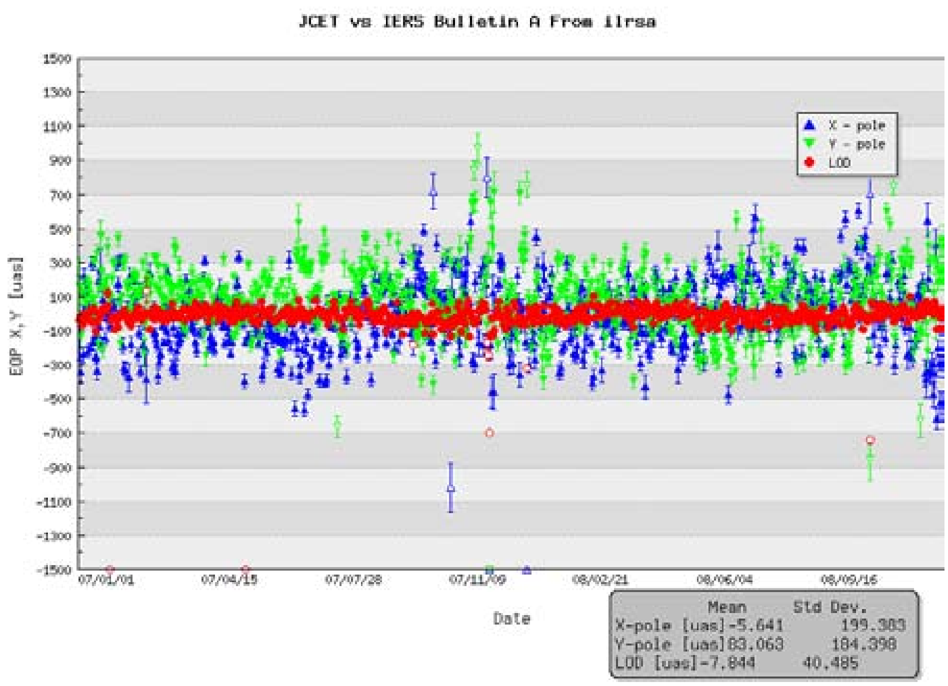
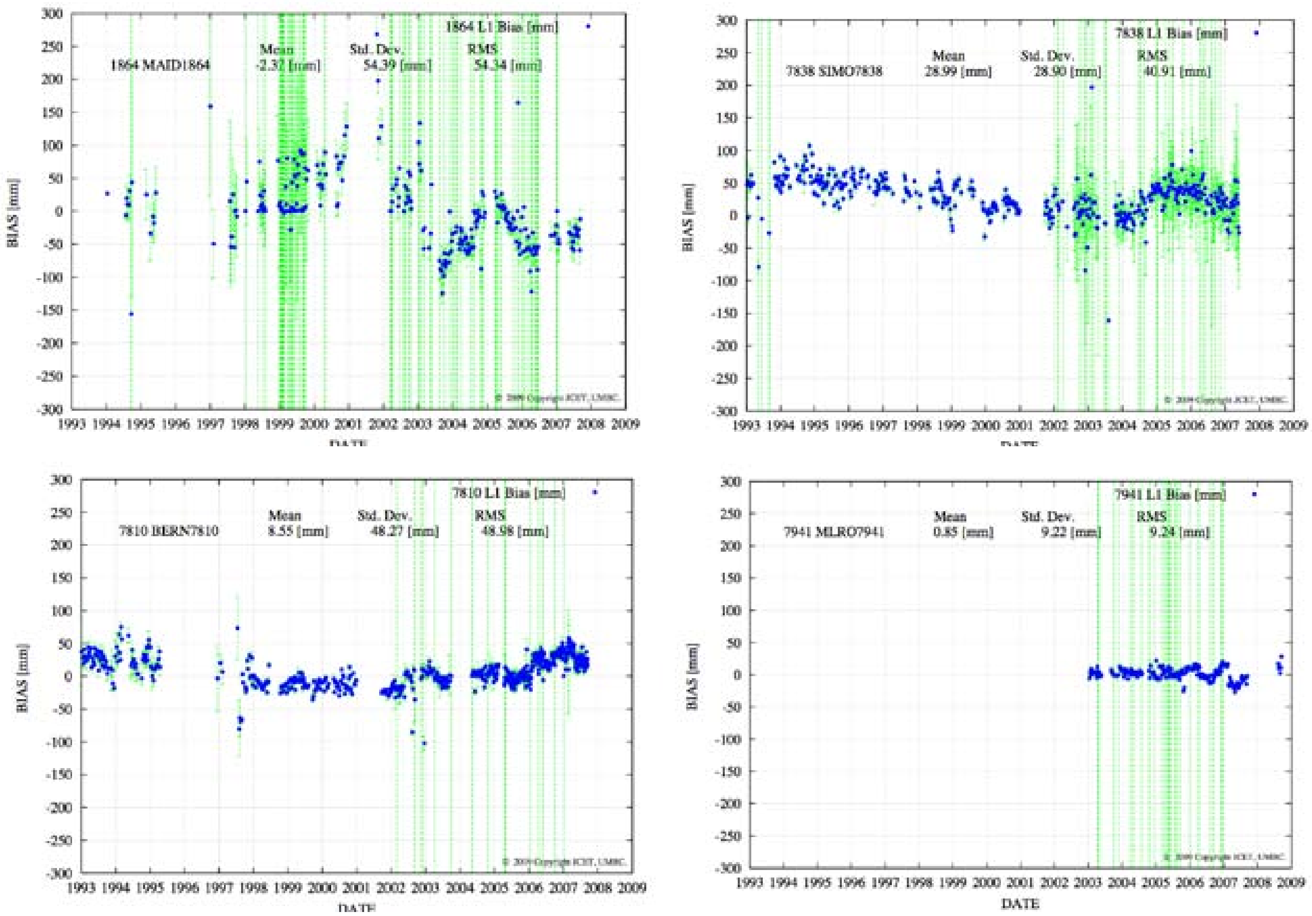


Figure 12-8. Time series of JCET EOP daily offsets from IERS' Bulletin A, for 2007 – 2008.

Figure 12-7 shows the evolution of the weekly scale estimates from JCET over the reporting period, indicating a very small bias with respect to the SLRF2005 a priori frame, and a stability of less than 1 mm (0.141 ppb). The differences of the daily JCET EOP estimates from the Bulletin A series are shown in Figure 12-8. The statistics of these differences are only 10% larger than the corresponding statistics or the final combined ILRS product, indicating a high level of consistency with that product.

Following the evaluation of the ILRS contribution to ITRF2005, the AWG decided to undertake a closer look at station biases and to adopt an approach that would lead to a uniform treatment of biases by all ACs. Using long-term solutions base on all of the analyzed years since 1983, biases were estimated with respect to the frame that resulted from this solution. These are far more stable than those obtained from weekly solutions which are strongly correlated to the station height. Examples of such estimates are shown in Figure 12-9 for some of the stations with characteristic problems.

The need to recover biases at the data analysis stage is increasing, especially as we advance in the background modeling efforts and errors previously hidden in the noise, are now becoming the dominant ones. As the modeling progresses, smaller systematic errors, as the various measurement biases, are now becoming the leading errors. Through such investigations we attempt to identify biases at or below the 10 mm level, which are impossible to detect with engineering tests. When correlated with events at the station, then these biases are adopted and applied a priori, leading to by far more stable solutions.



Figures 12-9a-d. Time series of weekly biases from a JCET long-term solution based on LAGEOS data from 1993 to 2008.

Finally, one of the additions to JCET's ILRS data analysis related contributions during this period is the development of a quality control and assessment solution on a daily basis. The biases of all ILRS sites with respect to the two LAGEOS and Etalon are monitored and reported via a standardized email message. This contributes to the ILRS combined bias estimate and the quarterly report cards, starting with the last quarter of 2007: *http://ilrs.gsfc.nasa.gov/stations/site_info/global_report_cards/perf_2008q4_wLLR.html.*

JCET has been selected by NASA as the US PI for the Italian Space Agency (ASI) mission LARES, to launch a cannoball satellite in a ~1500 km circular orbit with an inclination of ~71°.5, in order to improve the results of the joint relativistic experiment and measurement of the GR-predicted Lense-Thirring effect or "frame-dragging". The team that submitted the successful proposal includes GSFC, USNO and University of Texas at Austin co-investigators. The proposed work involves studies for the improved modeling of forces acting on the satellite, improved geometric correction models for the accurate description of the satellite's "center-of-mass" offset, thermal force modeling and spin-axis orientation and rate estimation.

Future Plans

ILRS-related activities will continue, with emphasis on the near-real-time generation of weekly products and their dissemination via the web. We have extended our analysis to years prior to 1993, with the generation of 15-day SINEX files beginning with the launch of LAGEOS in May 1976. Emphasis is now placed on the completion of simulation studies that will provide guidelines in the design of the future geodetic network to support the accuracy goals of the GGOS program of IAG. GGOS is focused on addressing very tough problems, e.g., Mean Sea Level monitoring, imposing stringent accuracy requirements in the definition of the underlying reference frame (less than 1 mm accuracy in the origin definition at epoch, and less than 0.1 mm/y stability).

References, Publications, Presentations (2007-2008)

Ciufolini, I. A. Paolozzi, S. Dell'Agnello, I. Peroni, F. Graziani, G. Sindoni, C. Paris, C. Vendittozzi, P. Ialongo, C. Cerruti, A. Lucantoni, A. Boni, C. Cantone, G. Delle Monache, A. Franceschi, T. Napolitano, N. Intaglietta, M. Martini, M. Garattini, G. Bellettini, R. Tauraso, L. Caputo, F. Passeggio, F. Longobardo, E. C. Pavlis, R. Matzner, D. P. Rubincam, D. Currie, V. J. Slabinski, D. A. Arnold, "The Design of LARES: a Satellite for Testing General Relativity", paper IAC-07- B4.2.07 in proceedings of 58th International Astronautical Congress, Hyderabad, India, 24 - 28 September, 2007.

Ciufolini, I., E.C. Pavlis, et al., (2009), "Gravitomagnetism and its Measurement with Laser Ranging to the LAGEOS satellites and GRACE Earth Gravity Models", in *Lectures at the Wheeler school on relativity*, 2006 Erice Summer School Lecture series, (in press).

Hulley, G. C. and E. C. Pavlis, A ray-tracing technique for improving Satellite Laser Ranging atmospheric delay corrections, including the effects of horizontal refractivity gradients, *J. Geophys. Res.*, 112, B06417, doi:10.1029/2006JB004834, 2007.

Hulley, G. C., E. C. Pavlis and V. B. Mendes (2007), Model validation for improved atmospheric refraction modeling for Satellite Laser Ranging, *Dynamic Planet - Monitoring and Understanding a Dynamic Planet with Geodetic and Oceanographic Tools,* (Chapter 119), Tregoning, P., Rizos, C., (eds.), IAG Symposia 130, ISBN: 978-3-540-49349-5, pp. 844-852, 2007.

Hulley, G., and E. C. Pavlis, (2007), Improvement of Current Refraction Modeling in Satellite Laser Ranging (SLR) by Ray Tracing through Meteorological Data, 15th Int. Laser Workshop, John Luck (ed.), pp. 345-350, Geosciences Australia, Canberra.

Kopeikin, S.M., E. C. Pavlis, D. E. Pavlis, V.A. Brumberg, A. Escapa, J. Getino, A. Gusev, J. Müller, W.-T. Ni, N. Petrova, (2008), Prospects in the orbital and rotational dynamics of the Moon with the advent of sub-centimeter lunar laser ranging, *J. Adv. Space Res., doi:10.1016/j.asr.2008.02.014.*

Pavlis, E. C., (2007), The Global SLR Network and the origin and scale of the TRF in the GGOS era, 15th Int. Laser Workshop, John Luck (ed.), pp. 159-166, Geosciences Australia, Canberra.

Pavlis, E. C., V. Mendes and G. Hulley, (2007), Tropospheric Model: Optical Techniques, *IERS Conventions 2003*, G. Petit and B. Luzum eds., IERS Technical 32, (Chapter 9, pp. 1-7), online version: *http://tai.bipm.org/iers/conv2003/conv2003.html*, Paris, France, 2007.

Pavlis, E. C., I. Ciufolini, and R. König (2007), Recent Results from SLR Experiments in Fundamental Physics, 15th Int. Laser Workshop, John Luck (ed.), pp. 69-78, Geosciences Australia, Canberra.

Pavlis, E. C., (2007), SLR-based evaluation and validation studies of candidate ITRF2005 products, 15th Int. Laser Workshop, John Luck (ed.), pp. 173-179, Geosciences Australia, Canberra.

Pavlis, E. C., V. Mendes and G. Hulley, (2008), Tropospheric Model: Optical Techniques, in IERS Conventions 2003, G. Petit and B. Luzum eds., IERS Technical 32, online version: *http://tai.bipm.org/iers/convupdt/convupdt.html, Paris, France, 2008.*

Pearlman, M., Z. Altamimi, N. Beck, R. Forsberg, W. Gurtner, S. Kenyon, D. Behrend, F.G. Lemoine, C. Ma, C.E. Noll, E.C. Pavlis, Z. Malkin, A.W. Moore, F.H. Webb, R.E. Neilan, J.C. Ries, M. Rothacher, and P. Willis, GGOS Working Group on Networks, Communication, and Infrastructure, Dynamic Planet - Monitoring and Understanding a Dynamic Planet with Geodetic and Oceanographic Tools. Rizos, C., Tregoning, P. (Eds.) , IAG Symposia 130,ISBN: 978-3-540- 49349-5, 2007.

Pearlman, M., C. Noll, J. McGarry, W. Gurtner, E. Pavlis, The International Laser Ranging Service, AOGS 2007, *Adv. Geosciences, v. 13, pp. 129-153*, World Scientific.

Willis, P., J.C. Ries, N.P. Zelensky, L. Soudarin, H. Fagard, E. C. Pavlis, and F.G. Lemoine, (2009), "DPOD2005 : An extension of ITRF2005 for Precise Orbit Determination", *Advances in Space Res., 44 pp.535–544, Elsevier, The Netherlands, doi:10.1016/j.asr.2009.04.018.*

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Natural Environment Research Council (NERC) Space Geodesy Facility (NSGF)

Graham Appleby, Philip Gibbs, Matthew Wilkinson, and Vicki Smith/NERC

Introduction

The primary work of the NSGF Analysis Center has been an ongoing global laser ranging re-analysis effort as a contribution to the ILRS combination that will be part of the next realization of the International Terrestrial Reference Frame, ITRF2008. Several attempts have been made by the AC to mitigate systematic range effects of up to 15mm in both the Herstmonceux data itself and potentially for other stations that have used similar time-of-flight counters; various generations of these corrections have meant that all the ACs have been asked on several occasions to repeat the analysis work to produce for the early time-frame (1983-1992) 15-day and for the more modern (1993-date) 7-day coordinate solutions. Finally, it was decided within the ILRS Analysis Working Group that a mixture of engineering and empirical range corrections best fitted the ITRF efforts, and final analyses are being carried out.

Furthermore, the availability of laser ranging, GPS, and absolute gravity data from the Herstmonceux site, plus the ability to analyze each data set, has opened up some exciting opportunities for research, especially into vertical signals at the site. Supporting data in the form of high-time-resolution water table depth measurements are also available continuously from 1996 to date, and have been used in some recent investigations, as outlined below. The AC continues to supply back-up daily satellite orbital predictions in CPF form, and to carry out daily web-based global QC of the four primary geodetic satellites LAGEOS and Etalon.

Possible Systematic Bias in SGF Laser Range Data

The NSGF AC has been re-analyzing global laser ranging data to the geodetic satellites from 1983 to present, for later combination by the primary and backup Combination Centers into the ILRS contribution to the forthcoming ITRF2008. During the course of this work, coordinated by the ILRS Analysis Working Group, it became apparent that either there was a dramatic decrease in the height of the 7840 Herstmonceux station of some 15mm from early 2007, or that some systematic error had entered the laser ranging data from that date. This was the time that the new, highly accurate event timer was introduced operationally into the ranging system, and the extensive tests did not reveal any problems, certainly of the magnitude experienced with the Stanford counters used from 1993 to 2007. Reports were also received from other users of the SGF data, especially those doing precise orbital determination of the altimeter missions (Lemoine, F, private communication, 2008) that a jump had occurred in the laser ranges to those satellites as well. To test whether there was a data problem or a site-motion or stability problem, an analysis of the vertical motion of the site from 2006 to 2008 using GPS, SLR and AG data was carried out, and the results reported in a presentation at the 16th International Workshop on Laser Ranging in Poznan, Poland, in October 2008 (Appleby, Luceri, and Gibbs, 2008) and in a poster at the AGU (Appleby et al., 2008), in December. Neither the GPS nor the AG results supported the anomalous vertical motion of the site implied by the laser data, and indeed the conclusion is that it is the data prior to the installation of the event timer that is in error.

This work led the group to question its detailed evaluation of the effects of non-linear behavior of the Stanford interval counters that have been used at the station since 1993. It had been discovered previously that the non-linear behavior can corrupt both target-board calibration results and satellite ranging results at levels of up to 10mm each. These results were presented at the 15th International Laser Ranging Workshop in Canberra (Gibbs and Appleby, 2006) and at an invited presentation at the EGU 2007 (Appleby, Otsubo, and Gibbs, 2007). This careful evaluation led to the release to the community of a table of corrections for the SGF data and estimates of the likely errors in the data from a number of other ILRS stations that use or have used Stanford counters. However, more recent work, presented by Luceri et al. (EGU, 2009) and based on range-bias solutions and analyses, implied that the corrections in this table are in some instances themselves in error by up to 8mm; the most likely cause is inherent, high-frequency, non-linearity of the counters, always a limitation of the calibration process. In those instances, which coincide with subtle system changes at the station, empirical range corrections are clearly superior and have to be used. This is unfortunate since some long-term, small, geodetic signals, such as GIA effects, will likely be lost from the data set. It is also clear that SGF's attempts to improve the data from other stations that used Stanford counters will also be of less value than previously considered.

Height Signals from SLR, GPS and AG

Analysis of residual height signals at Herstmonceux has begun, using all three on-site techniques, in collaboration between SGF and University College London (Prof. M. Ziebart) and the UK Proudman Oceanographic Laboratory (POL, Dr. S. Williams). The space geodetic height time series for Herstmonceux (SLR and GPS) for the period from late 2006 until late 2008 has been used to remove vertical signals from the gravimeter results. A comparison of this height-corrected gravity time series with variations in the local water table shows very little agreement and a simple, Bouguer-based computation of the magnitude of the water table effect overestimates the observed gravity amplitude by some five times. A paper on this initial work was presented by V. Smith at an IAG symposium on Gravity, Geoid and Earth Observation, and is now in press in a Springer series (Appleby et al., 2009).

Future work will involve a thorough investigation into the local geology including the use of soil-moisture probes to better quantify hydrological effects on local gravity. It is very important to measure the dry and wet densities of the local compacted clay, as errors in the values assumed in the previous investigation will directly impact the computed gravity variation. In addition, particular areas of interest for further work are an evaluation of the treatment of atmospheric attraction on the test-mass of the gravimeter and models of site atmospheric and hydrological loading. This effort should improve the value of gravimetry in the interpretation of the SGF space geodetic results and have wider implications for similar multi-technique space geodetic facilities.

Daily QC of LAGEOS and Etalon Range Observations

On a daily basis, 7-day orbital solutions are carried out using global ILRS observations of the four LAGEOS and Etalon geodetic satellites. The station coordinates and velocities are held fixed at their ITRF2005_SLR values and corrections are made to the daily a-priori, IERS and rapid service predicted Earth orientation parameters. Post-fit residuals for each station for all four satellites are displayed in graphical form on the SGF website, along with residual mean and precision (RMS) values. The plots allow a rapid identification of outlier normal points at the level of a few cm, as well as any overall mean systematic bias with respect to the assumed station coordinates.

For any passes observed simultaneously by more than two "core" stations a further short-arc solution is carried out, based on a scheme developed many years ago by Andrew Sinclair to monitor tectonic motion by computing inter-station baselines (Sinclair and Appleby, 1993). The scheme solves for empirical, constrained, along-track, across-track and radial corrections to the fitted 7-day orbit that are valid only during the times of each of the simultaneous tracking periods. The residuals with respect to these "short-arc" orbits for all stations that tracked these arcs are also displayed in graphical form daily on the website, and reveal more subtle, perhaps 10mm-level, data or station-coordinate problems.

The SGF website recently has been relocated and is now hosted at Herstmonceux at *http://sgf.rgo.ac.uk/*.

References

Appleby, G.M., Smith, V., Wilkinson, M, Williams, S., Ziebart, M., 2009. "Comparison of height anomalies determined from SLR, absolute gravimetry and GPS with high frequency borehole data at Herstmonceux", in press, IAG Springer.

Appleby, G.M., Smith, V., Wilkinson, M, Williams, S., Ziebart, M., 2008, "Height signals determined from SLR, absolute gravity and GPS observations at the Space Geodesy Facility, Herstmonceux, UK", poster presentation, AGU, San Francisco, December 2008.

Appleby, G.M., Wilkinson, M., Luceri, V., Gibbs, P., Smith, V. 2009. "Attempts to separate apparent observational range bias from true geodetic signals", in press in *Proceedings of the 16th International Laser Ranging Workshop*, Poznan, Poland, October 2008.

Appleby, G.M., Otsubo, T., Gibbs, P., 2007. "Further Improvements in Understanding Subtle Systematic Effects in Laser Ranging Observations", (abstract and presentation), Geophysical Research Abstracts, Vol 9, EGU General Assembly 2007.

Gibbs, P., Appleby, G.M. and Potter, C.B., 2006. "A reassessment of laser ranging accuracy at SGF Herstmonceux, UK", in *Proceedings of the 15th International Laser Ranging Workshop*, Canberra, Australia, October 2006.

Greaves M., Bingley R.M., Baker D.F., Appleby G., 2008. "National report of Great Britain, 2008". Report on the Symposium of the IAG Subcommission for the European Reference Frame (EUREF), June 2008.

Luceri, V., Sciarretta, C., Appleby, G.M., Bianco, G., 2009. "Measurement Bias Effects in the ILRS Product for the ITRF", (abstract and presentation), Geophysical Research Abstracts, Vol 11, EGU General Assembly 2009.

Sinclair, A.T., Appleby, G.M., 1993. "A Short-Arc Method for Determination of Station Coordinates and Baselines Applied to the Mediterranean Area", Contributions of Space Geodesy in Geodynamics: Crustal Dynamics, AGU Geodynamics Series, V.23, pp. 389-396, Edited by D.E. Smith and D.L. Turcotte, 1993.

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ILRS ASSOCIATE ANALYSIS CENTER REPORTS

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.

Center for Orbit Determination in Europe (CODE)

Daniela Thaller/Astronomical Institute, University of Bern, Switzerland

Introduction

The Center for Orbit Determination in Europe (CODE) is a joint venture of the Astronomical Institute of the University of Bern (AIUB), the Federal Office of Topography in Switzerland (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 Associate Analysis Center of the ILRS are located at AIUB. CODE performs two types of activities for the ILRS:

- Production of predictions for the GNSS satellites tracked by the ILRS;
- Generation of daily SLR quick-look reports.

Predictions for GNSS Satellites

CODE also acts as an Analysis Center of the International GNSS Service (IGS). For nearly six years, a rigorous combined analysis of the GPS and GLONASS microwave measurements is carried out not only for the final but also for the rapid and ultra-rapid product line of the IGS. The ILRS network provides routine tracking of the two GPS satellites equipped with retro-reflectors (i.e., GPS-35 and GPS-36) and three of the GLONASS satellites. From the combined GPS/GLONASS rapid orbits – derived at CODE from the microwave data – orbit predictions for these five GNSS satellites are provided to the ILRS in the Consolidated Prediction Format (CPF).

The selection of the three GLONASS satellites for SLR tracking changed throughout the last years: On May 28, 2008, GLONASS-95 was replaced by GLONASS-109. Just recently (April 3, 2009), GLONASS-99 was replaced by GLONASS-115 in our predictions. Therefore, at the moment, CODE provides SLR predictions for GPS-35, GPS-36, GLONASS-102, GLONASS-109, and GLONASS-115.

CODE Quick-Look Reports

CODE provides daily SLR-GNSS quick-look reports for SLR observations of the GNSS satellites over the last six days. The residuals are computed with respect to the SLRF2005 station coordinates, and the GNSS microwave–derived orbits and Earth rotation parameters (ERPs) determined at CODE for the IGS. The GNSS orbits of the last two days result from the rapid GNSS analysis, whereas the orbits of the earlier four days are taken from CODE's final GNSS analysis.

The summary of the quick-look analysis is divided by station, by satellite, and by day. It contains the mean residual, the rms and the number of observations. The quick-look summary is distributed daily via e-mail and is available from the ILRS web site.

Scientific Analysis

SLR is a very important tool to validate the quality of the orbits derived from microwave data and to detect deficiencies in the orbit modeling. A set of very significant results in this field of research was recently compiled in the PhD thesis of Claudia Flohrer (Flohrer 2008). A continuation of this validation work will be given in a poster presentation at the EGU 2009 (Thaller et al. 2009).

References

Flohrer, C. (2008): Mutual validation of satellite-geodetic techniques and its impact on GNSS orbit modeling. PhD Thesis. Geodätisch-geophysikalische Arbeiten in der Schweiz, Vol. 75.

Thaller, D., A. Steinbach, and R. Dach (2009): Combined analysis of GNSS and SLR observations for the GIOVE satellites. Geophysical Research Abstracts, Vol. 11, EGU2009-2671, EGU General Assembly 2009.

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The University of Texas Center for Space Research (CSR)

John Ries, Minkang Cheng, Richard Eanes / UTCSR

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 (CSR) routinely analyzes the tracking data for several geodetic satellites in support of data quality assessment, station coordinate testing, monitoring long-wavelength geopotential variations (including geocenter motions), and reference frame evaluation.

Reference Frame

An important practical consideration for precision orbit determination (POD) is the set of coordinates (position and velocity), and associated range biases, adopted when processing the laser ranging tracking. Routine orbit determination and verification for missions such as the ocean and ice altimeter missions (TOPEX/Poseidon, Jason-1, Jason-2, and ICESat) and gravity missions (CHAMP and GRACE) rely on very precise coordinates and bias knowledge, since these missions operate at the 1-2-cm radial orbit accuracy level. To provide these missions with a consistent and validated set of precise coordinates, CSR has modified and augmented the current coordinate set based on ITRF2005 to correct for problems in that solution (usually due to bias issues not accommodated in the original solution), add stations not included in ITRF2005 and update coordinates based on improved bias knowledge. The result is a recommendation for a set of coordinates and range biases that are consistent with ITRF2005 and have been validated with the tracking of five precise geodetic targets (LAGEOS-1, LAGEOS-2, Starlette, Stella, and Ajisai) over the interval of 1993-2009. This set of tracking station coordinates, LPOD2005 (*ftp://ftp.csr.utexas.edu/pub/jason/models/coords/LPOD2005.doc*), is intended for laser ranging to be the equivalent of DPOD2005 for DORIS (*see http://www.ipgp.fr/~willis/DPOD2005.htm*).

Geocenter Motion

We have continued to monitor the variations in the geocenter location, since this represents both possible systematic drifts in the terrestrial frame as well as seasonal mass transport within the Earth system that is not well monitored by other techniques. The GRACE mission, for example, is able only to accurately determine the temporal mass changes for degrees 2 and above. The geocenter variations (equivalent to the degree-1 geopotential harmonics) contain an important mass variation signal. In Figure 12-10, we show a recent estimate of the geocenter motion obtained from SLR tracking of LAGEOS-1/LAGEOS-2 since the beginning of the LAGEOS-2 mission in late 1992. In this analysis, the network is held fixed to ITRF2005, and the geocenter offset is estimated every 60 days (constant over the 60-day arcs). A bias is also estimated for each station/arc with an a priori constraint of 5 mm. The estimation of the bias is especially important for the Z variation; if biases are not estimated, the annual Z variation can exceed 5 mm. We have previously noted a significant drift in such analyses relative to ITRF2000, especially in Z, but this analysis indicates only small drifts relative to ITRF2005; less than 0.1 mm/y for X and Y, and ~0.3 mm/y for Z. The bias is under 1 mm for X and Y, but ~5 mm for Z.

Table 12-3 (following page) shows that the annual variations determined from this series agree very well with a number of other estimates in both amplitude and phase. The estimated uncertainty is based on the scatter of the geodetic estimates, including this study. The scatter of the geophysical models was larger in X and Y but the same for Z.

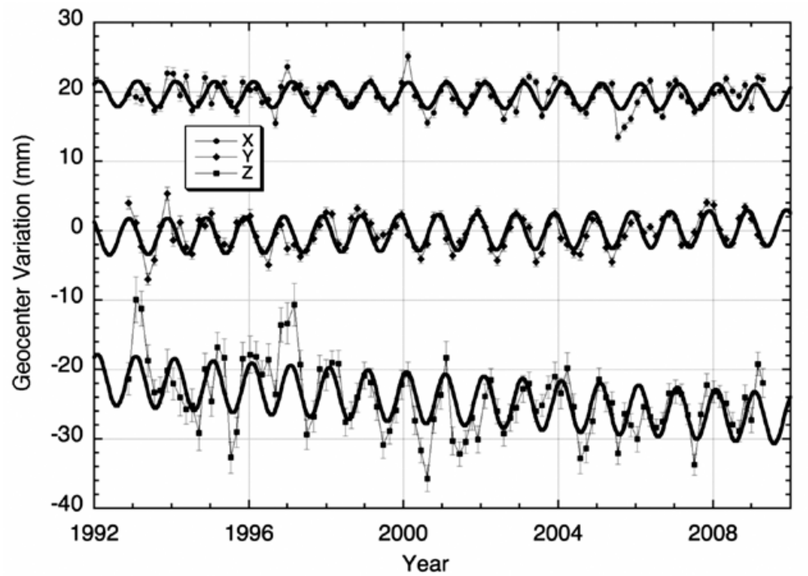

Figure 12-10. Geocenter variations estimated every 60 days from LAGEOS-1/LAGEOS-2. X and Z have had 20 mm added and subtracted, respectively. The fit curve is a bias, slope and annual term. The addition of a semi-annual term does not significantly improve the correlation.

Table 12-3. Estimates of annual amplitude (mm) and phase (deg) from this analysis compared to the mean of five studies based on SLR or combinations of GPS, GRACE and ocean bottom pressure models, and the mean of five geophysical model predictions. The amplitude and phase are defined by amp*cos(ωt-phase), where t is years past January 1 and ω is the annual frequency.

Case	X (amp)	X (phase)	Y (amp)	Y (phase)	Z (amp)	Z (phase)
L1/L2 (this study)	1.9	44	2.6	325	3.7	31
Mean of geodetic estimates	2.0	44	2.5	322	2.9	40
Mean of model estimates	2.4	34	2.2	329	3.2	34
Estimated uncertainty	0.4	7	0.4	6	0.7	14

We have obtained a new determination of the long-term variations in J2, shown in Figure 12-11. It is clear that J2 has undergone significant variations during the past 33 years. The estimate of the secular rate is significantly affected by the interannual variations. In particular, two large fluctuations in J2 are correlated with the strong ENSO events of 1986-1991 and 1996-2002, and it appears that a new cycle has started around 2007.

Testing General Relativity

In an independent analysis of the SLR tracking to LAGEOS-1 and LAGEOS-2 using several models resulting from the GRACE gravity mission, we have been able to confirm the effect of the Lense-Thirring precession predicted by General Relativity to better than 15%, consistent with previously published results. The uncertainties in J4 and J6 still dominate the current error budget, but improvements in the mean gravity field model from the GRACE mission should make even more precise tests possible in the future.

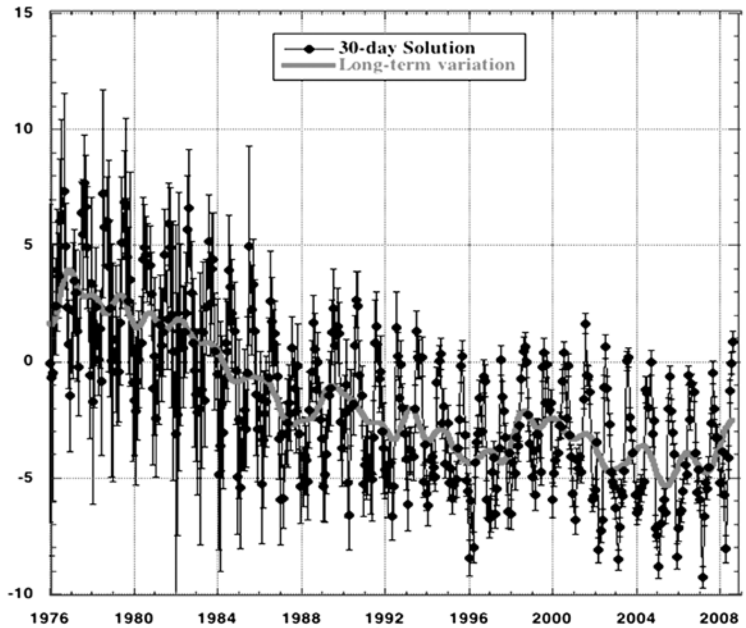

Figure 12-11. Monthly estimates and the long-term variation of J2 determined from up to seven geodetic satellites.

References

Cheng M. K. and B. D. Tapley, Variations in J2 from GRACE and 33-years of SLR data, paper: PSD1-0042-08, the 37th COSPAR Scientific Assembly, 13-20 July 2008, Montreal, Canada.

Cheng M. K. and B. D. Tapley, A 33-Year Time History of the Earth Dynamic Oblateness Changes from SLR Data, 16th International Laser Ranging Workshop, Poznan, Poland, 15-19 October 2008.

Cheng M. K. and B. D. Tapley, Recent variation in the Earth Dynamic Oblateness, J2, from SLR and GRACE data, GRACE Science Team Meeting, December 12-13, San Francisco, 2008, and 2008 AGU Fall meeting: Eos Trans. AGU, 89(53), Fall Meet. Suppl., Abstract G33A-0673.

Ries, J. C., Satellite Laser Ranging and the Terrestrial Reference Frame; Principal Sources of Uncertainty in the Determination of the Scale, Geophysical Research Abstracts, Vol. 9, 10809, 2007, EGU General Assembly, Vienna, Austria, April 15-20, 2007 [SRef-ID: 1607-7962/gra/EGU2007-A-10809].

Ries, J. C., R. J. Eanes, M. M. Watkins, Confirming the Frame-Dragging Effect with Satellite Laser Ranging, 16th International Laser Ranging Workshop, Poznan, Poland, 15-19 October 2008.

Ries, J. C., LPOD2005: A Practical Realization of ITRF2005 for SLR-based POD, presented at Ocean Surface Topography Science Team Meeting, Nice, France, 10-12 November 2008 (*http://www.aviso.oceanobs.com/fileadmin/documents/OSTST/2008/oral/ries.pdf*).

Ries, J. C., M. Cheng, S. Bettadpur, D. P. Chambers, SLR-Determined Low-Degree Geopotential Harmonics and their use with GRACE Data Products, Eos Trans. AGU, 89(53), Fall Meet. Suppl., Abstract G13AC-0632, December 2008.

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Delft University of Technology (DUT)

Nacho Andrés de la Fuente, Eelco Doornbos, Ron Noomen/DUT

Introduction

The Delft Institute for Earth Observation and Space Systems (DEOS) at Delft University of Technology has been active in the field of SLR analysis since about 1980. The activities relevant for the reporting period include (i) LAGEOS orbit modeling and (ii) ERS-2 and Envisat orbit computations.

LAGEOS Orbit Modeling

A main application of the SLR observations on LAGEOS-1 and -2 is their use for crustal dynamics investigations and reference frame definitions. Here, it is extremely important to model the orbit of the LAGEOS spacecraft as well as possible. An element of the dynamic model for these vehicles, which has gained significance during the last few years is the modeling of thermal forces (the net pressure force exerted by the photons emitted by the satellite surface). In the reporting period and the years directly before, DEOS has developed a number of essential elements for the characterization and understanding of such forces: LOSSAM (LAGEOS Spin Axis Model) an LOSTHERM (LAGEOS Thermal Model). LOSSAM gives (predictions of) the instantaneous rotation (direction and magnitude) of the two LAGEOS satellites, with uncertainties typically in the order of about 5 deg for attitude and about 5 sec (depending on the moment of evaluation) for the spin period. The finite-element model LOSTHERM describes the thermal behavior of 2133 different elements of each satellite; by evaluating the temperature and resulting force (emitted photon momentum) of each surface element and integrating these, it is possible to derive values for the net thermal acceleration that acts on the spacecraft. The LOSTHERM results show a consistent temperature behavior of the various LAGEOS elements, and yield accelerations that are in line with the results obtained from orbital computations. In addition, an accurate modeling of the accelerations due to the interaction with the magnetic field and collisions with charged particle has also been developed.

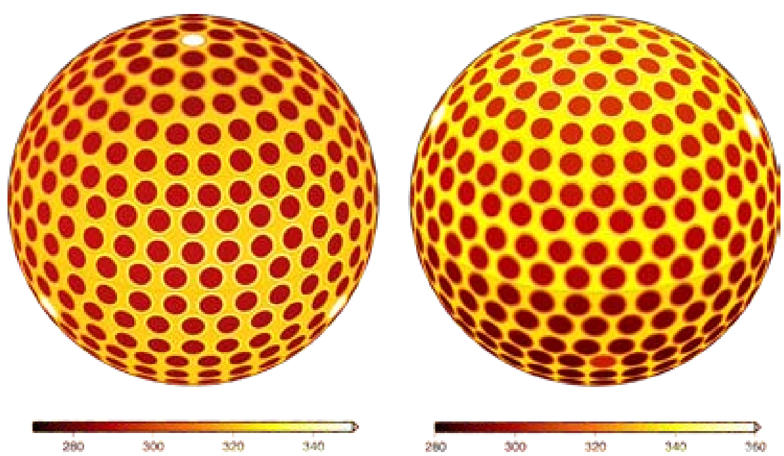

Figure 12-12: an illustration of the temperature distribution over the surface elements of LAGEOS-1 (left) and LAGEOS-2 (right).

ERS-2 and Envisat precise orbit determination

The orbit determination of ERS-2 and Envisat has had a low priority in recent years, because of lack of manpower. Instead, work has been performed on investigations of satellite drag using other data sources. At the moment, DEOS is gearing up for a re-analysis of the complete ERS-1 and ERS-2 data set, with updated models for the network coordinates, measurement modeling and satellite dynamics, including improvements to the density and drag modeling.

Publications

Andrés de la Fuente, N., Enhanced modeling of LAGEOS non-gravitational perturbations, PhD report, 321 pp, Delft University of Technology, September 7, 2007

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European Space Operation Centre (ESOC)

Michiel Otten, John Dow, Rene Zandbergen, Dirk Kuijper, Tim Springer/ESA/ESOC

Introduction

One of the tasks of the Navigation Support Office of the European Space Operation Centre (ESOC) is to provide high-precision orbit data for ESA's Earth Observation missions (ERS-2, Envisat). This orbit data are used, among other applications, to assist in the calibration and validation of the altimeter instrument and data processing techniques. To achieve this task, SLR data for ERS-2 and Envisat are processed on a daily basis, together with other instrument data for the two missions. Furthermore, we are generating precise orbit solutions for the GIOVE-A spacecraft since continuous reliable SLR tracking became available in June 2006 and for GIOVE-B since May 2008.

In addition to this activity, ESOC is the prime prediction center responsible for the delivery of predictions for the ERS-2, Envisat, GOCE, GIOVE-A, and GIOVE-B spacecraft. The predictions are disseminated to all SLR stations using the standard ILRS CPF prediction format and exchange mechanisms. These activities include predictions over orbit maintenance maneuvers for ERS-2, Envisat and GOCE, which are planned by and executed at ESOC.

Facilities/Systems

All orbit solutions and related products are generated using a common software package (NAPEOS) and are generated automatically. The orbit solutions for ERS-2 and Envisat consist of 7-day arcs with varying timeliness of availability, depending on the mission. For ERS-2 the solution is generated with a delay of six days to allow collection of all SLR tracking data. For Envisat the final precise orbit solution has a typical delay of around 4-6 weeks depending on when the DORIS Doppler data become available.

Current Activities

For ERS-2, since the failure of the last onboard tape recorder in August 2003, the SLR tracking data have become the sole means to generate routinely precise orbit solutions. This process has been running very reliably for the last five years thanks to the consistent tracking support provided by the ILRS community.

For Envisat, two different precise orbit solutions are generated. The first solution is a fast-delivery solution, which uses the SLR data together with the fast-delivery altimetry data. This solution is used to support the operational activities of Envisat and is also used to monitor the long-term performance of the Envisat altimeter. The second (and final) precise solution for Envisat is generated when the DORIS Doppler data for Envisat become available and is used to monitor the SLR and DORIS Doppler data performance.

For GIOVE-A and GIOVE-B, precise orbit solutions based on SLR tracking data have been generated since June 2006 and May 2008 respectively. These precise orbits have also been the basis for the orbit predictions as provided to the ILRS community. The precise orbit solutions have been used in studies inside the Galileo project to validate the orbit solutions based on the microwave data, to validate the microwave data, and to study the behavior of the GIOVE-A and GIOVE-B onboard clocks.

In 2008 the ESOC Navigation Support Office reprocessed all the historic IGS data from 1994 to 2008. We have analyzed the quality of the reprocessed GPS satellite orbits by using all the ILRS SLR tracking data of the two GPS satellites for the period from 1995 to 2009. The resulting residuals are given in Figure 12-13. below. This is the first time that a homogeneous time series for the GPS satellite orbits was available and was used in an SLR analysis. The results are very encouraging, except for the eclipse phases of the satellites (the dark circle in the middle of the figure). The agreement between the SLR observations and the GPS orbits is at the 20 mm level. Both the mean and the residual RMS are at the 20 mm level (if we ignore the eclipsing part).

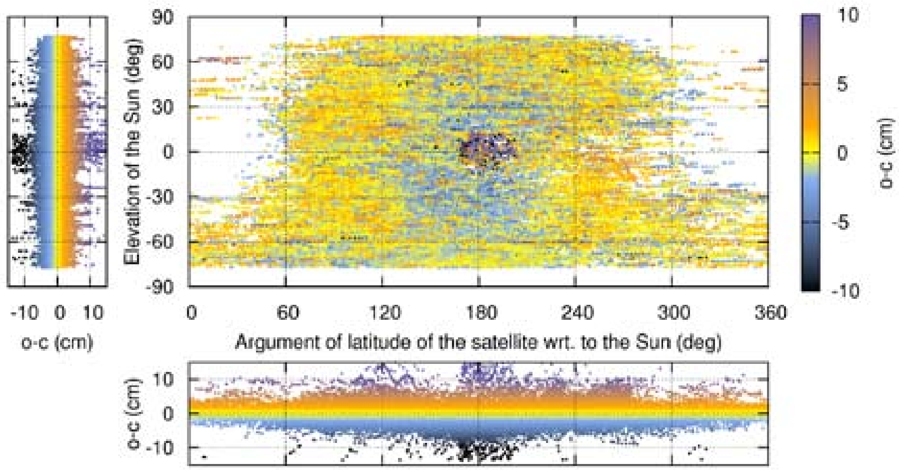

Figure 12-13. The residuals of the SLR observations from the GPS satellites over the time frame of 1995 to 2008 using the ESOC reprocessed orbits of the GPS satellites.

The ILRS data are extremely valuable since they provide a unique and fully independent quality check. This historic ILRS tracking data of the GNSS targets are of significant value for the IGS reprocessing efforts. Besides using the data to validate our reprocessing results it should be possible to include the data in the actual data processing and thus connect the SLR and GPS reference frame directly "in Space" and not (only) through Earth based on local site ties. The period from 1995 to 2008 yielded ~90,000 SLR observations of the GPS satellites and thus would contribute 90,000 local ties or more specifically "Space Ties".

Future Plans

Besides the ongoing activities, the Navigation Support Office plans to process the SLR tracking data from Cryosat-2 where again the data will play an important role in the monitoring of ESOC's operational and predicted solutions.

Furthermore, ESOC has also participated in the reprocessing of the ILRS data of the LAGEOS-1 and -2 and Etalon-1 and -2 satellites and is planning to become a full analysis center of the ILRS. However, the rather lengthy approval process for becoming an ILRS AC has kept us from contributing to the ILRS reprocessing results for the ITRF2008. Nevertheless, we hope to be able to contribute as a full AC to the ILRS in the near future.

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Forsvarets Forskningsinstitutt (FFI)

Per Helge Andersen/FFI

Introduction

FFI has during the last 26 years developed a software package called GEOSAT for the combined analysis of VLBI, GNSS (GPS, Galileo, GLONASS), SLR, and other types of satellite tracking data (DORIS, PRARE and altimetry). The observations are combined at the observation level with a consistent model and consistent analysis strategies. With this procedure, the time-evolution of the common multi-technique parameters (for example EOP, geocenter, troposphere, or clock parameters) are treated consistently across the techniques. This is not the case when the techniques are combined "rigorously" at the normal equation level. The data processing is automated except for some manual editing of the SLR observations.

In the combined analysis of VLBI, GNSS, and SLR observations the data are processed in arcs of 24 hours defined by the duration of the VLBI session. The result of each analyzed arc is a state vector of estimated parameter corrections at the last epoch of observation and a Square Root Information Filter array (SRIF) containing parameter variances and correlations for the same epoch. The individual arc results are combined into a multi-year global solution using a Combined Square Root Information Filter and Smoother program called CSRIFS. With the CSRIFS program any parameter can either be treated as a constant or a stochastic parameter between the arcs. The estimation of multi-day stochastic parameters is possible and extensively used in the analyses.

Activities

After five years of development and validation a completely new version of the GEOSAT software (called GEOSAT_2010) is ready for routine processing of space geodesy observations and tracking data towards spacecrafts in the solar system. The new version of GEOSAT has several useful features:

- It can simultaneously combine data from virtually any number of VLBI, SLR, and GNSS instruments at a co-located site either observing simultaneously or in different time windows. All information will contribute to the estimation of the migration of an automatically selected master reference point at each station. Time series of eccentricity vectors will also be estimated: For GNSS the vector from the reference marker to the antenna phase center will behave as a step function where steps are introduced at epochs where instrumental changes (new antennas, installation or removal of a radome etc) have taken place. In practice the eccentricity vectors for GNSS will be estimated using a stochastic parameterization where close to zero noise are added except for the epochs of instrumental changes where a big amount of noise are added so that the values may jump to a new level. The same strategy is used to represent the motion of sites suffering from earthquakes. For VLBI and SLR the eccentricity vectors will usually be invariant in time and estimated as constants.
- The solved-for model parameters in combined processing of the VLBI+SLR+GNSS can either be instrument-dependent, technique-dependent, microwave-dependent, optical-dependent, or site-dependent. The switching between the different types is extremely simple. A simple application would be to, in a first run, treat the zenith wet delay parameters as instrument-dependent parameters which means that, for example, a station with two GPS receivers and one VLBI instrument will have three estimates of this parameter. If the results are consistent, these parameters can be estimated as a single parameter represented by a microwave-dependent parameter in a second run. The same can be tested for clock parameters for co-located clocks etc.

- New to this version of the software is ambiguity resolution of undifferenced GPS data. Due to a very precise a priori model the ambiguity resolution is performed using a priori residuals and not as part of a aposteriori filter solution which is the common procedure. Thus, no phase biases are estimated in the filter. Only resolved data are used in the analysis, which have reduced the number of GPS stations in the solution for each arc (24 h of data) from approximately 175 to typically 135. The actual station IDs involved in an arc changes in general from day to day so that many more GPS stations will be present in the global multi-year solution.
- Analysis of tracking data to spacecraft in deep space has been added. The software automatically detects the central body, if any (Earth or a body in the solar system), and accordingly performs the analysis either in a local geocentric frame of reference (if Earth is the central body) or in a solar system barycenter frame of reference. The contributing forces necessary to match the observation precision are automatically accounted for. It is, for example, in principle possible to calculate the trajectory of the spacecraft and the orbit and gravity field of the central body.
- For any technique, the delay due to the troposphere is determined with 3D raytracing (rescaled with actual pressure for SLR) using the European Center for Medium-range Weather Forecast Numerical Weather Model.

The status of the analysis as of May 2009 is as follows. After extensive testing a “close to optimal” mix of solve-for parameters, constraints and weighting has been found for the combined analysis. Among the estimated parameters are a GPS antenna phase center offset to be added to the satellite-dependent phase center offsets/variations tabulated by IGS, and time dependent estimates of the geocenter, C20, C22 and S22. So far, 1201 arcs have been processed at the combination level with this strategy. This is 63% of the days in the period October 1, 2002 through December 31, 2007. Several runs at the global multi-year level with these 1201 arcs have been performed with very interesting results.

The expected outcome will be new realizations of TRF, CRF, and EOP relying on consistent models and estimation strategies. As a by-product, a file of estimated eccentricity vectors will be produced. This type of analysis is along the lines of the ideas behind the GGOS project where geometry, gravity and Earth orientation are to be simultaneously and consistently determined.

Future Plans

We hope to include space-borne gravity (accelerometer, gradiometer, satellite-satellite range/Doppler, altimetry etc) in GEOSAT for a simultaneous analysis with VLBI, SLR and GPS. This extension will be made possible by a close collaboration between Statens Kartverk and FFI.

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Main Astronomical Observatory of the National Academy of Sciences of Ukraine (GAOUA)

Olga Bolotina/Main Astronomical Observatory of the National Academy of Sciences of Ukraine

Introduction

The SLR Data Analysis Center of the Main Astronomical Observatory of the National Academy of Sciences of Ukraine (MAO NASU) was created in 1988. The center was accepted as an ILRS Associate Analysis Center (GAOUA AAC) in 1998. The primary interests of our SLR data analysis center are: software development, data processing of SLR observations, creation of an archive of SLR observations, and collaboration with the Ukrainian Branch of the World Data Center for Solar and Terrestrial Physics (UB WDC-B).

A collection of the observation data from all Ukrainian permanent SLR stations is kept in a local archive. The Kiev-Geodynamics software, developed by GAOUA, is used for SLR data analysis. Since 1989, we have calculated EOP, coordinates, and velocities of SLR stations. Detailed information about the GAOUA AAC is available on the Ukrainian Center of Determination of the Earth Orientation Parameters webpage, *http://mao.kiev.ua/EOP/*.

Scientific Results

The main scientific results during the period 2007-2008 are as follows. The stability of the network of the Ukrainian SLR stations (Simeiz, Katzively, Golosiiv-Kiev, and Lviv) was investigated through processing LAGEOS-1 and LAGEOS-2 observations from January 5, 1989 through November 11, 2004. The stability of the coordinate determinations for each station was estimated. The factors influencing this stability of the network are outlined below.

A new algorithm for parameter estimation with an arbitrary time interval was developed and programming was completed. The main principles for estimation of the parameters for the combined analysis of SLR, VLBI and GPS observations, as well as the parameter estimation algorithm with an arbitrary time interval, were described.

The stability of the positions of Ukrainian co-location stations Simeiz, Katzively, Golosiiv-Kiev, and Lviv was investigated. Our findings:

- Conclusions concerning the instability of the Simeiz-Katzively geodynamic test area have been made. Systematic errors were detected in ITRF2000 with incorrect determination of the velocities of VLBI, SLR and GPS reference points at the co-located (i.e., same DOMES number) Simeiz-Katzively site. A proposition to assign different DOMES numbers to these reference points was made to the ITRF combination center.
- High-precision coordinates of reference points, as well as the estimation of the local deformations during the period from 1997 to 2006 of the Golosiiv-Kiev geodynamic test area, were obtained. Conclusions about the existence of the tendencies relative to the local displacement of the reference points of the test area MAO NAS of Ukraine are made.

Determination of individual and combined ILRS, IVS, IGS, and IDS series the Earth Orientation Parameters has been investigated. Analysis and geophysical interpretation of the spectrum of polar motion time series were made.

Current Activities

- Monitoring of the stability of the Ukrainian SLR network
- Processing of all available LAGEOS-1 and LAGEOS-2 SLR observations
- Investigation of stability of the geodynamical test of area (co-location station)
- Combination of VLBI, SLR, and GPS observations
- EOP time series investigations
- Organization of regular SLR workshops “The activity of the SLR Network of Ukraine”
- Preparing and publishing “The Bulletin of the Ukrainian Center of the Earth Orientation Parameters” (since 2007)
- Collaboration with the UB WDC-B

Future Plans

- Developing the Kiev-Geodynamics ver. 6.0 software
- Operational analysis of the SLR observations

References

Bizouard Ch. , Bolotina O., Bolotin S. Atmospheric and oceanic normal modes in polar motion, Proc. of the Journees 2008 “Systemes de Reference Spatio-Temporels”, Dresden, Germany, September, 22-24, 2008 (in press).

Bolotina O.V., Samoilenko A.N., Bolotin S.L., Kozel V.L. Investigation of instability of points position of collocation station “Simeiz-Katzively”, Kinematics and Physics of Celestial Bodies. Vol. 24, No 5. pp 388-400. 2008.

Bolotina O., Medvedskij M. Some results of investigation of the stability of the Ukrainian SLR stations, Kinematics and Physics of Celestial Bodies. Vol. 23, No 1. pp 11-17. 2007.

Bolotina O., Bolotin S., Khoda O., Bizouard Ch. Combination of Different Space Geodetic Techniques: Algorithm of Parameters Estimation, Proc. of the Journees 2007 “Systemes de Reference Spatio-Temporels”, Paris, France, September, 17-19,. pp 204-205. 2007.

Bolotina O., Review of Ukrainian SLR network activity during 2005-2008, Bulletin of the Ukrainian Center of the Earth Orientation Parameters. No 3. pp 35-37. 2008.

Bolotina O., Bolotin S., et al. UCEOP in UB WDC system, Bulletin of the Ukrainian Center of the Earth Orientation Parameters. No 3. pp 32-34. 2008.

Bolotina O. Associate Analysis Center of SLR observation, Bulletin of the Ukrainian Center of the Earth Orientation Parameters. No 1. pp 80-81. 2008.

Bolotina O., Ukrainian SLR network activity in 2007, Bulletin of the Ukrainian Center of the Earth Orientation Parameters. No 2. pp 32-33. 2007.

Bolotina O., UCEOP archive of the SLR observations, Bulletin of the Ukrainian Center of the Earth Orientation Parameters. No 2. pp 34. 2007.

Bolotina O., Medvedskij M. About stability of coordinates estimation of SLR stations, Bulletin of the Ukrainian Center of the Earth Orientation Parameters. No 2. pp 17-20. 2007.

Bolotina O., Samoilenko A.N., Bolotin S.L. et al., Investigation of local ties of reference points of collocation station “Simeiz-Katzively”, Bulletin of the Ukrainian Center of the Earth Orientation Parameters. No 2. pp 21-25. 2007.

Samoilenko O., Adamenko O., Bolotina O., Zayets V., Khoda O. The Results of the Third Geodetic Campaign at the Local Geodynamic Range MAO NAS of Ukraine, Kinematics and Physics of Celestial Bodies. Vol. 24, No 6. pp 452-462. 2008.

Yatskiv Ya., Bolotina O., Veles O., Sergeeva T., MAO NASU in the structure of the international data base, Proceedings of IX International scientific conference “System analysis and Information techniques”, Kiev, Ukraine, 15-17 May, pp 25. 2007.

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Hitotsubashi University

Toshimichi Otsubo and Mihoko Kobayashi/ Hitotsubatshi University (HIT-U)

Introduction

Hitotsubashi University became a new Associate Analysis Center of the ILRS in April 2007 when Toshimichi Otsubo moved from NICT. We hope to contribute to the ILRS over a long period of time.

Multi-Satellite Analysis Report

The daily quality check analysis was also moved from NICT to this university. The basic hardware/software component for this analysis remains almost the same; the main software engine is 'concerto v4' developed at NICT. We thank NICT for temporally lending the computing facilities to us. Newly added satellites in the past two years are: GIOVE-A, -B, GLONASS-102, -109, -115, and Jason-2. In total, we analyze data from as many as 17 satellites daily although some satellites are occasionally dropped from the analysis report when the quality or quantity is not sufficient. We issue and upload a daily report (Figure 12-14) between 09:00-10:00 JST (00:00-01:00 UT). Upon a request from the ILRS Analysis Working Group, the station coordinates were switched from a modified ITRF2000 to the strict SLRF2005. Based upon some discussion within Task Force 1, we quickly issue e-mail alerts to the laser stations, as well as the Task Force, when we detect a series of obvious anomalous passes. More than 10 cases of such incidents occurred in 2008.

This quality control activity began in 1997. To commemorate our 10-year development and operation, we published a technical report in Journal of the Geodetic Society of Japan: T. Otsubo, M. Kobayashi, T. Gotoh and T. Kubo-oka: "Daily Quality Control System of Satellite Laser Ranging Data for the ILRS Network," Journal of the Geodetic Society of Japan, Vol. 54, No. 2, 69-79, 2008 (in Japanese with English abstract) part of which was presented at the ILRS workshops in 2007 and 2008.

We would like to improve this reporting system based upon user input. We would appreciate any comments or requests on this work from the worldwide community of ILRS users.

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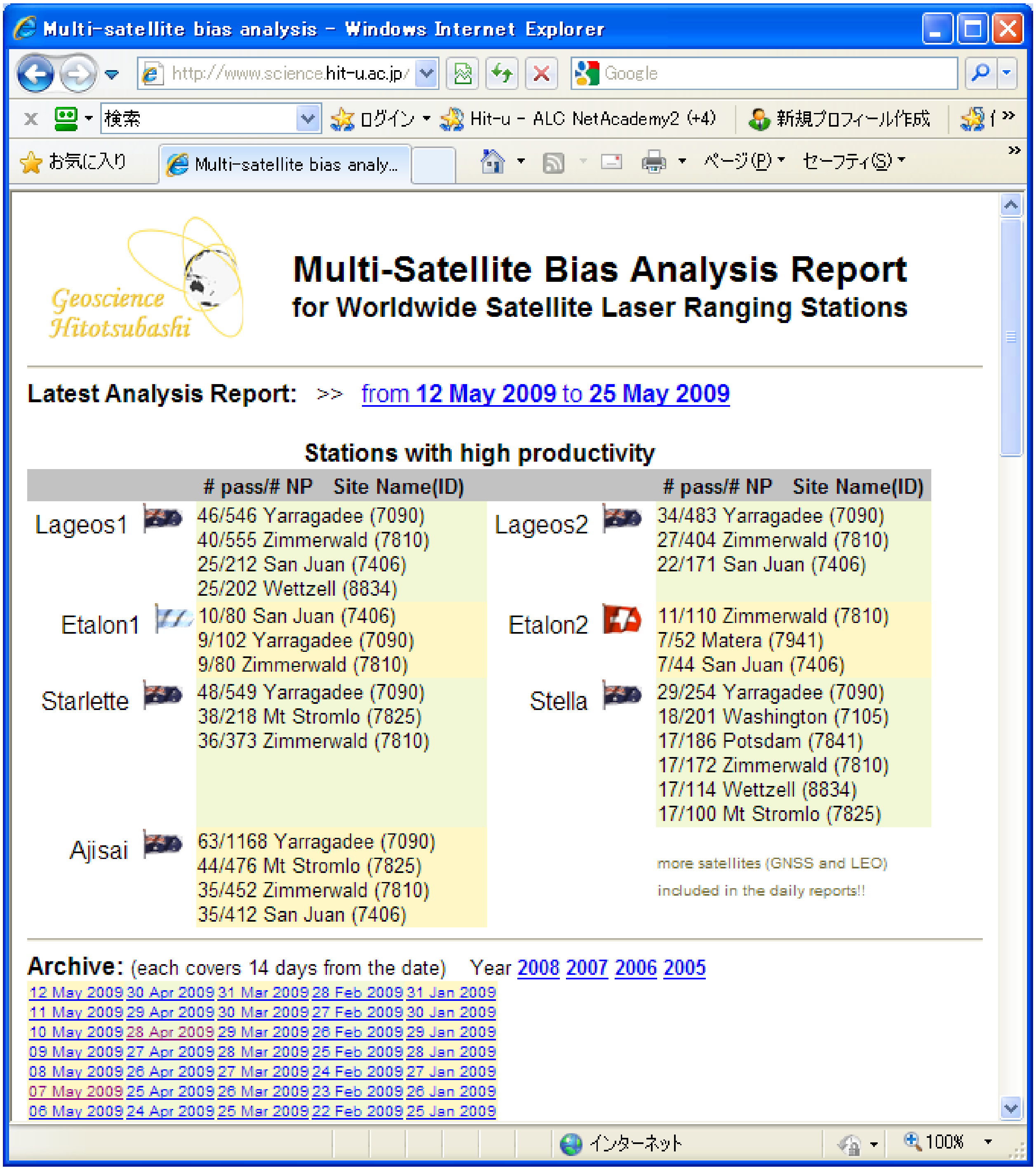

Figure 12-14. Multi-satellite bias analysis webpage at Hitotsubashi University (http://www.scicence.hit-u.ac.jp/otsubo/slr/bias/).

Institute of Applied Astronomy (IAA)

Iskander Gayazov, George Krasinsky, Eleonora Yagudina/IAA

Operational EOP Determinations

Daily operational processing of LAGEOS-1 and -2 observations is performed using GROSS software in support of the IAA EOP Service. Results are submitted to the OPA and NEOS combination centers.

Analysis of LLR Data (G. Krasinsky, E. Yagudina)

LLR data (1970–2008) have been processed to improve the lunar portion of the numerical luni-solar ephemeris of the program package ERA. The dynamical model of the lunar rotation takes into account the effects of elasticity of the lunar body and the tidal dissipation in the Moon. Values of 65 parameters have been estimated and fed back into the theory by iterations. Making use of the calculated partial derivatives, the LLR observations were also processed applying DE403, DE405 and DE421 theories. The pre-fit, post-fit residuals are presented in Table 12-4 (while calculating the pre-fit values for the DE theories, only corrections to the coordinates of the laser stations and the lunar reflectors, and the lunar Love numbers h_2, l_2 might be implemented).

Table 12-4. WRMS errors for pre-fit and post –fit LLR residuals.

Ephemeris	Pre-fit RMS, cm	Post-fit RMS, cm	Number of LLR observations
DE403	23.66	5.24	16105
DE405	23.20	5.10	16102
DE421	22.06	5.06	16087
ERA	6.32	6.32	16115

Somewhat larger post-fit WRMS errors for the ERA theory have proven to be due to the simplified method of taking into account the dissipative effects in the lunar rotation. More correct modeling is required in order to integrate differential equations of lunar rotation with the retarded time-argument. At present, such work is in progress. Our analysis has demonstrated that while the orbital and rotational parts of the DE lunar ephemerides are of high internal accuracy, some of their parameters still need improvement.

Analysis of laser measurements of LAGEOS-1 and LAGEOS-2 (1988-2003) for estimating the dynamical Love number k_2^d, and secular and seasonal variations of the coefficients J_2 of geopotential (G. Krasinsky)

The measured laser distances to LAGEOS-1 and LAGEOS-2 (time interval 1988-2003, about 1.5 millions of measurements) have been processed using the program package ERA. Combining the observations of each year into one series, all weekly sub-series involved were processed simultaneously, determining for each week the elements of the satellites and other local parameters. For each year the estimates of the so-called dynamical Love number k_2^d were derived. (The dynamical Love number k_2d is a scaling factor of the near-diurnal oscillations of the coefficients C_{21}, S_{21} caused by the differential rotation of the fluid core; in a commonly used equivalent approach, this effect is interpreted as a frequency dependence of the Love number k_2 in the near-diurnal frequency band). Yearly derived estimates of k_2^d (15 estimates for LAGEOS-1 and 9 estimates for LAGEOS-2) after averaging provide the value $k_2^d = 0.0613 \pm 0.0013$ in good accordance with the theoretical value $k_2^d = 0.063$. Simultaneously, weekly corrections to the adopted value of the coefficient J_2 of geopotential were also derived, considering these corrections be constant for each monthly interval. The set of these corrections was fitted by a model that includes a constant shift, linear secular trend and the sine- and cosine terms of the annual and semi-annual periods.

$dJ_2=A_0+A_1T+A_c\cos(\omega T) + A_s\sin(\omega T) + A_{2c}\cos(2\omega T) + A_{2s}\sin(2\omega T)$,

where T is the time elapsed from the epoch 2000.0 and ω is the annual frequency. For the amplitudes of the annual and semi-annual terms the following statistically significant estimates are derived:

$A_s= (-1.49 \pm 0.16)\times10^{-10}$, $A_{2s}=(1.67 \pm 0.16)\times10^{-10}$,
$A_c= (-1.74 \pm 0.16)\times10^{-10}$, $A_{2c}=(-0.66 \pm 0.16)\times10^{-10}$.

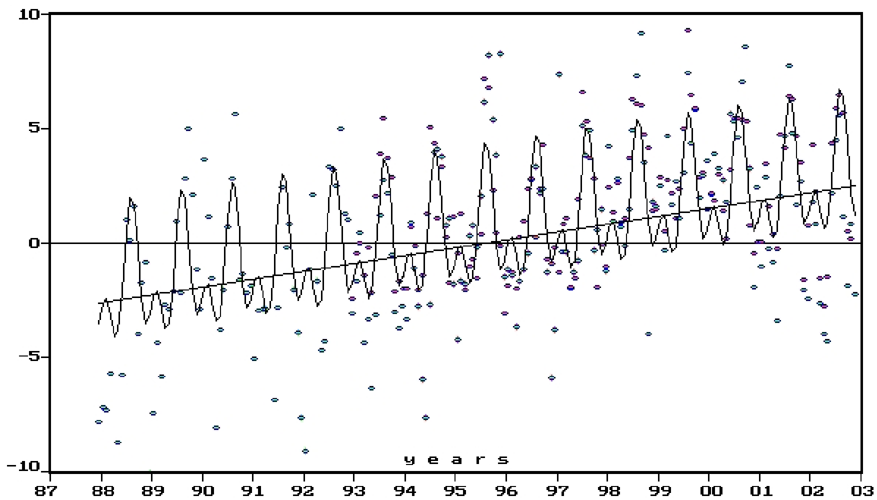

Figure 12-15. Observed and modeled variations of the corrections dJ_2

The amplitude and phase of the annual variations are consistent with the corresponding results of other studies, parameters of the semi-annual variations seem to be obtained for the first time. The observed corrections dJ_2 is presented in Figure 12-15, as well as the six-parametric model referenced above (the solid line). This more complete model demonstrates a spike in July-August and a practically constant value in other months. Note that Figure 12-15 presents not absolute variation of J_2 but the variation of J_2 calculated with the adopted negative trend recommended by IERS standards.

The evident positive trend in the corrections dJ2 presented by the straight line means that the adopted negative trend $dJ_2/dt=-26\times10^{-10}$/cy (and recommended by IERS standards [2]) should be significantly diminished and becomes negligible on the 3σ level:

$dJ_2/dt=(9 \pm 3)\times10^{-10}$/cy.

This statement is true only for the considered time interval 1988-2003.

References

Krasinsky, G. Estimating the dynamical Love number k_2^d from the analysis of the laser ranging data of LAGEOS- and LAGEOS-2. Transactions of IAA, 2009 (in press).

Yagudina, E. Lunar numerical theory EPM2008 from analysis of LLR data. Proceedings of Journees 2008., Dresden, 22-24 September 2008 (in press).

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Information-Analytical Center (IAC), formerly Mission Control Center (MCC)

Vladimir Glotov/Information-Analytical Center

Introduction

The Information-Analytical Center (IAC) of the Coordinate-Time and Navigation Service (previously known as the Mission Control Center/MCC) has been involved in SLR data analysis since 1990. The IAC has continued our activities in several areas: the determination of Earth Orientation Parameters (EOPs), SLR network quality control, studies in the use of SLR measurements of GLONASS satellites to check the quality of the available microwave-based orbital solutions, and support of the Russian SLR network and Russian SLR missions (Larets, BLITS, etc.).

For the convenience of the user community, we will continue to use the abbreviation MCC in the names of files and products and plan to transition to using the abbreviation IAC in the near future.

Facilities/Systems

The IAC SLR analysis group utilizes three of its own PC-oriented software packages in routine activities: STARK, POLAR, and STARK-AUTO&STARK-SYSTEM (SLR, GPS/GLONASS "phases" and code navigation data processing in the near-automatic regime).

Current Activities

Weekly EOP Estimation and SLR Network Quality Control

The IAC began routine determination of EOP in cooperation with the IERS in 1993. Based on SLR data from the LAGEOS-1 and -2 satellites, IAC (MCC) EOP estimations are sent to the Central and Rapid IERS Bureaus. Plots are available at *http://maia.usno.navy.mil/plots.html*.

In 1996, the IAC (MCC) began a regular service of assessing performance of the SLR stations. All LAGEOS-1 and -2 data are analyzed to obtain values of time and range biases and RMS. This routine service requires two levels of data filtering: automatically exclusion of outliers and problem sessions and running a manual check and correction of the results. Since 2008, we have sent these analysis reports daily for the SLReport publication.

The IAC SLR analysis group also provides the satellite prediction files in the Consolidated Prediction Format (CPF) for the Russian SLR missions (Larets and the planned BLITS).

GLONASS Orbit Determination and Verification

The IAC has made contributions to the International GNSS Service (IGS) by providing precise orbits based on SLR observations for those GLONASS satellites that are observed by the ILRS network. These independent orbits help to validate and evaluate precise orbits computed by analysis centers from the IGS tracking network observations. Since 1995, the IAC has supported orbit determination of GLONASS satellites based on SLR data. Orbits for GLONASS satellites (in SP3 format) are regularly sent to the IGS global data center at the CDDIS for the determination of the final orbits based mainly on the GLONASS "phase" data.

Future Plans

The IAC will continue its ILRS-related activities through the routine processing and analysis of SLR data.

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Japan Aerospace Exploration Agency (JAXA)

Takahiro Inoue, Shinichi Nakamura, Ryo Nakamura/Flight Dynamics Division, JAXA

Introduction

One of the tasks of the JAXA Associate Analysis Center is to provide the precise orbit determination for Ajisai, LAGEOS-1, and LAGEOS-2. In addition, JAXA has performed precise orbit determination experiments for the ALOS mission using onboard GPS receiver data and its accuracy evaluation using SLR data. JAXA has also performed the clock synchronization experiments using ETS-8, a geostationary satellite launched in December 2006. In 2009, SLR tracking of SOHLA-1 will be performed to evaluate the navigation accuracy, which comes from an onboard COTS GPS receiver.

Facilities/Systems

JAXA developed and completed a precise orbit determination system that uses both GPS and SLR data. In comparison with last year, we adopted some correction models, including a solar radiation pressure model. We also changed our observational model from the IERS 1996 standard to the IERS 2003 standard. The JAXA SLR station at Tanegashima was completed by the end of March 2004.

Current and Upcoming Activities

- Processing SLR tracking data of Ajisai, LAGEOS-1, and LAGEOS-2.
- Generating CPF predictions for the above satellites.
- Processing GPS satellite data (SLR normal point and RINEX) for precise orbit determination Comparison of our orbit determination results with those of the IGS analysis center shows that our precise orbit determination system has almost equivalent performance as an IGS analysis center.
- Analyzing the data obtained from ETS-8. The analysis shows that the accuracy of orbit determination and time synchronization has achieved within about 20m (RMS) and 10 nsec.
- Confirming navigation accuracy of the GPSR instrument onboard SOHLA-1.

Current and Future Satellite Missions

ETS-8

ETS-8 is an advanced satellite developed primarily to establish and verify the world’s largest-class geostationary satellite bus technology, which is necessary for space missions at the beginning of the 21st century. ETS-8 was launched in December 2006 and has been conducting orbital experiments on the Large-scale Deployable Reflector (for S-band), which is widely applicable to large-scale space structures, as well as the High-Power Transponder, and the On-Board Processor, which are all required to realize mobile satellite communications with hand-held terminals, similar to popular cellular phones. Moreover, the ETS-8 satellite carries the High Accuracy Clock (HAC) system and a Time Compare Equipment (TCE) system for the study of satellite positioning system. SLR data from ETS-8 is essential for these two experiments. Laser ranging can be performed to ETS-8 from the stations of WPLTN including the Tanegashima JAXA-station. JAXA carried out the link budget calculation in consideration of the station performance and verified the possibility of SLR tracking. Consequently, the ILRS stations Mt. Stromlo, Yarragadee, Koganei, Changchun, and Beijing became candidate tracking stations for ETS-8. JAXA has requested that these stations range to ETS-8 once every two weeks [1].

SOHLA-1

SOHLA-1 is a 50kg-class spin stabilized satellite, which was manufactured by universities and middle and small-sized enterprises joining in an organization called SOHLA (Space Oriented Higashiosaka Leading Association) established to embark on space business. The mission of SOHLA-1 is the engineering demonstration by a 50kg-class micro satellite for validation of techniques to identify a location of lightning discharge on the Earth. Other goals of the mission include a short period of development time and a low cost. SOHLA-1 carries a newly developed miniature GPS receiver and a Laser Reflector Array (LRA). Since one of the goals of SOHLA-1 is to evaluate the GPS receiver's performance, SLR data are needed in order to calibrate the receiver's data. In March 2009, JAXA requested all ILRS stations range SOHLA-1, and will request another campaign around the end of 2009 [2].

QZS

The QZSS (Quasi-Zenith Satellites System) is a constellation of several identical satellites (Figure 12-16), with at least one satellite positioned near zenith over Japan at all times; the first satellite will be launched in 2010. Users can receive the communication and positioning signals from one of QZSS near zenith direction without obstruction in urban and mountainous areas. Due to this advantage, people in moving vehicles and using mobile phones can speak and send/receive high quality content without interference. In addition, the system, used together with a GPS, will provide much more accurate positioning information than with GPS alone. The system is aimed at improving availability of GPS signals for relevant users through QZSS, which is equipped with instruments capable of generating and transmitting signals compatible with modernized GPS signals. SLR ranging data from QZS are essential for these missions in order to transmit precise orbit ephemeris through a navigation message similar to GPS.

Figure 12-16. QZSS constellation of QZSS

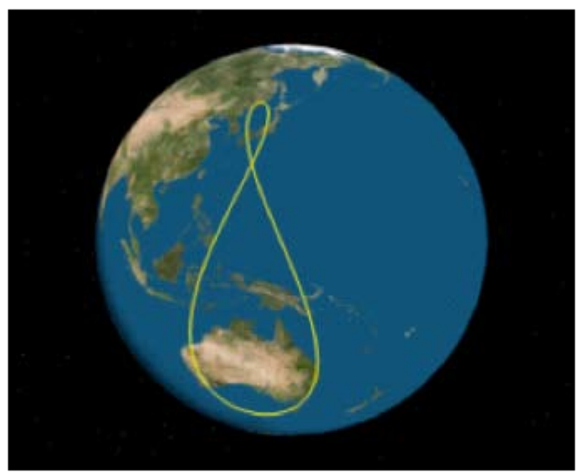

Figure 12-17. ASTRO-G satellite

ASTRO-G

ASTRO-G (Figure 12-17) is a next-generation space radio telescope designed to reveal phenomena such as the relativistic phenomena in the space around super-massive black holes at the centers of galaxies. ASTRO-G will be launched in 2012 and injected into an elliptical orbit with an apogee height of 25,000 km and a perigee height of 1000 km. The project features direct imaging observation of astronomical phenomena with a level of high-spatial resolution (40 micro arc sec. at its best) never achieved before. In order to successfully conduct a phase referencing observation, one of the observation modes in which the antenna points to a target radio source and a calibration source in a switching manner, requires precise orbit determination (POD). The accuracy requirement is at least 10 cm. In order to achieve the orbit determination accuracy, the satellite will carry a GPS receiver and a laser retro-reflector array (LRA) for SLR [3].

References

[1] ETS-8 Tracking Standard, *http://god.tksc.jaxa.jp/*
[2] T. Inoue et al, "SLR Return Analysis for SOHLA-1", *http://ilrs.gsfc.nasa.gov/docs/ILRS_Sohla_lw16.pdf*
[3] R. Nakamura et al, "SLR Return Analysis for ASTRO-G", *http://cddis.gsfc.nasa.gov/lw16/docs/presentations/ops_11_Inoue.pdf*

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Newcastle University

Philip Moore, Peter J. Clarke/Newcastle University.

The School of Engineering and Geosciences (CEG) at Newcastle University has continued its activity in space geodesy involving SLR, DORIS, VLBI, GNSS and altimetry. SLR activities utilize our in-house software FAUST. Our ILRS Associate Analysis center activities over the past two years have involved precise orbit determination of geodetic satellites with application to geocenter motion, temporal variation in Earth's gravity field and synergy of tracking techniques.

SLR analyses within precise orbit determination of LAGEOS-1 and LAGEOS-2 in particular have been used to infer temporal variability for the lower order and degree gravitational harmonics along with station coordinates, etc. directly from the tracking data. The station coordinates are subsequently used along with the gravitational results to infer degree one harmonics associated with geocenter motion.

Inversion of geodetic site displacement data to infer surface mass loads normally uses a spherical harmonic representation of the load. This method suffers from the continent-rich, ocean-poor distribution of the geodetic data. Fine-scale inversion rapidly becomes unstable due to the rapidly increasing number of parameters, which are poorly constrained by the data geometry. Several approaches have previously been tried to mitigate this, including the adoption of constraints over the oceanic domain derived from ocean circulation models, the use of smoothness constraints for the oceanic load, and the incorporation of GRACE gravity field data. However, these methods do not provide appropriate treatment of mass conservation and of the ocean's equilibrium-tide response to the total gravitational field. We have proposed a modified set of basis functions as an alternative to standard spherical harmonics that allow variability of the load over continental regions, but impose global mass conservation and equilibrium tidal behavior of the oceans. Tests of the basis functions for efficiency of fitting to realistic modeled surface loads, and for accuracy of the fit of the inferred load using synthetic geodetic displacements to the known model load have shown a better fit to the model loads and provide a more accurate and stable fit using the synthetic geodetic displacements than conventional spherical harmonics. The modified basis functions have been employed within comparisons of SLR and GNSS signatures against those from the GRACE mission. Results to date have revealed that degree 2 and 3 harmonics from SLR complement the higher degree variability obtainable from GNSS and GRACE.

Additional SLR studies with LAGEOS, Starlette, and Stella have been used for teaching purposes and for final year undergraduate projects.

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National Institute of Information and Communications Technology (NICT)

Tadahiro Gotoh/NICT

Introduction

NICT has developed precise orbit determination software, 'concerto v4' and utilizes this software to study the improvement of the force models acting on satellites. During the 2007-2008 timeframe, we have mainly studied the non-gravitational perturbation model.

Ajisai Orbit Determination using Anisotropic Radiation Pressure (Sengoku) Model

The Ajisai satellite strongly suffers from a non-gravitational perturbation force because of its large diameter and light mass. The Japan Coast Guard has developed a precise anisotropic radiation pressure model for Ajisai. We implemented this force model into the concerto v4 software, and evaluated the orbit determination accuracy when compared to a simple "cannonball model". The orbit determination accuracy improved by a factor of 1.3 compared to the cannonball model.

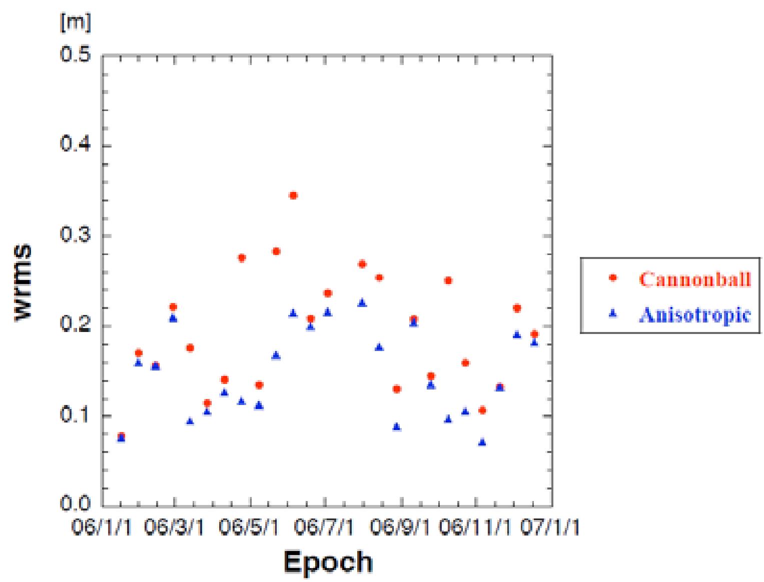

Figure 12-18. Post-fit residual wrms after least square adjustment.

Study of Non-gravitational Perturbation Model for ASTRO-G Satellite

ASTRO-G is the radio astronomy satellite for the next space VLBI observation program. The mission requires accurate orbit determination to a few centimeters despite the fact that its orbit is highly elliptic. Since the GPS satellites tracked in the vicinity of apogee by the onboard receiver are fairly old (decaying), a precise force model is necessary to maintain orbit quality over that region of the trajectory. Development of a non-gravitational perturbation model is ongoing at NICT, in collaboration with JAXA. We have computed the dense radiation forces acting on the entire satellite by applying a ray-tracing method of computer graphics, and developed the macro model based on those forces.

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Shanghai Astronomical Observatory (SHAO)

Xiaoya Wang, Xiaogong Hu, Yuanlan Zhu, Weijing Qu, Bin Wu/SAO

Introduction

The main tasks of the Shanghai Astronomical Observatory (SHAO) Associate Analysis Center are to perform SLR data quick-look processing for LAGEOS and provide weekly range and time bias analysis reports to the ILRS. In addition, SHAO has performed some precise orbit determination for Compass/Beidou using SLR data and microwave signals and evaluated their orbit accuracy. SHAO has also been preparing for automated SLR data processing including specifying a satellite (any satellite with SLR data is allowed), downloading data, preparing files, executing software, and outputting results. We have also been preparing for weekly SLR SINEX solutions using our multi-satellite SLR data processing software.

Facilities/Systems

SHAO developed and completed two precise orbit determination systems (SHODE I and COMPASS) for SLR. SHODE I is single satellite processing software and can only process one satellite at a time; COMPASS, however, can process multi-satellite data. We have also developed another software system (SHODE II) that incorporates both GPS data and SLR data. We plan to compare results and investigate new models, which will allow us to modify our software to provide ILRS products.

LAGEOS Quick-Look Processing Analysis

SHAO has been operating our weekly quick-look data analysis since 1999. The main objectives of this activity are a semi real-time quality control (QC) of the global SLR observations on LAGEOS-1 and LAGEOS-2 and on their orbits. Those orbits can be used in the calibration of some radar satellites. The weekly analysis report is provided to the ILRS. Prior to 2008, our colleagues Yuanlan Zhu and Cheng Huang performed this work; after 2008 Dr. Wang and Dr. Hu assumed responsibility for this activity at the SHAO AAC. Since 2008, a PhD student (Weijing Qu) produces these weekly analysis reports; we plan to fully automate our data processing in the near future.

SHAO reviewed the related models and constants used in our processing during 2007 and 2008 (see our AAC description at *http://ilrs.gsfc.nasa.gov/reports/analysis_reports/SHAO-QC.dsc.txt*). We continue to use the ITRF2000 reference frame because the residual rms becomes too large when using ITRF2005. We will continue to study possible changes to our software to include the new IERS convention models and reference frame. Typical rms-of-fit values are in the range of 10 to 20 mm. We also hope to induce the corrections for atmospheric pressure loading and the estimation of the geocenter after our auto-processing is completed. Based on initial tests, we hope to generate analysis reports including Etalon and perhaps additional satellites. We continue to compare the range and time biases of individual LAGEOS-1 and -2 passes with the estimates obtained by other analysis centers (DGFI and Hitotsubashi University), and strive to give the stations a realistic feedback on the performance on their equipment. This work continues in test phase at this time.

Our most important action item is the reactivation of our analysis procedures. SHAO intends to introduce several new elements in the operational analysis: (1) the dissemination analysis results through the network, (2) the addition of other satellites, probably Etalon-1 and -2, (3) the implementation of new models to handle the refraction effects.

Compass Precise Orbit Determination

Compass, the Chinese satellite navigation system, launched the test satellite Compass-M1 on April 13, 2007. A laser reflector array was installed on Compass-M1. The satellite has microwave tracking data but unfortunately no SLR data were available until December 2008. We analyzed some microwave tracking data based on a regional network and validated the orbit accuracy with SLR data during 2007. The accuracy is in the order of a meter. The orbit determination based only on SLR tracking data began in December 2008 and is calculated once every three days. We succeeded in determining SLR-only orbits of Compass covering data arcs of seven days with a three-day overlap both at the beginning and at the end of the arc. The residual rms is typically better than 5 cm with values better than 1 cm in the best situations. Additional details will be presented at the ILRS Technical Workshop on SLR Tracking of GNSS Constellations to be held in Greece in September 2009. All SLR related results will be available on the SHAO web site currently under development.

Recent Activities

Recently, we completed our auto-processing system that includes weekly quick-look processing analysis, post-processing that provides weekly loose SINEX solutions, and long time series analysis based on SINEX solutions. In addition, SHAO has performed precise orbit determination for Compass. In the very near future we will start the pre-processing and analysis of LAGEOS-1 and -2 data and provide SINEX-formatted solutions for site coordinates, EOP, and geocenter time series.

Future Plans

Most current activities will continue, with particular attention to the ILRS and IERS oriented products. During automatic processing, a number of quality checks are performed and the weekly results of the bias analysis will be sorted by satellite and year and be available from the SHAO web server. We will continue to explore the application of multi-satellite analysis to the long time series of EOP, station coordinates and velocities, and the position variation of Earth's mass center. We will also do some comparisons based on our different software. In addition, we will test our combined analysis of microwave data and SLR data based on SHODE II and demonstrate the possible improvement in the orbit accuracy.

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ILRS LUNAR ASSOCIATE ANALYSIS CENTER REPORTS

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.

Institut Fuer Erdmessung/Forschungseinrichtung Satellitengeodaesie (IFE/FESG)

Jürgen Müller, Liliane Biskupek, Franz Hofmann/IfE, Ulrich Schreiber/FESG

Recent Activities

The transformation between the celestial and terrestrial systems was updated according to the IERS Conventions 2003. The transformation, however, is still implemented following the equinox-based representation using the IAU 2000A precession-nutation model, not the CIO-based version. Further model changes covered the gravity field of Earth and the loading effects of the atmosphere and the ocean. Also new initial values for our own ephemerides computation, based on JPL ephemeris DE405, have been introduced.

The IAU 2000 nutation model is described in the IERS Conventions 2003 as a series for nutation in longitude $\Delta\psi$ and obliquity $\Delta\varepsilon$, referred to the mean ecliptic of date:

$$\Delta\psi = \sum_{i=1}^{N} \left(A_i + A_i^{'} t\right)\sin\left(ARG\right) + \left(A_i^{''} + A_i^{'''} t\right)\cos\left(ARG\right)$$

$$\Delta\varepsilon = \sum_{i=1}^{N} \left(B_i + B_i^{'} t\right)\cos\left(ARG\right) + \left(B_i^{''} + B_i^{'''} t\right)\sin\left(ARG\right)$$

with t in Julian centuries from epoch J2000 and $ARG = \sum_{j}^{5} N_j F_j$, N_j: multipliers, F_j: Delaunay parameters. With the updated analysis software, the nutation coefficients A_i, A_i", B_i and B_i" of different periods (18.6 and 9.3 years, 1 year, 182.6 and 13.6 days) were determined and compared to the values of the MHB2000 model of Mathews et al. (2002). Table 5 gives our preliminary results. The post-fit residuals of the standard solution were processed to determine corrections for Earth rotation ΔUT0 and variation of latitude $\Delta\psi$ with the daily decomposition method.

Another study covered data from the new observatory APOLLO (Apache Point Observatory Lunar Laser-ranging Operation in New Mexico, USA). The APOLLO data set was analyzed for outliers and possible biases. For the overall weighting, which is based on the accuracy estimates of the observatory, the accuracy of the observed Earth-Moon distances was reduced by 0.1 ns to make the new data consistent with our LLR system. The APOLLO data improve the overall quality of our LLR solution. Furthermore, the data set of all observatories was analyzed for biases, affecting the normal points over short periods. But no new significant biases were found besides the known ones.

In the area of relativity, a study related to the parameterization of gravito-magnetic effects by means of LLR was carried out. The corresponding terms in the equation of motion were parameterized introducing a new quantity ηG. Furthermore, the preferred-frame parameter $\alpha 1$ was introduced in the equations of motion given in the extended PPN framework (Will, 1993) and was analyzed in our global adjustment. Frame-dependent effects due to the gravito-magnetic effect as predicted by Einstein's theory could be verified at the 10^{-3} level. For more details see Soffel et al. (2008).

Table 12-5. Nutation coefficients from IfE LLR computation

Period	A_i [mas]	B_i [mas]	A_i" [mas]	B_i" [mas]
18.6 years	-17201.93	9203.41	3.84	3.88
182.6 days	-1316.88	572.98	-3.25	-0.98
13.6 days	-230.54	99.26	0.16	0.31
9.3 years	207.13	-90.75	1.63	-0.21
1 year	146.83	7.86	0.27	-0.58

Ongoing Activities and Future Plans

In February 2009, a new co-worker, Franz Hofmann, started in the cluster of excellence QUEST (Centre for Quantum Engineering and Space-Time Research). One task group of this cluster focuses on possible modifications of Einstein's theory. Here, IfE will support this work by improved modeling and analysis of LLR data and investigation of relativistic parameters.

The LLR model has been improved, by updating the model of the lunar interior with support from Jim Williams (JPL). A next step will be to update the modeling of the effect from the asteroids. The determined nutation coefficients will be compared with VLBI results in the future. Also comparisons on the level of normal equations are planned.

Publications

Biskupek, L., Müller, J.: Lunar Laser Ranging and Earth Orientation; in: Astrometry, Geodynamics and Astronomical Reference Systems, Proceedings of Journées "Syst mes de référence spatio-temporels" and X. Lohrmann-Kolloquium, Dresden, Germany, 22.-24.09.2008, submitted 2009.

Biskupek, L., Müller, J.: Relativity and Earth Orientation Parameters from Lunar Laser Ranging, in: Electronic Proceedings of the 16th International Workshop on Laser Ranging, Poznan, Poland, 12.-17.10.2008, submitted 2009.

Kopeikin, S. M., Pavlis, E., Pavlis, D., Brumberg, V. A., Escapa, A., Getino, J., Gusev, A., Mueller, J., Ni, W. -T., Petrova, N.: Prospects in the orbital and rotational dynamics of the Moon with the advent of sub-centimeter lunar laser ranging, Advances in Space Research, 42, 1378-1390, 2008.

Müller, J.: Lunar Laser Ranging: A Space Geodetic Technique to Test Relativity, in: Proceedings of the 11th Marcel Grossmann Meeting, Berlin, 23.-29.07.2006, Kleinert, H.; Jantzen, R.T. & Ruffini, R. (eds.), World Scientific, Part C, 2576-2578, 2008.

Müller, J., Biskupek, L.: Variations of the gravitational constant from lunar laser ranging data, Classical and Quantum Gravity, 24, 4533-4538, 2007.

Müller, J., Soffel, M., Klioner, S. A.: Geodesy and relativity, Journal of Geodesy, 82, 133-145, 2008.

Müller, J., Williams, J.G., Turyshev, S.G.: Lunar Laser Ranging Contributions to Relativity and Geodesy, in: Lasers, Clocks and Drag-Free Control: Exploration of Relativistic Gravity in Space, Dittus, H., Lämmerzahl, C. & Turyshev, S.G. (eds.), Springer, 349, 457-472, 2008.

Soffel, M., Klioner, S., Müller, J., Biskupek, L.: Gravitomagnetism and lunar laser ranging, Physical Review D, 78, 024033, 2008.

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References

Mathews, P.M., Herring, T.A., Buffett, B.A.: Modeling of nutation and precession: New nutation series for nonrigid Earth and insights into the Earth's interior, J. Geophys. Res. (B4), 107, 10.1029/2001JB000390, 2002.

Will, C. M.: Theory and Experiment in Gravitational Physics, Cambridge University Press, England, 1993.

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Analysis and Science Activities 2007-2008

Lunar Laser Ranging (LLR) data analysis at JPL has fit the operational data sets from the McDonald, Observatoire de la Côte d'Azur (Grasse) and Apache Point Observatory sites plus historical data from Haleakala. A total of 16,960 normal points have been processed from 1970 through the end of 2008. Retroreflector arrays include Apollo 11, 14, and 15 missions and Lunokhod 2.

The computer code for lunar laser ranging data analysis continues to be reviewed and upgraded. Solutions now detect the lunar fluid core moment of inertia. Daily UT0 and variation of latitude solutions have been made for a 38 yr LLR data span.

Standard solution parameters now include ranging station coordinates and motions, Earth orientation, lunar orbit, tidal acceleration, GM of Earth+Moon, lunar orientation, Love numbers, tidal Qs, dissipation at and oblateness of the lunar fluid-core/solid-mantle boundary (CMB), moment of inertia of fluid core, mantle moment differences, gravity coefficients and retroreflector array positions. In addition, solutions were made for any equivalence principle violation (related to PPN beta and gamma), dG/dt, geodetic precession and scale change. Gravitational physics results are in agreement with general relativity.

With Nicolas Rambaux, we studied lunar free librations. The 2.9 yr longitude and 74.6 yr wobble modes are strongly detected, but the 81 yr precession in space is much weaker. The free core nutation was not detected. There must be a source of stimulation for the two large modes.

DE418 and DE421 orbital ephemerides of the Moon and planets plus physical librations were generated and made publicly available. DE421 is available in two formats via ftp: *ftp://ssd.jpl.nasa.gov/pub/eph/planets/ascii/de421* and *ftp://ssd.jpl.nasa.gov/pub/eph/planets/bsp.*

Looking to future laser ranging activities, we investigate a corner cube design for future lunar landers. We also investigate transponders for future laser ranging to the Moon, Mars and Phobos.

Papers

Müller, J., J.G. Williams, S.G. Turyshev, Lunar Laser Ranging Contributions to Relativity and Geodesy, in proceedings of 359th WE-Heraeus Seminar on "Lasers, Clocks, and Drag-Free: Technologies for Future Space Exploration in Space and Tests of Gravity," eds. H. Dittus, C. Lämmerzahl, S. Turyshev, 457-472, Springer, 2007. http://arxiv.org/abs/gr-qc/0509114

Murphy, T.W., K. Nordtvedt, S.G. Turyshev, Gravitomagnetic Influence on Gyroscopes and on the Lunar Orbit, Phys. Rev. Lett., 98, 071102, 2007. arXiv: gr-qc/0702028

Murphy, T.W., W. Farr, w. Folkner, A. Girerd, H. Hemmati, S. Turyshev, J.G. Williams, J.J. Degnan, Testing Fundamental Gravity via Laser Ranging to Phobos, in proceedings of 16th Int. Workshop on Laser Ranging, in press, 2009.

Turyshev S., J.G. Williams, Space-Based Tests of Gravity with Laser Ranging, International Journal of Modern Physics D16 (12a), 2165-2179, doi:10.1142/S0218271807011838, (Dec) 2007. arXiv:gr-qc/0611095v1

Williams, J.G., S.G. Turyshev, D.H. Boggs, "Williams, Turyshev, and Boggs Reply", Phys. Rev. Lett., 98, (#5) doi: 10.1103/PhysRevLett.98.059002, (Feb 2) 2007.

Williams, J.G., A Scheme for Lunar Inner Core Detection, Geophysical Research Letters, 34, L03202, doi:10.1029/2006GL028185, (Feb 9) 2007.

Williams, J.G., D.H. Boggs and W.M. Folkner, DE421 Lunar Orbit, Physical Librations, and Surface Coordinates, JPL IOM 335-JW,DB,WF-20080314-001, March 14, 2008.

Williams, J.G., S. Turyshev, D.H. Boggs, Lunar Laser Ranging Tests of the Equivalence Principle with the Earth and Moon, Int. J. of Modern Physics D, in press, 2009.

Williams J.G., D.H. Boggs, Lunar Core and Mantle. What Does LLR See?, in proceedings of 16th International Workshop on Laser Ranging, in press, 2009.

Abstracts

J. G. Williams, D. H. Boggs, and J. T. Ratcliff, Lunar Mantle and Fluid Core Results and Inner Core Possibilities, abs. #2004, *Lunar and Planetary Science Conf. XXXVIII*, March 12-16, 2007.

S. G. Turyshev, J. G. Williams, and D. H. Boggs, Lunar laser ranging research: recent progress and future plans, American Geophysical Union meeting, San Francisco, CA, Dec. 10-14, 2007.

J. G. Williams, D. H. Boggs, and J. T. Ratcliff, Lunar Tides, Fluid Core and Core/Mantle Boundary, abs. #1484 of *Lunar and Planetary Science Conference XXXIX*, March 10-14, 2008.

N. Rambaux, J. G. Williams, and D. H. Boggs, A Dynamically Active Moon – Lunar Free Librations and Excitation Mechanisms, abstract #1769 of *Lunar and Planetary Science Conference XXXIX*, March 10-14, 2008.

J. T. Ratcliff, J. G. Williams, and S. G. Turyshev, Lunar Science from Laser Ranging – Present and Future, abs. #1849 of *Lunar and Planetary Science Conference XXXIX*, March 10-14, 2008.

S. G. Turyshev, J. G. Williams, H. Hemmati, and W. M. Folkner, New Laser-Ranging Instruments for Science Investigations on, of, and from the Moon, abstract #2134, NLSI Lunar Science Conference, Ames Research Center, July 20-23, 2008.

B. Archinal, C. Acton, B. Bussey, B. Campbell, G. Chin, A. Colaprete, A. Cook, D. Despan, R. French, L. Gaddis, R. Kirk, W. Mendell, F. Lemoine, M. Nall, J. Oberst, J. Plescia, M. Robinson, D. Smith, K. Snook, T. Sweetser, R. Vondrak, M. Wargo, and J. Williams, Lunar Science Support by the NASA LPRP Lunar Geodesy & Cartography Working Group: Recommendations for Lunar Cartographic Standards, NLSI Lunar Sci. Conf., Ames Res. Center, July 20-23, 2008.

J. G. Williams, Lunar Core and Mantle. What Does LLR See?, 16th Int. Workshop on Laser Ranging, Poznan, Poland, 2008. *cddis.gsfc.nasa.gov/lw16/docs/presentations/sci_1_Williams.pdf*

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Paris Observatory Lunar Analysis Center (POLAC)

Sébastien Bouquillon, Jean Chapront, Gérard Francou /Observatoire de Paris

The lunar analysis center POLAC works in cooperation with the laser ranging team of the Observatoire de la Côte d'Azur (GRGS ILRS Analysis Center) and with the two IERS centers based at the Observatoire de Paris (EOP and ICRS centers). During these last two years, our activities have been reduced because of the retirement of Jean Chapront and the temporary break in the observations of Grasse (OCA). We have revisited the entire set of LLR observations made since 1969. This inventory has been performed with our existing archives completed with those given by Grasse and by James Williams. We have compared them to the observations already available at the data centers of ILRS. Some of these data, which were obviously wrong or redundant, have been corrected or excluded. Thus, more than 18,000 LLR normal points have been gathered with the same format over the time interval 1969-2008 divided into several units according to the sites and the periods of observations (Figure 12-19 and Table 12-6): McDonald 1969-2008, Grasse 1984-2005, Haleakala 1987-1990 and Apache Point 2006-2008.

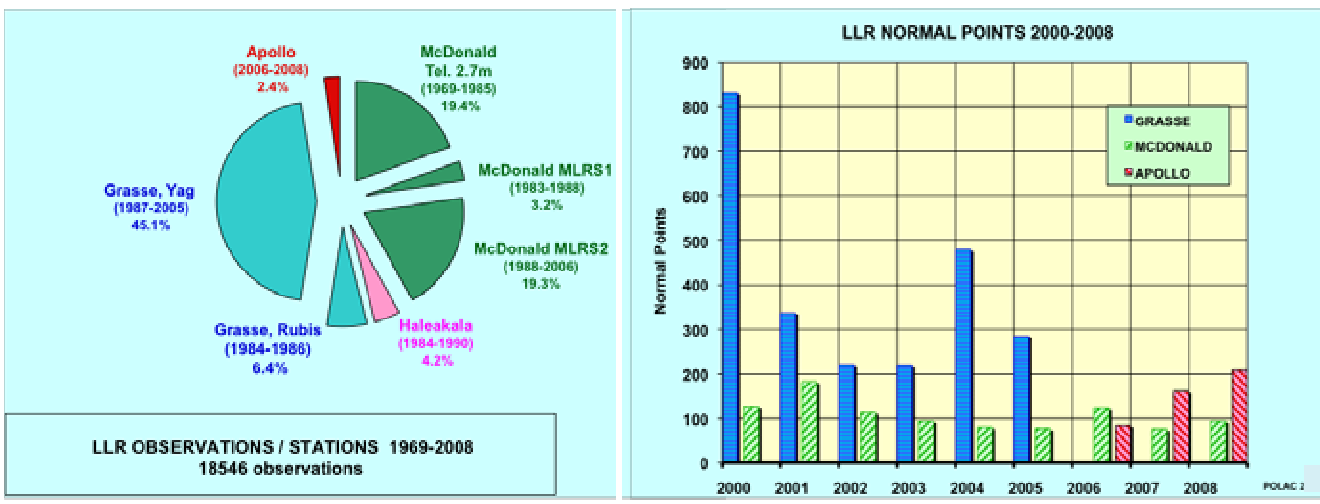

Figure 12-19a and -b. LLR data archive statistics

References

Manche H., J. Laskar, A. Fienga, N. Capitaine, S. Bouquillon, G. Francou, M. Gastineau, 2008, "The geodesic precession in the INPOP ephemerides", Journées.2008 - Systémes de référence spatio-temporels, Dresden, Germany, M. Soffel, N. Capitaine (eds.).

Manche H., Bouquillon S., Fienga A., Laskar J., Francou G., Gastineau M., 2007, "Towards INPOP07, adjustements to LLR data", Journées 2007 - Systémes de références spatio-temporels, Paris, France, N. Capitaine et al. (eds).

Zerhouni W., N. Capitaine, G. Francou, 2008, "What could bring LLR observations in determining the position of the celestial pole", Journées 2008 - Sysémes de référence spatio-temporels, Dresden, Germany, M. Soffel, N. Capitaine (eds.).

Zerhouni W., Capitaine N., Francou G., 2008, "The determination of the corrections to the IAU 2000A-2006 X,Y coordinates using LLR observations", Société astronomique de France.

Zerhouni W., Capitaine N., Francou G., 2007, "The use of LLR observations (1969-2006) for the determination of the celestial coordinates of the pole", Journées 2007 - Systémes de références spatio-temporels, Paris, France, N. Capitaine et al. (eds).

Table 12-6. Available LLR Normal Points

Stations and Instruments	Periods of the Observations	rms of the Post-Fit Residuals
McDonald Tel 2.7m	1969-1976	45.4 cm
McDonald Tel 2.7m	1976-1980	24.4 cm
McDonald Tel 2.7m	1980-1986	23.0 cm
McDonald MLRS1	1983-1988	29.3 cm
McDonald MLRS2	1988-1991	5.6 cm
McDonald MLRS2	1991-1995	3.9 cm
McDonald MLRS2	1995-2001	3.5 cm
McDonald MLRS2	2001-2008	8.0 cm
Haleakala	1984-1990	7.0 cm
Grasse Rubis	1984-1987	16.3 cm
Grasse Yag	1987-1991	5.5 cm
Grasse Yag	1991-1995	4.0 cm
Grasse Yag	1995-2002	3.2 cm
Grasse Yag	2002-2005	4.5 cm
APOLLO	2006-2008	4.1 cm

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