Section 7

Analysis Center Reports

This Page Deliberately Left Blank

SECTION 7 - ANALYSIS CENTER REPORTS

The Analysis Centers receive and process information from the Data Centers and regularly make the results of their analysis available to ILRS participants. Standard products are delivered to the Global Data Centers and to the IERS, among other recipients. The Analysis Centers also provide a level of quality assurance on the global data set by monitoring individual station performance via the fitted orbits used in generating the quick-look science results. The interval and time lag for product delivery specified by the Governing Board determines the credential as Analysis or Associate Analysis Center, and three institutions currently qualify as Analysis Centers.

CSR at the University of Texas monitors and disseminates results on LAGEOS-1 and LAGEOS-2 analysis on a weekly basis. This information is also accessible, together with CSR 3-day EOP values via the web and anonymous ftp. NASA uses the EOP information for the operational orbit determination for TOPEX/Poseidon. CSR also provides evaluation and technical support of new systems in engineering status and supports the determination of the ITRF through the submission of annual SLR tracking station position and velocity solutions.

Delft University of Technology's QLDAC also provides a semi real-time quality control of observations on LAGEOS-1 and LAGEOS-2, and reports to the stations on a regular basis to assist in monitoring the performance of operational systems, as well as for technical support of systems in engineering status. QLDAC also produces accurate EOPs for inclusion in the USNO/IERS bulletins, and provides information for scientific interpretation and for the motivation of data analysis.

Moscow's MCC provides regular daily values of polar motion and length-of-day, and adds GLONASS analysis to its bulletins of Lageos-1 and Lageos-2 SLR station data performance, as well as producing precise orbits for GLONASS and Westpac orbits and other low satellites.

Associate Analysis Centers provide a variety of capabilities to supplement the products of the main Analysis Centers. For example, the Norwegian Defence Research Establishment's FFI, which is also an IVS Analysis Center, offers the capability to combine VLBI, GPS, and SLR data at the observation level. The DGFI in Munich focuses on the automation of the SLR data analysis in its plans to establish an operational analysis center and on the computation of a global SLR solution for the ITRF2000. The prediction and quality control work at the NERC SLR facility at Herstmonceux and Monks Wood, UK was developed to better equip the SLR system, and the wide use of these products within the ILRS network is a valuable spin-off from the work. The Italian Space Agency's CGS provides standard, special and multi-technique analysis products. The standard products are routinely distributed to the IERS and include the coordinates and velocity field of the SLR network and EOP values provided yearly, as well as monthly EOP to contribute to the Bulletin B distributed to the scientific community. Special and the multi-technique products include precise orbit determination for Lageos I, Lageos II, Starlette, Stella and ERS-1, with supporting data interpretation, and time series of low degree geopotential coefficients and geocenter motion, supported by inter-technique combination and comparison.

The GFZ in Potsdam complements its operation of the local SLR station with the routine generation and distribution of IRVs and two-line elements for ERS-1, ERS-2 and GFZ-1 and continuously monitors the predictions. GFZ has also contributed to the Earth gravity field, station position and velocity model GRIM5, jointly with GRGS/CNES. The AUSLIG Space Geodesy Analysis Center in Canberra is participating in the ILRS Analysis Working Group pilot projects for station coordinates and EOPs, orbit comparison and the software/standards comparison. AUSLIG also continues to submit results to the IERS Time Series Pilot Project, and will contribute a significant SLR solution to the ITRF2000. In Grasse, CERGA's data analysis of LAGEOS observations, permanent GPS receiver measurements, and absolute gravimetry measurements has led to improvements in orbitography and positioning quality control. In particular, this analysis has allowed an accurate calibration of the Grasse Lunar Laser Ranging station. The group at JCET/GSFC in Greenbelt, Maryland continues to generate weekly solutions as a contribution to the IERS/ITRF Pilot Project for monitoring the episodic and seasonal variations in the definition of the geocenter, and is also re-generating weekly SINEX following ILRS-adopted standards.

The Russian Academy of Science's IAA Associate Analysis Center continues to regularly submit EOP operational and final solutions to the IERS. IAA is also developing software for the combination of SLR, GPS and VLBI EOP series, for combined processing of the SLR and VLBI observations, and for processing of the microwave and laser range observations of GPS and GLONASS satellites. The CODE group at the Astronomical Institute of the University of Berne has set up the SLR-GPS Quick-look Service to monitor the SLR observations using IGS rapid and final orbits. These are available only 12 hours after the end of the observation day and thus provide the possibility to give very rapid feedback on the quality of the SLR observations. Potsdam's BKG provides station coordinates, velocities and EOPs to the IERS on an annual basis, and has developed a system providing solutions which are not constrained by fixing parameters but by using a-priori sigmas to introduce the datum. The BKG also joins the other Analysis Centers and Associate Analysis Centers in contributing to the ILRS Analysis Working Group pilot projects for improving station coordinates and EOPs.

7.1 SATELLITE LASER RANGING

The Analysis Centers fall into three categories: Analysis Centers, Associate Analysis Centers and Lunar Analysis Centers.

7.1.1 ANALYSIS CENTERS

The Analysis Centers receive and process tracking data from one or more data centers for the purpose of producing ILRS products. The Analysis Centers are committed to produce the products, without interruption, at an interval and with a time lag specified by the Governing Board to meet ILRS requirements. The products are delivered to the Global Data Centers, to the IERS (as per bilateral agreements), and to other bodies, using designated standards. At a minimum, the Analysis Centers must process the global LAGEOS-1 and -2 data sets and are encouraged to include other geodetic satellites in their solutions. The Analysis Centers provide, at a minimum, Earth orientation parameters on a weekly or sub-weekly basis, as well as other products, such as station coordinate, on a monthly or quarterly basis or as otherwise required by the IERS. The Analysis Centers also provide a second level of quality assurance on the global data set by monitoring individual station range and time biases via the fitted orbits (primarily the LAGEOS-1 and -2 satellites) used in generating the quick-look science results.

7.1.1.1 Center for Space Research

Richard Eanes and John Ries, *Center for Space Research, University of Texas*

INTRODUCTION / DATA PRODUCTS PROVIDED

Researchers at The University of Texas at Austin have analyzed SLR data since about 1974 when the UTOPIA orbit determination software was developed and applied to the determination of baseline lengths using Beacon-Explorer-C tracking obtained by stations deployed by GSFC in various locations, most notably in San Diego and Quincy, California which span the San Andreas fault. The UTOPIA software was soon applied to the Geos-3 SLR tracking to support this pioneering satellite altimeter mission and to make our first polar motion determinations (Schutz et al., 1979). When Starlette and LAGEOS-1 were launched, the SLR tracking of these first “cannonball” targets was applied to gravity field research and towards improvements in the techniques used for precise orbit determination. As the number, distribution and accuracy of the global network improved, the challenge of modeling increased and the number of applications grew. This process continues today even as RMS fits to the SLR tracking of LAGEOS have shrunk to the sub-centimeter level.

The operational analysis at UT/CSR includes the following activities:

(i) The quality of observations on LAGEOS-1 and LAGEOS-2, taken by the global network of SLR stations, are monitored on a weekly basis. Every Tuesday, the analysis is performed and the results are disseminated to the SLR stations and other institutions. The analysis covers the observations taken during the week prior to the date of the computations, so that the quality assessment lags the actual data collection by somewhere between 3 and 10 days. The observed biases, time biases and noise levels are determined for each pass from every station. The results are reported through the web at http://www.csr.utexas.edu/slr/.

(ii) As part of the LAGEOS analysis, 3-day Earth Orientation Parameters (EOPs) are estimated, with NAVNET VLBI used for long term UT1, for inclusion in the USNO/IERS bulletins. These results are also available via the web and anonymous ftp. These EOP values are used by NASA for the operational orbit determination for the TOPEX/Poseidon (T/P) altimeter satellite and for the creation of the T/P altimeter Geophysical Data Records (GDR).

(iii) Evaluation and technical support of new systems in engineering status is provided.

(iv) The determination of the International Terrestrial Reference System (ITRF) is supported through the submission of annual SLR tracking station position and velocity solutions.

(v) Preliminary information for scientific data analyses are also provided, such as high precision satellite orbits and preliminary coordinates for new stations.

FACILITIES/SYSTEMS

The University of Texas Center for Space Research occupies 23,000 sq-ft of office and laboratory space. CSR also maintains a variety of computers and other scientific equipment. The computer assets include an Origin 2000 server managing 6 TB of archival storage, as well as a variety of workstations and PCs. CSR has recently acquired a Cray SV1-1A supercomputer that is operated jointly with UT's Texas Advanced Computation Center. The SV1-1A has 16 1.2 GFLOP processors, 16 GBytes memory, and 4 fiber channel RAID drive arrays (with 640 GB of disk total). UT provides operational support for the SV1-1A as well as a file system and data migration facility supported by a four-processor SGI Origin 2000 server with approximately 800 GB of on-line storage and 30 TB of tape archive.

CURRENT ACTIVITIES

Weekly EOP estimation and SLR Network Quality Control

Typically, the observations are taken from NASA's Crustal Dynamics Data Information System (CDDIS), then merged, time-sorted and edited for double entries. The main element of the weekly analysis is the fitting of 3-day continuous orbits through the last 12-18 days of observations. A summary of the computation model currently in use is given in Table 7.1.1.1-1. The fitting results in an average value for the weighted rms-of-fit of 15-20 mm. Table 7.1.1.1-2 shows the results obtained for a recent 18-day span based on the 3-day arcs, 3-day EOP and linearly-varying coordinates used in the weekly analysis. Clearly visible is the variety in the post-fit residuals between the various stations.

Seasonal Variations of the Earth's Gravity Field

Mass redistributes itself in the Earth system on a variety of temporal and spatial scales reflecting complex interrelated processes in the oceans, atmosphere, groundwater, glacial/polar ice, among others. The measurement of these variations is thus important for a variety of studies attempting to understand the interrelations of the different components of the Earth system, and how they may change with time due to anthropogenic influences. We have used LAGEOS-1 and LAGEOS-2 laser ranging data to determine long wavelength seasonal variations of the Earth's gravity field from 1993 to the present. Due to the altitude of these satellites, and the non-continuous nature of the measurements, these data can detect seasonal gravitational variations only for wavelengths of roughly 10,000 km and longer (a degree 4 spherical harmonic expansion). We have compared the observed annual variations for a complete 4 x 4 spherical harmonic expansion as observed by LAGEOS 1/2 SLR data to those predicted from a variety of atmospheric, oceanic, and hydrologic models. We have used the observed variations to optimally select the best set of model predictions. The correlation of the maps of the observed and modeled annual geoid variation is as high as 0.8, with an rms difference of close to 1 mm. Given the sparse temporal and spatial distribution of the SLR data, and the limitations of the geophysical models, we consider this agreement to be as good as can be expected (Chen et al., 1999; Nerem et al., 2000). To further enhance the resolution of the time-variable gravity field (up to degree 6 or more), SLR from T/P, Ajisai and Stella have been analyzed (Cheng et al.,1999), and the recent tracking campaign for the BEC satellite may help further resolve the various coefficients.

Utilized in LAGEOS-1 and LAGEOS-2 SLR Analysis	
Reference Frame	
Conventional Inertial System (CIS)	J2000
Precession	1976 IAU
Nutation	IERS-96
Planetary Ephemerides	JPL DE-200
Conventional Terrestrial System	CSR95L01 (new stations adjusted)
Polar Motion	EOP estimated every 3 days (IERS a priori)
Reference Ellipsoid	a_e = 6378136.3 m 1/f = 298.257
GM	GM = 398600.4415 km^3s^{-2}
Observation models	
Source	Collected from CDDIS
Center of Mass offset	251 mm
Elevation Cutoff	10 degrees
Troposphere	Marini-Murray model
Rotational Deformation	IERS-96
Ocean Loading	IERS-96
Relativity	IERS-96
Atmosphere Loading	not modeled
Observation Weighting	Station dependent (precision plus overall modeling uncertainty)
Force Models	
Gravity Model	IERS-96 (JGM-3)
Temporal Gravity	J_2-dot = -2.6 x 10^{-11}/yr Epoch 1986.0
N-Body	DE-200 (Sun, Moon and planets)
Solid Earth Tides	IERS-96
Ocean Tides	CSR 3.0
Rotational Deformation	IERS-96
Relativity	Central Body (Earth)
Solar Radiation Pressure	Cr for LAGEOS-1 fixed at .1125, LAGEOS-2 fixed at .125
Earth Radiation Pressure	Albedo/Infrared
Numerical Integration	Cowell 14th order; step-size 300 sec (298 sec for LAGEOS-2)
Empirical Accelerations	1 constant along-track, 1 1-cpr along-track and cross-track
Arc Length	3 days

Table 7.1.1.1-1. Reference Frame and Force Models UT/CSR computation model summary.

Station	number of obs	mean (mm)	rms (mm)	precision (mm)
Maidanak, Uzbekistan	59	-49	51	13
Riga, Latvia	49	-2	22	9
Kazivili, Ukraine	33	12	30	9
McDonald Observatory, Texas	106	-9	12	2
Yarragadee, Australia	163	-4	14	2
Greenbelt, Maryland	102	3	11	4
Monument Peak, California	360	-1	17	2
Wuhan, China	136	-2	29	9
Changchun, China	121	7	16	10
Arequipa, Peru	54	-15	23	7
Cagliari, Italy	50	-28	50	9
Zimmerwald, Switzerland	311	-8	16	5
Borowiec, Poland	89	-6	18	5
Kunming, China	27	--	--	--
San Fernando, Spain	183	-49	50	7
Helwan, Egypt	18	9	19	6
Grasse, France (7835)	305	5	10	2
Potsdam, Germany	94	10	17	4
Shanghai, China	7	--	--	--
Simosato, Japan	14	-12	11	6
Graz, Austria	339	-9	14	2
Herstmonceux, United Kingdom	186	-13	20	3
Grasse, France (7845)	193	1	14	4
Mount Stromlo, Australia	279	-16	20	4
Matera, Italy	76	-6	40	19
Wettzell, Germany	249	-17	27	6
Totals (weighted)	3603	-5	16	4

-- all data edited

Table 7.1.1.1-2. Example of analysis results for LAGEOS-2: the number of normal points, the mean and rms of the post-fit residuals and the estimated precision for the period June 17–July 5, 2000.

GPS/GLONASS Orbit Analyses

The Center for Space Research contributed to the International GLONASS Experiment 98 (IGEX-98) campaign through the evaluation of GLONASS orbits computed by different centers using Satellite Laser Ranging (SLR) data and through the computation of GLONASS orbits using SLR data and the CSR's UTOPIA software. When used directly to compute range residuals relative to each center's radiometric orbit, we find the SLR data to be a very effective discriminator of the radial orbit accuracy. We also find that the mean of the SLR range residuals has a value of -5 cm, similar to what has been observed in SLR/GPS comparisons. This implies the presence of a mean radial acceleration of 4–5 nm/s^2 (we consider it unlikely that an error in GM could account for more than a small part of this), or there is a systematic error in both the GPS and GLONASS center-of-mass offset corrections (Eanes et al., 1999) caused by effect of target signature on the ranging data from systems operating at different return signal strengths.

Precision Orbit Determination and Verification

SLR and DORIS tracking provide the principal means of precise orbit determination for the T/P altimeter spacecraft, supporting an orbit accuracy of 2 to 2.5 cm in the radial direction (Ries and Tapley, 1999). Studies have demonstrated that the DORIS data are providing the dominant contribution to the overall orbit accuracy, but it was also apparent that the variations in the centering of the orbit from cycle to cycle in the Z direction (along the Earth's spin axis) increased significantly when the SLR data were excluded. This centering is critical to avoid artificial signals in the observed sea surface variations between the hemispheres that might be erroneously interpreted. The SLR data, due to the absolute ranging information that they provide, help to center the orbit more precisely and consistently, as well as contribute to the overall orbit accuracy. They also provide an unambiguous determination of the height of the spacecraft above a tracking station, particularly for passes which cross at a high elevation angle. This capability is unique to SLR, and it is crucial for orbit accuracy assessment at the current levels. It is clear that the SLR data are an important component of the tracking system. The two systems have also provided invaluable redundancy, since each system has experienced periods of reduced or interrupted tracking.

Geocenter

SLR analyses have shown that the coordinate frame of tracking stations attached to the Earth's crust moves detectably relative to the Earth's center of mass. This translational motion, when viewed from a crust-fixed frame, is known as "geocenter motion" and is caused by the mass movement of planetary fluids, primarily the atmosphere and oceans. Observing the geocenter motion at seasonal and interannual time scales can provide important constraints on the mass transport within the Earth system. Two geocenter time series, one based on LAGEOS-1/2 and one on T/P, are shown in Figure 7.1.1.1-1. The geocenter coordinates have been derived from the translational offsets of monthly solutions with respect to a multi-year mean solution. There is fairly good coherence between the two series for the X and Y components. For the Z component, agreement is less good, and the seasonal variation is not as clear.

GM and Terrestrial Reference Frame Scale

We continue to try to refine the estimation of the Earth's gravitational coefficient (GM), which is best determined by laser ranging data to geodetic satellites. The current determination was based primarily on SLR tracking to LAGEOS-1, and the principal contributions to the uncertainty of the solution (~2 ppb) was determined to be possible biases (both constant and frequency-dependent) in the ranging data as well as a possible bias in the standard Marini-Murray tropospheric refraction model (Ries et al., 1992). A truly complete solution for GM, with an uncertainty estimate that adequately reflects the various sources of systematic error, requires the simultaneous adjustment of the station coordinates, the range biases, and the satellite orbits, as well as the refraction model bias and possibly even satellite center-of-mass offset biases. Such a solution is singular unless satellites at significantly different heights are used. The current estimate for GM is based primarily on Lageos-1, so not all of these parameters could be adjusted. Consequently, it was necessary to consider their contribution as part of the error estimate of 2 ppb. Preliminary results using several satellites (LAGEOS-1/2, Ajisai, Stella, and T/P) do indicate the probability of a few mm bias in the refraction model. Efforts in this area are ongoing in an attempt to reduce the uncertainty in the estimate for GM, and consequently the uncertainty in the SLR determination of the scale of the terrestrial reference frame, to 1 ppb or better. A reduction in the scale uncertainty to less than 0.5 ppb would be particularly valuable, as there are questions at the 0.7 to 1.4 ppb level regarding the scale factor between VLBI, GPS and SLR determinations of the terrestrial reference frame.

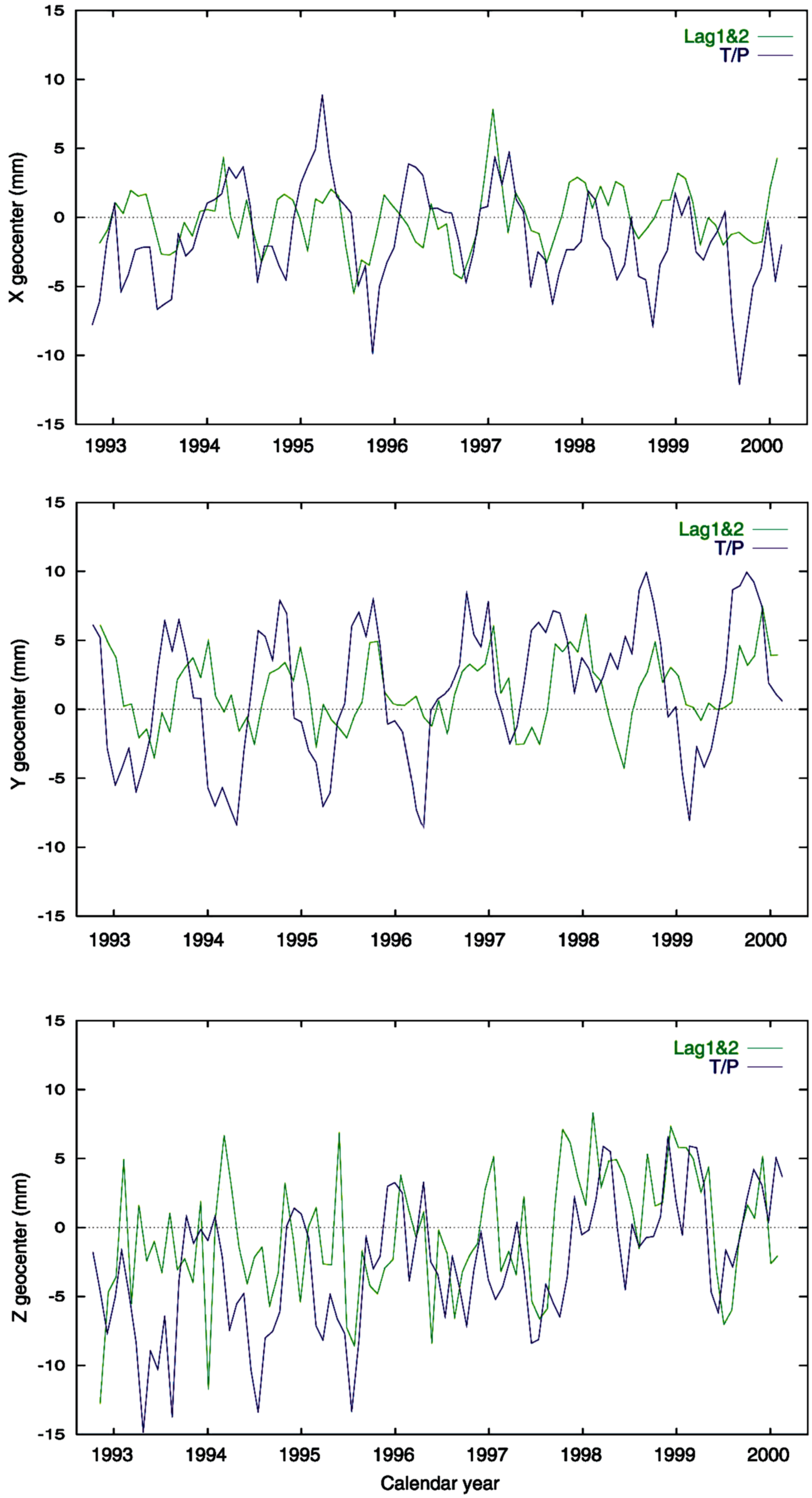

Figure 7.1.1.1-1 Geocenter motion determined by LAGEOS-1/2 and TOPEX/POSEIDON

Outlook for the Future

In order to improve the quality of the analysis, UT/CSR intends to introduce a new model for station coordinates based on a joint SLR and DORIS solution from LAGEOS1, LAGEOS2 and T/P. The model which is currently in use was computed in 1995. Models for ocean loading are already part of the analysis, but the effect of atmospheric pressure loading deformation is not yet included in the operational analysis. We will continue to explore the application of multi-satellite analysis to the question of quality control for the SLR network. The question of sub-cm systematic errors in the Marini-Murray refraction model is being investigated. In addition, the analysis system needs to be automated more than is the case in the current situation. UT/CSR will strive for a continuous improvement in order to serve the SLR community as well as possible.

Analysis Working Group Members

Richard Eanes, Minkang Cheng, Rick Pastor, John Ries, Bob Schutz

References

Chen, J. L, C. R. Wilson, B. D. Tapley and R. J. Eanes, Low-degree gravitational changes from Earth rotational variations, submitted to *J. Geophys. Res.*, 1999.

Cheng, M. K. and B. D. Tapley, Seasonal variations in low degree zonal harmonics of the Earth's gravity field from satellite laser ranging observations, *J. Geophys. Res.*, *104*(B2), 2667-2681, 1999.

Eanes, R. J., R. S. Nerem, P. A. M. Abusali, W. Bamford, K. Key, J. C. Ries, and B. E. Schutz, GLONASS orbit determination at the Center for Space Research, proc. International GLONASS Experiment (IGEX-98) Workshop, Nashville, Tennessee, September 13–14, 1999.

Nerem, R. S., R. J. Eanes, J. C. Ries, and G. T. Mitchum, The use of a precise reference frame in sea level change studies, proc. International Association of Geodesy Conference "Integrated Global Geodetic Observing System", Munich, October 5–9, 1998.

Nerem, R. S., R. J. Eanes, P. F. Thompson, and J. L. Chen, Observations of annual variations of the Earth's gravitational field using satellite laser ranging and geophysical models, *Geophys. Res. Lett.,* 27(12), 1783–1786, 2000.

Ries, J. C., R. J. Eanes, C. K. Shum, and M. M. Watkins, Progress in the determination of the gravitational coefficient of the Earth, *Geophys. Res. Lett.,* 19(6), 529–531, 1992.

Ries, J. C., and B. D. Tapley, Centimeter level orbit determination for the TOPEX/POSEIDON altimeter satellite, Paper AAS 99-142, proc. AAS/AIAA Spaceflight Mechanics Meeting, Breckenridge, CO, February 7–10, 1999.

Schutz, B. E., B. D. Tapley, J. C. Ries, and R. J. Eanes, Polar motion results from GEOS-3 laser ranging, *J. Geophys. Res.*, 84(B8), 1979..

7.1.1.2 Delft Analysis Center

Ron Noomen, *Analysis WG Coordinator, the Netherlands*

BACKGROUND

The Quick-Look Data Analysis Center (QLDAC) has been operational at Delft University of Technology since the beginning of 1986. Originally organized to support the observational campaigns of the WEGENER-MEDLAS Project (with short occupations of sites in the Mediterranean area by mobile Satellite Laser Ranging (SLR) equipment and a clear necessity for rapid performance feedback) QLDAC has evolved into a service for the entire network of SLR stations. Over time, operations by mobile laser systems have become rare, but the need for rapid-turnaround quality control (QC) results and productivity parameters continues at a slightly more relaxed rate.

Today QLDAC provides the following services:

(i) near real-time quality control of observations on LAGEOS-1 and LAGEOS-2, taken by the global network of SLR stations. The results are reported to the stations on a regular basis, and are used for monitoring the performance of the systems.

(ii) production of highly accurate Earth Orientation Parameters (EOPs), for inclusion in the USNO/IERS bulletins.

(iii) evaluation and technical support of (new) systems in engineering status.

(iv) provision of preliminary information for scientific data analyses (e.g. satellite orbits, station coordinates, etc.).

(v) motivation of the data analysts.

Many of the goals mentioned here are or will be worked on in coordination with the International Laser Ranging Service (ILRS).

STATUS

Currently, the computations are performed on a weekly basis. Every Tuesday, the analysis is performed and the results are disseminated to the SLR stations and other interested people. Each analysis basically covers the observations taken during the week prior to the date of the computations, as the QC lags the actual data taking by somewhere between 3 and 10 days.

DEVELOPMENTS IN 1999

To best serve the needs of quality control, QLDAC continuously strives for improvements in the procedures, strategies and models to better simulate the physical truth (i.e. model the satellite orbit and the dynamics of the Earth). However, practical and operational issues limit the amount of effort that can be spent here. Manpower is a very practical limit for such developments: typically, QLDAC can spend about 2 man-days on operational analysis and development work per week. As for operational constraints: changes in the analysis procedure or models can be expected to introduce sudden shifts in the analysis results, albeit in post-fit residuals (measurement systematics), in EOP solutions, or in other elements. Stability of the system will serve the customers better than continuous modifications.

Therefore, significant changes are typically planned ahead and are introduced at one single epoch. In 1999, developments were mainly in the representation of the analysis results. In particular, the weekly report was fine-tuned for customer purposes several times (a completely new layout was introduced at the end of 1998), and preparatory work was performed to make the results available on the Internet. The latter activity is not finalized yet, but is expected to come on line in early 2000. Also, the system was checked for potential Y2K problems and adjusted where necessary.

OPERATIONS IN 1999

As can be expected from a service, QLDAC operated routinely in 1999. An overview of the LAGEOS-1 and -2 passes that were processed is given in Figure 7.1.1.2-1. Typically, the observations are taken from the data centers at NASA's Crustal Dynamics Data Information System (CDDIS) and the EUROLAS Data Center (EDC), merged, time-sorted and edited for double entries. On average, the global network produced about 120 and 100 passes for LAGEOS-1 and -2 per week, respectively.

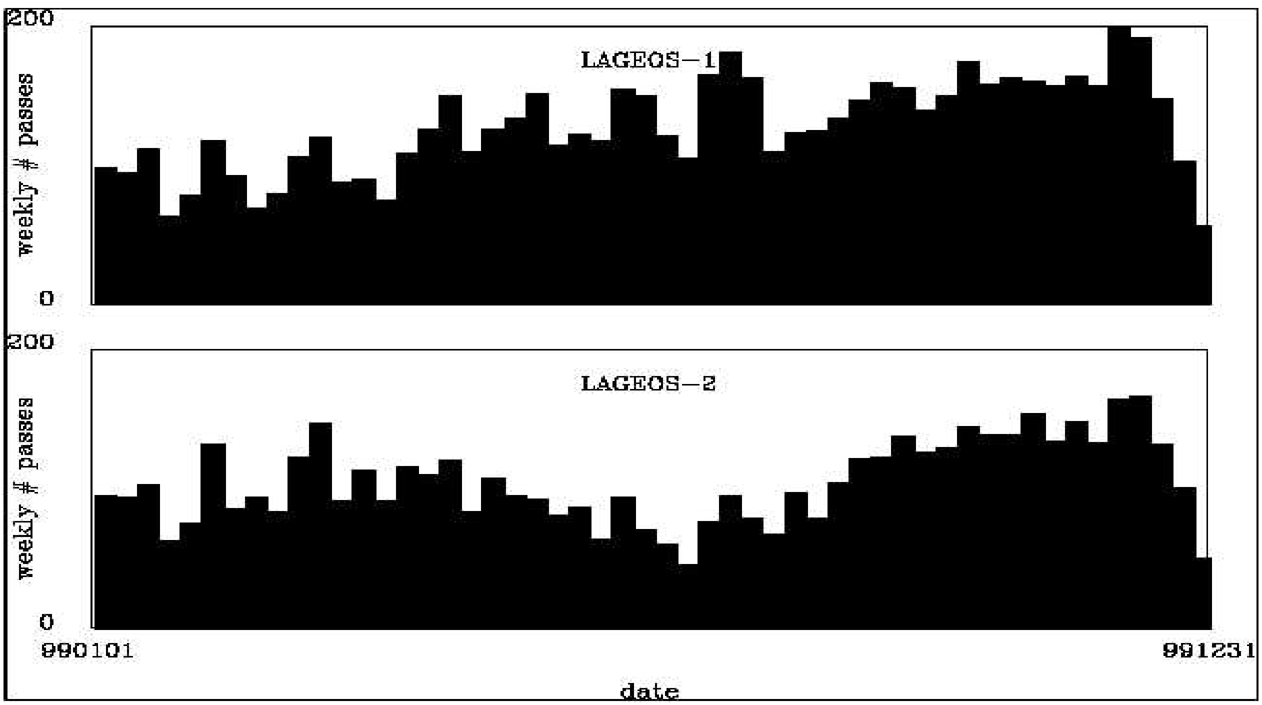

Figure 7.1.1.2-1. Overview of the weekly number of passes per week of LAGEOS-1 and LAGEOS-that were acquired by the global network of SLR stations.

The main element of the weekly analysis is the fitting of a 10-day continuous orbit through 10 days of global observations. Typically, such a data arc starts on Thursday, 00:00 hours, and ends on Saturday evening 24:00 hours. A summary of the computation model currently in use is given in Table 7.1.1.2-1.

The fitting processing results in a value for the weighted rms-of-fit of about 0.9 on average. An overview of the corresponding rms-of-fit is given in Figure 7.1.1.2-2, which shows that QLDAC achieves a value of about 40 mm on average. It must be stressed here that this rms-of-fit is not the parameter which is minimized in the estimation process: differences in quality of observations will be compensated for by assigning different values for the weights of the observations in the analysis. Table 7.1.1.2-2 gives a good impression of this: it shows the results obtained for a 10-day data arc at the end of October 1999. Clearly visible is the variety in post-fit residuals (realistic rms values range between 16 and 97 mm), but generally these individual numbers follow the corresponding weights which are given in the final column). The overall rms-of-fit (again, not the parameter which is minimized) amounts to 36 mm for this arc.

Observations

- collected from CDDIS and EDC;
- center-of-mass 251 mm;
- Marini-Murray model for troposphere;
- elevation cutoff 20 degrees;
- data weighting root-summed-square of single-shot precision and overall model uncertainty;
- relativistic effects not modeled;
- 3.5-sigma data editing.

Dynamics

- NASA/CSR JGM-2 gravity field and tides model;
- 3rd body attraction of Sun, Venus, Moon, Mars, Jupiter, Saturn;
- dynamic polar motion;
- direct solar radiation pressure (scaling coefficient kept fixed at 1.13);
- albedo and thermal radiation of earth not modeled;
- 1 constant and 2 1-cpr along-track acceleration parameters solved for per satellite and per arc;
- relativistic effects not modeled.

Geometric model

- SSC(DUT) 93L05 model for station coordinates (stations of choice solved for);
- IERS Bulletin A a priori EOPs (EOPs solved for at 3-day intervals);
- JPL DE200/LE200 ephemerides;
- Love model for solid earth deformation;
- dynamic polar motion;
- ocean loading and atmospheric pressure loading deformation not modeled.

Integration

- Cowell 11th order; step-size 100 sec.

Table 7.1.1.2-1. QLDAC computation model summary.

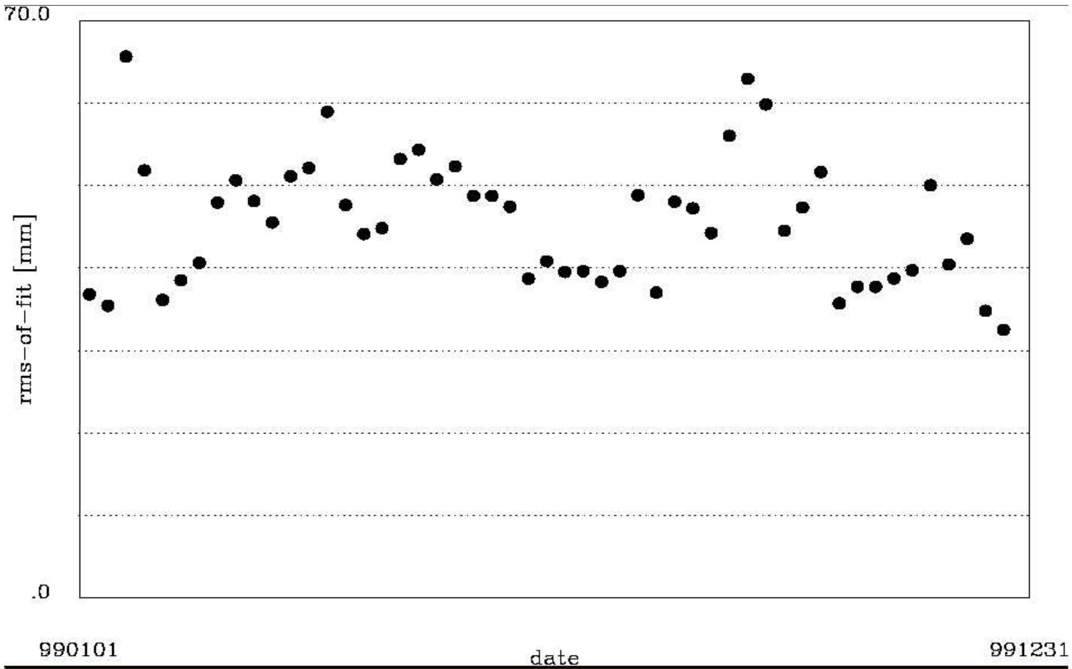

Figure 7.1.1.2-2. The weekly rms-of-fit obtained in the weekly quick-look analysis; note that this value is not minimized.

Station	#Obs	Mean	Rms	Weight
Riga, Latvia	132	45	53	104
Kazivili, Ukraine	21	-3	21	104
McDonald Observatory, Texas	33	2	19	36
Yarragadee, Australia	125	-17	37	31
Greenbelt, Maryland	343	-12	28	31
Monument Peak, California	317	-17	30	31
Changchun, China	265	-6	29	58
Beijing, China	79	-8	41	58
Koganei, Japan	122	1	26	36
Kashima, Japan	48	13	29	36
Miura, Japan	50	13	20	36
Tateyama, Japan	45	7	20	36
Arequipa, Peru	23	18	24	31
Cagliari, Italy	7	-1	92	76
Metsahovi, Finland	22	5	25	42
Zimmerwald, Switzerland	130	-10	34	67
Borowiec, Poland	23	-5	19	67
San Fernando, Spain	28	-0	27	50
Helwan, Egypt	1	4	4	31
Grasse, France	31	9	16	42
Potsdam, Germany	59	-11	21	42
Graz, Austria	84	19	29	31
Herstmonceux, United Kingdom	173	9	23	36
Grasse, France	18	-27	28	36
Mount Stromlo, Australia	207	-11	24	31
Matera, Italy	113	-6	97	123
Wettzell, Germany	67	-32	42	31

Table 7.1.1.2-2. Example of analysis results: the number of observations, mean and rms of the post-fit residuals and the individual data weights [mm], for the period October 21-30, 1999.

Another example, Figure 7.1.1.2-3 shows the time-history of the range bias for the Graz (station 7839), based on LAGEOS-1 measurements only (similar results, both in quantity and in numerical values, are available for LAGEOS-2, but inclusion of these results would lead to confusion in a plot like this). The consistency is, again, a good indicator of the quality of the analysis.

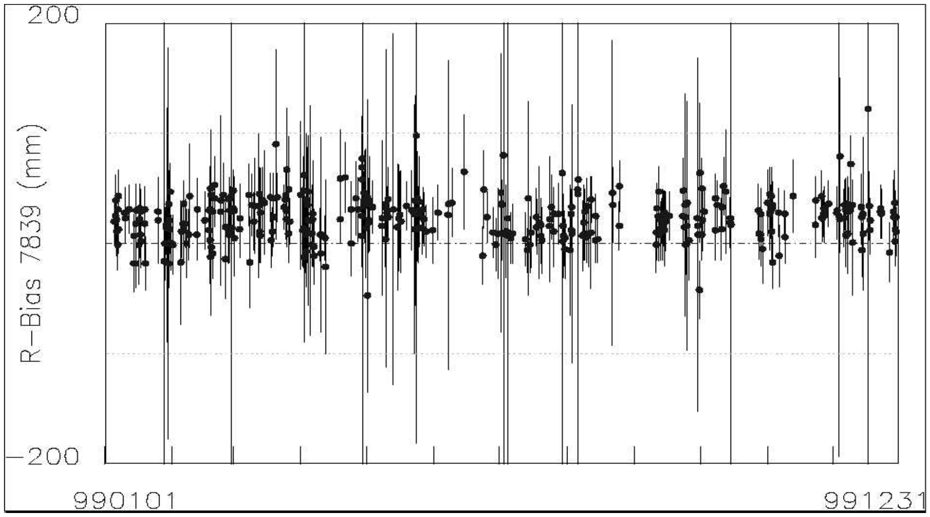

Figure 7.1.1.2-3. Time-history of the apparent range bias in the LAGEOS-1 passes as observed by the SLR station in Graz (Austria) for the year 1999, as determined by QLDAC.

OUTLOOK FOR 2000 AND BEYOND

In order to improve the quality of the QC analysis and the results, QLDAC intends to introduce several new elements in the operational analysis. First of all, the results will also be made available on the Internet. Users will have the opportunity not only to look at the latest analysis results, but also to look for time-series of certain performance parameters, both general and station-specific. Second, QLDAC intends to introduce a new model for station coordinates. The model which is currently in use was computed in 1993, and represents in fact an extrapolation of about 8 years by now. In order to achieve mm-level quality assessments, uncertainties in station coordinates of 1 cm or more are of course unacceptable. Directly related to this is the inclusion of models for ocean loading and atmospheric pressure loading deformation, and the modeling of station biases where necessary. Recently QLDAC has gained some experience with these issues. A long-standing wish is the inclusion of GPS satellites in the operational analysis. And, finally, QLDAC intends to increase the frequency of the analysis to 2 or 3 times per week, so that stations will receive more up to date reports on their performance. To accomplish this the analysis system needs to be automated.

The implementation of these improvements depends on the capabilities at QLDAC, in particular the manpower. Under any circumstances, QLDAC will strive for a continuous improvement to serve the SLR community as much as possible.

7.1.1.3 MCC Analysis Center

Vladimir Glotov, *Russian Mission Control Center*

INTRODUCTION/DATA PRODUCTS PROVIDED

Processing of the precise SLR and radio data started at the MCC in 1991. Previously most of the people were involved in the ballistic service supported by MCC. They supported the Mir orbital station and all related Russian manflight program missions. The MCC had many tasks, and up to 10 mission were served simultaneously in 1970's and 1980's. By the beginning of the 1990's there was considerable experience in data processing over a period of more than 20 years. Although the accuracy of the tracking radio data was much worse than that of SLR, it was extremely useful for new tracking systems calibration and verification, data analysis, data filtering, etc.

In 1993 the first version of the precise software (SW) was prepared at MCC for the processing of high-accuracy data, especially SLR. That SW was not of course absolutely perfect but the general idea was to provide simultaneous processing of an arbitrary number of satellites covering long time spans.

In 1993 the MCC started routine determination of Earth Orientation Parameters (EOP) first in the frame of the Russian National Program and then in cooperation with the IERS. Based on the LAGEOS satellites SLR data, EOP are sent weekly to the Central (Paris) and Rapid (Washington) IERS Bureaus. As reported in IERS Bulletins A and B, MCC EOP series are very comparable to those determined by other Centers using the satellite data. EOP accuracy has been improved to the level of a few millimeters. Plots are available at

http://maia.usno.navy.mil/plots.html

In 1996 the MCC and its subsidiary company GEOZUP (ZUP is the Russian abbreviation for MCC) performed the first annual solution based on LAGEOS SLR data since the end of 1992 in the framework of cooperation with the IERS. The adjusted set of the SLR station network coordinates from these analyses have allowed us to improve the accuracy of EOP by nearly a factor of 3. Obviously this improvement is related to the quality of orbits and SLR data analysis.

In 1996 MCC started a regular service of assessing SLR station performance. All the data of LAGEOS-1 and -2 have been analyzed to get values of time and range bias and the range RMS. In that analysis the mentioned values are determined with and without orbit height error. Comparison of the results allows us to get a more realistic evaluation of the SLR data. The routine service requires two levels of data filtering:

- automatically exclude outliers and wrong sessions
- manually check and correct results.

Special graphics SW was used to detect quality of observations in the manual mode. At the moment our official bulletin on station performance is issued once per week and sent to the CDDIS and EDC as well as directly to several SLR stations within WPLTN. Normally it includes estimations of almost all LAGEOS passes.

The routine orbits for the LAGEOS satellites are used for the estimation of data quality. The complete procedure was reported at the Deggendorf Workshop in 1998. In most cases the estimations are very close to those obtained by CSR. The major difference is seen for the new Keystone stations, probably due to the short time span of data available so far for position determination.

Since 1995, the MCC has permanently supported orbit determination of GLONASS satellites using SLR data. For this work a GLONASS solar pressure model was developed in 1996. All the data from GLONASS-63, 67 and 71 from 1995 through June 1997 have been processed to get high accuracy orbits. These orbits have been compared with the ephemerides obtained by the GLONASS System Control Center to get the transformation from the PZ90 reference frame to the ephemeris frame. Those results were obtained in 1997, long before IGEX and reported at ION98. In 1998-1999 MCC took an active part in IGEX98 (International GLONASS Experiment) as an Analysis Center for SLR data. Since October 1998 the MCC has provided routine precise orbit determination of all GLONASS satellites.

Orbits for the GLONASS satellites (in SP3 format) are regularly sent to the processing center for the determination of the final orbit using the phase data. As reported at the IGEX99 meeting, the MCC orbits are very compatible with those determined by BKG, CODE, JPL, and GFZ despite the differences in the amounts of laser and radio data. Accuracy has proved to be few decimeters. Due to the limited number of SLR measurements, MCC currently determines 8 days SLR GLONASS orbits with 4-days time shifts between solutions. The middle four days from each arc are then used for the generation of SP3 format.

The activity of the MCC is not limited to LAGEOS and GLONASS. MCC continually tries to improve the models and techniques of SLR data processing. In particular MCC has developed strong experience in the processing of relatively low orbits such as Meteor-3, ERS-1 and 2, Zeya, and Westpac. Despite the fact that these missions have not been sufficiently supported to provide a posteriori accurate orbits for several years, we have continued an activity in the improvements of the models. In particular several times it was our intention to start routine accurate orbit determination on WESTPAC for the preparation of bulletins like those issued for LAGEOS. However, corresponding orbits have been calculated but the amount of data were insufficient to allow us to determine accurate orbits. Due to the very short duration of the sessions, estimations of time and range biases varied much more than those on LAGEOS. So it was decided not to include WESTPAC data for PM and LOD nor for SLR data bulletins.

The data products available from MCC are:

- annual solutions
- regular daily values of PM and LOD
- bulletins of LAGEOS (GLONASS) SLR data performance
- GLONASS orbits in SP3 format
- transformation from PZ90 reference frame to WGS-84
- Westpac IRVS
- low satellites precise orbits
- etc.

BACKGROUND

In order to improve the quality of the generated products MCC performs two annual solutions each year. Both solutions are based on LAGEOS QL-NP data from the end of 1992 until the beginning of 2000. The first solution labeled as MCC(yy)L01 is performed by MCC specifically to adjust laser network and the EOP series from Bulletin B. The main idea is to improve the quality of PM and LOD reported to IERS. In 1999, positions of 58 stations and 40 stations velocities were adjusted simultaneously with satellite state vectors and some station biases in MCC99L01. These determined biases have been fixed in the MCC99L02 solution where PM values have also been adjusted. Both solutions have the same following constraints to ITRF96 solution.

- Horizontal velocities for stations 1864, 1868, 1873, 1893, 7236, 7249, 7548, 7824 have been fixed to zero relative to the NUVEL-1A NNR model because either their biases change with time or data quality is insufficient.
- The velocities of 7105 and 7918, 1873 and 1893, 8834, 7597 and 7594, 7080 and 7850, 1884 and 1885, 7090 and 7847, 7835 and 7845, 7843 and 7849 were considered as equivalent. That does not mean that the velocities are identical but that the corrections made during the solution to the initial values from NUVEL1A-NNR model are identical. As a result the velocities of station 7843 differ slightly from the station 7849 due to several kilometers deference in their positions. A similar but smaller effect is visible for 1873 and 1893 pair.
- The motion of stations whose velocities were not estimated, due to the short time span covered, was constrained to the NUVEL1A-NNR model.

For the definition of orientation and time evolution in the MCC99L01 solution, EOP has been fixed to the EOP (IERS) C04 values. Additionally the longitude and its rate of station 7105 have been fixed to ITRF96 values. State vectors consisting of positions and velocities in J2000 and along track empirical acceleration for both LAGEOS satellites were adjusted on 6-days time intervals. In addition reflectivity coefficients were solved for on 24-day intervals, each covering 4 SV intervals. Time dependant biases for some stations were also included in the solution MCC99L01 where necessary.

Because of frequently changed biases, the data from 7847 and 1884 has been processed without applying Mathematical Expectation (ME). Such methods have been applied for stations: 1864 until 01/11/97, 1868 until 27/02/96, 1873 until 01/01/96, 8834 until 01/06/96 and 7249 for the summer of 1996. Those measurements have been considered as good but affected by unknown biases that change from pass to pass. This approach is extremely effective when there is a strong suspicion of changing bias (one of the reasons may be poor calibration).

Weighted RMS of residuals for the 1999-year solutions is about 2.5 cm. Unlike previous annual solutions (1996-1997 years) the number of raw measurements in each NP was not used in calculations. This method was used previously in 1998 and it has been proven by the MCC experience in polar motion determination since May 1998. The use of the number of raw measurements in the processing significantly improves the weighted RMS of the solution because the most stable and precise stations produce most of the measurements. However this approach actually excludes the influence of other stations in the orbit and EOP. In practice the models are not completely perfect and also relatively small and infrequent biases and drifts occur even in data from the best stations. So the use of extremely heavy weights for some non-optimally located stations can lead to the wrong results. To reduce this effect all NP were treated as single measurements with an RMS depending upon station and time. The adopted pass RMS values are in the range of 5 cm for the best US and European stations to 40-50 cm for some other stations.

It must be mentioned that every annual MCC solution is completely independent of previous results. This requires the estimation of a large number of parameters simultaneously, including: station coordinates, site velocities, time depending biases of some stations, satellite orbits and polar motion. In particular the MCC99L02 solution has 7221 adjusted parameters. One of the advantages of such an approach is the possibility to use state-of-the-art models for the processing of the whole data set. The quality of the solution is monitored by the comparison of independent 6-day arcs, which is very useful for the determination of the problematic periods.

Unlike the SSC determination, the routine MCC EOP determination is based on 3-days arcs. Data from both LAGEOS are processed simultaneously with PM and LOD values. Thus single determination solves for the following parameters:

- state vectors of both satellites in J2000
- empirical along track accelerations- solar pressure coefficients
- PM and LOD. Clearly the quality of 3-day orbits in most cases is better than of 6-day orbits.

That is why the EOP determined on 3-days arcs in the operational mode is even better than that obtained in the MCC(yy)l02 solutions. In the routine service, initial values of PM and UT1-UTC corrections are either extracted from Bulletin A predictions or predicted by MCC SW. Celestial pole offset prediction is normally set to Bulletin A prediction. MCC does not produce UT1-UTC correction because it is not visible with SLR data. Any SLR based UT1 corrections are based on fixing the orbit node which must be updated over time.

In the regular EOP determination for IERS, special post-processing procedures are used for the improvement of accuracy. The procedure is repeated in the routine daily service. For any point there is 3 different solutions of EOP, which are averaged in the post-processing procedure. Usually that special averaging improves the accuracy by about 10-15%.

FACILITIES/SYSTEMS

Generally the facilities and systems of MCC Analysis and the Operation Centers are same (see section 5.2 of the Annual Report), but there are some additional details. The POLAR SW is used for the generation of all MCC products except IRVS. The POLAR SW has no database or graphics, but the number of parameters that can be determined is unlimited. It is completely flexible and different programs within POLAR can be used for different spacecraft. All of the coordinate solutions have been obtained using it.

The force and measurement models used in the solutions conform generally to the IERS Standards 1996 (TN21), with the following exceptions:

- the gravity field used is JGM3 with C20, C21 and S21 rates applied (the information was obtained directly from CSR),
- nutation corrections dPsi and dEps are applied,
- Earth infrared emission (with seasonal effects) and reflected light (with latitude dependent albedo) is taken into account,
- indirect C20 acceleration from the Moon is modeled.

The degree and order of the gravity field and tides clearly depends on the mission. Special methods of interpolation are used in the calculation of:

- nutation,
- sidereal time,
- solid and ocean tides,
- solid tides in station coordinates,
- UT1R,
- Daily and sub-daily variations of EOP,

These methods allow us to reduce computation time without loosing accuracy. So, even though the SW is suited for the PC, it imposes no limitations on data processing.

CURRENT ACTIVITIES

At the moment, five products described above are available from MCC:

- annual solutions
- regular daily values of PM and LOD
- bulletins of LAGEOS SLR data performance
- Westpac IRVS
- GLONASS orbits in SP3 format

KEY POINTS OF CONTACT

Coordinator of the work	Vladimir Glotov	cnss@mcc.rsa.ru; vd.g@g23.relcom.ru
Main expert and person responsible	Vladimir Mitrikas	cnss@mcc.rsa.ru
Administration support	Sergey Revnivych	cnss@mcc.rsa.ru

FUTURE PLANS

In 1998 the development of new SW combining the features of STARK and POLAR has been started. So perhaps this year the operational MCC team will change to the new SW under Windows. The new SW is written combining DEC FORTRAN and C++ Builder. Most of the new features are directed toward automation of the operations. In the framework of the MCC SLR data analysis, there are traditional plans to improve the accuracy and quality of the products.

7.1.2 ASSOCIATE ANALYSIS CENTERS

Associate Analysis Centers are organizations that produce special products, such as satellite predictions, time bias information, precise orbits for special-purpose satellite, station coordinates and velocities within a certain geographic region, or scientific data products of a mission-specific nature. Associate Analysis Centers are encouraged to perform additional quality control functions through the direct comparison of individual Analysis Center products and/or the creation of "combined" solutions, perhaps in combination with data from other space geodetic techniques (e.g. VLBI, GPS, GLONASS, DORIS, PRARE, etc.), in support of the IERS International Terrestrial Reference Frame (ITRF) or precise orbit determination. Organizations with the desire of eventually becoming Analysis Centers may also be designated as Associate Analysis Centers by the Governing Board until they are ready for full scale operation.

7.1.2.1 FFI Associate Analysis Center

Per Helge Andersen, *Forsvarets Forskningsinstitutt*

INTRODUCTION

Forsvarets forskningsinstitutt (FFI, Norwegian Defense Research Establishment) is centrally located in the Kjeller area, 30 minutes east of Oslo (near Lillestrøm). Here approximately 2400 people are engaged in several research establishments, technical institutions, university branches and Air Force Material Command. FFI is a state operated, civilian research establishment reporting directly to the Ministry of Defense. The number of employees is approximately 550.

For many years FFI has performed research in space science and remote sensing using satellites. As a part of this research FFI has developed a highly sophisticated software called GEOSAT [*Andersen,* 1995] for satellite orbit determination and space geodesy. With this software all types of high precision space geodetic observations (VLBI, GPS, SLR, DORIS, PRARE, crossover radar altimetry, and externally generated satellite ephemerides) can be combined and analyzed at the observation level with one consistent observation model and common between-technique parameterization. Presently, scripts exist for an automatic processing of any combination of the VLBI, GPS, and SLR observation types.

FFI is presently an IVS Analysis Center, an IVS Technology Development Center, and an ILRS Associate Analysis Center.

COMBINATION OF VLBI, GPS, AND SLR DATA AT THE OBSERVATION LEVEL

There are several advantages with the combination of VLBI and different types of satellite tracking data at the observation level:

- One consistent model is used to construct the observation equations and observation partial derivatives for all the different types of data. The GEOSAT software will for the first time make it possible to perform analyses of VLBI and satellite tracking data with one consistent model and strategy.
- The combination of independent and complementary information from different types of observations will reduce the parameter correlations and lead to more accurate results.
- The estimated satellite orbital elements, radio source coordinates, and nutation parameters will be realized in a long-term stable celestial reference frame realized primarily by the radio sources. GPS and SLR will contribute directly in the determination of UT1 and not only be used to estimate the length of day (LOD).
- All estimates of geodetic and geodynamic parameters are given in the same realization of the terrestrial reference frame.
- The combined analysis of VLBI, GPS, and SLR can be used to estimate (and control) the eccentricity vectors between the different antenna phase centers within each collocated station.

The main problems with the combination of different types of data at the observation level compared to an individual analysis of each data type are that the analysis software becomes extremely more complicated and the computation time increases with one to two orders of magnitude.

All planned components of GEOSAT have been successfully validated with a combination of data from VLBI, GPS, and SLR. Consistent models for all techniques have been verified at the sub-ppb level. The processing at the arc level (24 hours arc length) is completely automated.

PRESENT AND FUTURE PRODUCTS

FFI is currently producing a 10-year solution for the Celestial reference frame, the Terrestrial reference frame (including geocentric motion) and Earth orientation parameters based on a combination of VLBI and SLR data. A corresponding VLBI-only solution will also be generated. In addition, a SLR-only solution for LAGEOS I and II with data from January 1993 to the end of 1999 will be computed. The 10-years combined VLBI and SLR solution will be extended with arcs including also GPS data for selected periods. In the future it is planned to investigate the estimation of other types of parameters for example loading parameters (atmospheric/ocean), GM and possibly relativity parameters (β and γ).

TECHNICAL STAFF AND FACILITIES

The author runs a one-man internal FFI project that is approved until August 2002. The project covers all space geodesy activities within FFI and one of the main goals is to generate products for IERS, IVS, and ILRS.

A new HP J7000 workstation with 4 CPU's and 4 Gb RAM and presently 165 Gb disk space is dedicated to the IERS, IVS and ILRS activities at FFI. Within year 2000 we expect to extend the disk space to 365 Gb. Last year a HP C 180 workstation with 1 CPU and 256 Mb RAM and 65 Gb disk space was used in the analyses. The new workstation is expected to improve the computation power with one order of magnitude.

REFERENCES

Andersen, P. H. (1995) High-precision station positioning and satellite orbit determination. Ph.D. Thesis, NDRE/Publication 95/01094.

7.1.2.2 DGFI Associate Analysis Center

Detlef Angermann, *Deutches Geodatisches Forschungs Institut*

INTRODUCTION

For almost twenty years, the German Geodetic Research Institute (DGFI) has been strongly involved in the high precision processing of SLR data for many geodetic and geophysical investigations. These include the determination of the Earth's surface geometry and its variation with time, as well as the determination of the Earth's orientation in space and the determination of the Earth's gravity field and its variations with time [*Reigber, et al,* 1993].

DGFI is acting as an Associate Analysis Center within the ILRS and participated in the ILRS99 pilot project on the determination of station positions and Earth orientation parameters based on LAGEOS-1 data. The focus of the present activities is on the automation of the SLR data analysis in order to establish an operational analysis center for the determination of ILRS products and on the computation of a global SLR solution for the ITRF2000.

SOFTWARE AND PROCESSING TECHNIQUE

DGFI developed the software package DOGS (DGFI Orbit and Geodetic Parameter Estimation System), which has been used for the computation of SLR data since 1980. The DOGS software system comprises the following main modules:

DOGS-IN: Input Generation for the computation of global SLR solutions, including program regulation, composition of station data, observations, and geometrical and physical models.

DOGS-OC: Satellite orbit and parameter adjustment module for orbit improvement, satellite specific and geodetic parameter estimation or normal equations generation for these parameters.

DOGS-CS: Parameter estimation module to combine normal equation systems for different satellite arcs, different data types, to eliminate nuisance parameters, to generate normal equation systems with and without constraints and to perform the inversion of the combined normal equation systems.

DOGS-OV: A set of programs incorporated for quality control, calibration and graphical representation of the solutions.

The DOGS parameter solutions are based on efficient techniques for the orbital integrator, the integration of the variation equations and the weighted least squares adjustment procedures. The reference frame, conservative and non-conservative force field parameters and measurement model parameters are defined close to the IERS Conventions 1996 [*McCarthy,* 1996].

According to the processing strategy used, DOGS allows the adjustment of the following parameters: 6 orbital elements, solar radiation scaling factors, along track acceleration values, Earth orientation parameters, gravity field parameters, geocenter variations, station coordinates and velocities, range and time bias values. For the definition of the geodetic datum, minimum constraints are used. Since the origin of the reference system is the geocenter, by setting the first degree and order terms of the gravity model to zero and the scale being defined by the velocity of light, the orientation remains to be defined because of the insensitivity of the range observations to rotation. In general we define the geodetic datum with respect to the latest ITRF realization by minimizing the common rotation with respect to the initial coordinates of a well-defined set of globally distributed stations [*Gerstl,* 1999].

ILRS PILOT PROJECT 1999: DGFI RESULTS FOR POSITIONS AND EOP

Within the ILRS pilot projects "positioning" and "Earth orientations" the DGFI computed a coordinates solution for the global network of SLR stations and a time-series of Earth orientation parameters at 3-day intervals in one simultaneous solution with the DGFI software DOGS. We computed the 28 days of LAGEOS-1 data (5.9.-2.10.1999) on the basis of 7-day arc solutions and combined these weekly solutions into one unique solution [*Angermann et al.,* 2000]. The solved-for parameters are: 6 orbital elements, solar radiation scaling factors and acceleration along track values every 5 days, Earth orientation parameters at a 3-day interval and station coordinates. We used minimal constraints for the definition of the geodetic datum. We introduced *a priori* constraints of 0.0001 m for the y- and z-coordinate of station 7840 and the z-coordinate of station 7105, as well as an *a priori* constraint of 0.1 ms for the UT1-correction at one epoch. These constraints can easily be removed from the variance-covariance matrix for comparisons and combinations. The solution products were distributed in SINEX format. The quality of the adjusted station coordinates was assessed by a comparison with those of the ITRF97. The mean differences between both sets of station coordinates are in the order of 2 cm for 19 globally distributed SLR stations. The estimated pole coordinates and UT1 corrections agree with the corresponding IERS (EOP97C04) values at the 0.5 mas, 0.2 ms level, respectively.

FUTURE ACTIVITIES:

The DGFI will continue with its participation in future ILRS pilot projects and will establish an operational analysis center for the computation of SLR solutions based on LAGEOS-1 and -2 data and the estimation of geodetic and geophysical parameters, such as station coordinates and velocities, Earth orientation parameters, geocenter variations. The DGFI will produce a global SLR solution, which will be submitted to the IERS as a contribution to the ITRF2000.

REFERENCES:

Angermann, D., M. Gerstl, R. Kelm, H. Müller, W. Seemüller: ILRS 99 Pilot Project: DGFI Solution for Station Coordinates and EOP's, ILRS Analysis Working Group workshop, 17.-19.01.2000, Frankfurt a.M., 2000.

Gerstl, M.: Bezugssysteme der Satellitengeodäsie, Mitteilungen des Bundesamtes für Geodäsie und Kartographie, Band 5, Frankfurt a.M., 1999.

McCarthy, D.D. (ed.): IERS Conventions (1996), IERS Technical Note 21, Central Bureau of IERS, Paris, 1996.

Reigber, C., P. Schwintzer, F.-H. Massmann, C. Förste, H. Drewes: Ten Years of SLR Data Analysis at DGFI/I, Contributions of Space Geodesy to Geodynamics: Crustal Dynamics, D. E. Smith, D. Turcotte (eds.), Geodynamics Series, Vol. 23, American Geophysical Union, Washington, D.C., 1993.

7.1.2.3 NERC Associate Analysis Center

Graham Appleby, *NERC Space Geodesy Facility*

INTRODUCTION

In this report we outline some of the analysis and operational activities of the NERC SLR Facility at Herstmonceux and Monks Wood, UK, in the Facility's capacity as an ILRS Associate Analysis Center. Much of the prediction preparation and quality control work that is described here has been developed in order better to equip the Herstmonceux SLR system to maximize its productivity during periods of clear weather. For single-photon detector systems in particular, prediction accuracy is important as it allows the use of narrow range gates (<200 ns) to minimize background noise. That these products are used by many colleagues within the ILRS network is a valuable spin-off from the work.

SATELLITE PREDICTIONS

We compute two main prediction products, medium-term and daily, and are actively experimenting to improve their quality. The predictions are presented in the standard Inter-range Vector (IRV) format.

Access information and the full list of satellites for which we produce predictions is given on the official ILRS website. We compute predictions on a daily basis for most of the laser-tracked satellites and for the GLONASS satellites, we support the IGEX-98 tracking campaign by computing daily IRVS in collaboration with the CODE, Berne, group. We are currently generating predictions on an experimental basis for some LEO satellites twice per day using the most recent observations to check whether significant improvements to predictive quality can result. This latter work is being carried out as part of our involvement with the ILRS Data Formats and Procedures Working Group.

TIME BIAS FUNCTIONS

The computation of along-track corrections can significantly improve the quality of medium and long-term predictions. We routinely compute time bias functions applicable to most of the available prediction sets, and update the coefficients hourly using the latest observations from the network. Access to these functions is hourly via local ftp or by daily e-mail via EDC. We plan in the near future to present the same information in graphical form on the NERC SLR website.

DAILY QUALITY MONITOR

As an initiative within the EUROLAS network some years ago we began regularly to monitor the quality of LAGEOS and LAGEOS-II range data from the network, using ITRF97 station coordinates. In particular we exploited the strength of the EUROLAS cluster of stations to form short-arc orbital improvements and thus potentially detect system bias at the 10mm level. This procedure was automated and implemented on a daily basis in a valuable collaboration with the Department of Satellite Geodesy, Austrian Academy of Sciences, Graz, [*Hausleitner, et al,* 1999]. Each day we present on the NERC SLR website plots of normal-point range residuals from six-day orbital solutions for the two satellites for each station in the global network. Following some modelling improvements during this year, the post-solution residual RMS for these orbital solutions has improved to about 20mm, and the plots serve to provide a rapid check on the presence of outliers in the tracking data, as well as a quick daily check on network productivity. An example of the results from four stations is shown in Figure 7.1.2.3-1, where on the Website the LAGEOS-1 residuals are colored red and the LAGEOS-2 residuals are colored blue.

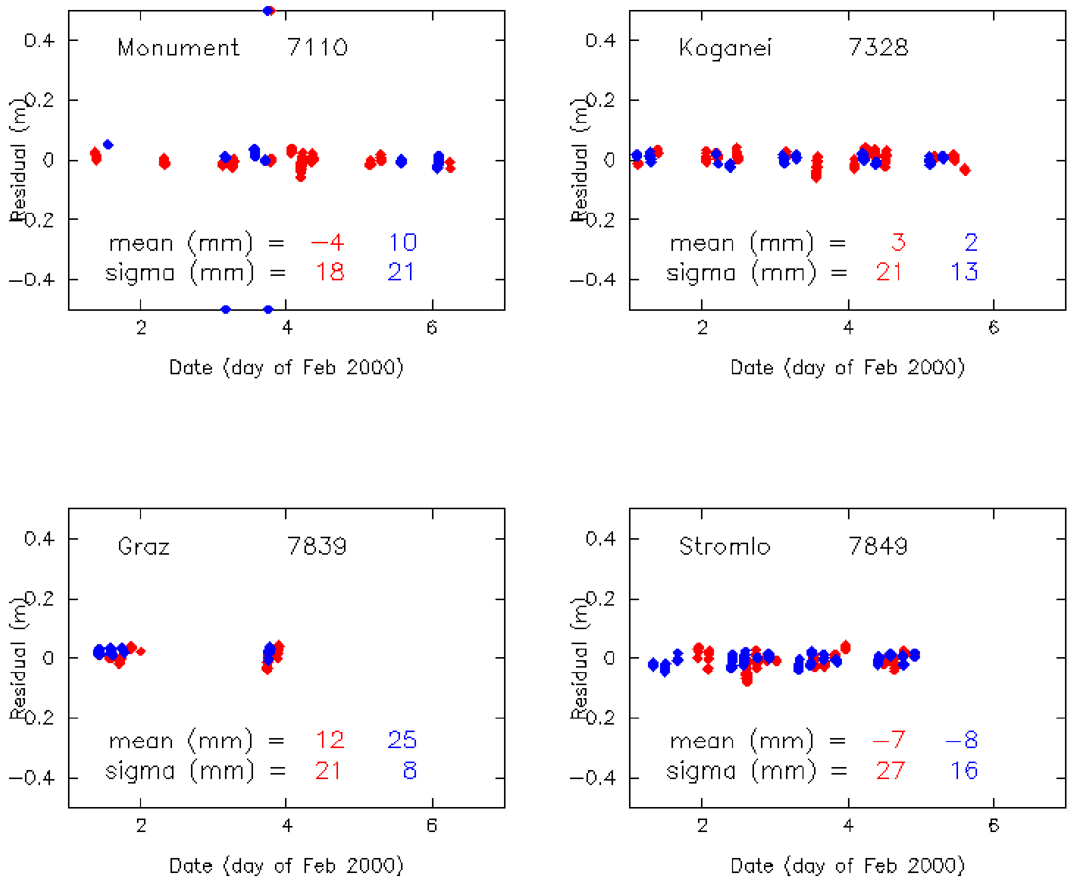

Figure 7.1.2.3-1. Plots of range residuals from fitted 6-day orbits of LAGEOS-1 and -2.

We then determine which, if any, passes during the six days have been tracked simultaneously by more than two EUROLAS stations, and carry out a short-arc orbital correction. The residuals from this improved orbit give a good indication of the relative tracking quality of the stations, at a level of 10mm or so, and again are presented daily in graphical form on the website.

We plan to take part in a study to compare these results with other groups' determinations of tracking quality, which is being coordinated by the ILRS Analysis Working Group.

GLONASS ORBITAL DETERMINATION

We are carrying out a study to use SLR observations of the GLONASS satellites during the continuing IGEX98 tracking campaign to check the quality of the available microwave-based orbital solutions. The SLR observations are used in two ways. Firstly we generate 7-day orbits and compare them to the microwave orbits, achieving RMS differences in the radial direction of about 20 cm. We are also comparing the laser range measurements directly to the positions of the satellites given by the microwave orbits, in order particularly to investigate possible laser-array-induced systematic differences. A paper by Appleby, Otsubo and Sinclair on this work was presented at the IGEX Workshop in Nashville during 1999 September, and has been submitted for publication in the proceedings.

ILRS ANALYSIS WORKING GROUP (AWG) PILOT STUDY

We are taking part in an AWG pilot study to determine the procedures required to compute a regular ILRS product. We have computed a monthly solution for station co-ordinates and EOPs using LAGEOS data and submitted it at the end of the year for comparison with results from other analysis groups.

REFERENCES

Appleby, G.M., Gibes, P., Sherwood, R.A., Wood, R. Achieving and maintaining sub-centimeter accuracy for the Herstmonceux single-photon SLR Facility, in SPIE Proc., U. Schrieber and C. Werner, eds., vol 3865, pp 52-63, (Florence) 1999.

Hausleitner, W., Appleby, G.M., Sinclair, A.T. Rapid quality checks within the EUROLAS Cluster. Proc 11th Int. Laser Ranging Workshop, pp 621-626, BKG, Frankfurt, 1999.

ACKNOWLEDGEMENTS.

The NERC SLR Facility at Herstmonceux and at Monks Wood, UK, is funded by the Natural Environment Research Council in collaboration with the British National Space Center and the Ministry of Defense.

It is a pleasure to acknowledge the contribution to many aspects of the work of the Facility by visiting scientist Mr. Toshimichi Otsubo, on leave from the Communications Research Laboratory, Tokyo, Japan, and to thank CRL for their continuing support.

7.1.2.4 ASI/CGS Associate Analysis Center

Vincenza Luceri, *Telespazio, SpA*

INTRODUCTION

The Space Geodesy Center, Centro di Geodesia Spaziale (CGS) "G. Colombo" (CGS) of the Italian Space Agency (ASI), is located near Matera, southern Italy.

The CGS began its activity on 1983 as a result of an agreement between ASI and NASA; when a SLR system, SAO-1, was installed at the CGS; it is still operational to date. In 1990 a Very Long Baseline Interferometry (VLBI) 20m radiotelescope was installed, in 1991 the Global Positioning System (GPS) activities started with the installation of a permanent GPS Rogue receiver and, at the beginning of 1996, also the operations of the Precision Range and Range-rate Experiment (PRARE) started.

The near future will be highlighted by the Matera Laser Ranging Observatory (MLRO), a state-of-the-art Satellite and Lunar Laser Ranging facility whose excellent data quality has already been demonstrated by the first results achieved during the collocation experiment at the Goddard Geophysical and Astronomical Observatory. The system is now being installed in Matera.

However, the CGS is not only an observing site; data from SLR, VLBI and GPS techniques are routinely analyzed by the CGS analysis group to investigate several geophysical processes.

Besides the space geodesy activities, the CGS is involved in various projects on remote sensing, space robotics and interplanetary missions.

All the operational activities, the engineering support and the geodetic data analysis have been committed to Telespazio SpA.

FACILITIES

The CGS computer configuration comprises some HP workstation and PCs on a LAN network. The SLR analysis is performed using the GSFC/NASA Geodyn-II/Solve software for orbit determination and geodetic parameter estimation. Several other locally developed programs are used for parameters postprocessing.

DATA ANALYSIS

The SLR data analysis has a relatively long history at the CGS. Started in 1984 with the on-site quality control, it is now a well established activity focused on the areas of tectonic plate motion, crustal deformation, post-glacial rebound and subsidence, Earth rotation and polar motion, time variations of the Earth's gravitational field, center of mass of the total Earth system monitoring, International Terrestrial Reference System (ITRS) maintenance, and satellite orbit determination.

The analysis products can be classified into three main types: *standard*, *special* and *multi-technique*.

The *standard* are the basic products of the SLR analysis and contribute to the monitoring of the terrestrial reference system through a set of coordinates and velocities of the worldwide network and the Earth orientation parameters. Those products are routinely distributed to the International Earth Rotation Services (IERS) and are listed below:

- estimated coordinates and velocity field (SSC/SSV) of the SLR network and the Earth Orientation Parameter (EOP) are provided yearly to the IERS in order to realize the Terrestrial References Frame;
- monthly estimated EOP are provided to the IERS as a contribution to the realization of the Bulletin B distributed to the scientific community.

The *special* and the *multi-technique* are those products requiring specific investigation and not routinely produced. They can be grouped into the following areas:

- precise orbit determination (POD):
  - orbit estimation for several geodetic satellites: LAGEOS I, LAGEOS II, Starlette, Stella and ERS1;
  - interpretation of the non-gravitational accelerations acting on LAGEOS satellites;
  - investigation on the LAGEOS rotation using MLRO data;
- gravitational field:
  - time series of estimated low degree geopotential coefficients from the analysis of different geodetic satellites and determination of their secular drift as a contribution to the definition of the Earth mantle viscosity profile;
- geocenter:

  - time series of the geocenter motion within the "IERS analysis campaign to investigate motions of the geocenter";
- inter-technique combination/comparison:
  - comparison of Terrestrial Reference Frames and velocity field estimated with SLR, GPS and VLBI data;
  - comparison of EOP from SLR and VLBI;
  - combination (at normal equation level) of SLR and GPS data;
  - estimation of tectonic movements in the Mediterranean area combining SLR, GPS and VLBI results.

The CGS is participating to the ILRS pilot projects, defined by the analysis working group, submitting its solutions and performing comparison/combination among solutions.

Other information on the CGS and some of the analysis results are available at the CGS WWW server Geodetical Data Archive Facility (GeoDAF) at:

http://geodaf.mt.asi.it

MOST RECENT PUBLICATIONS

Bianco, R. Devoti, M. Fermi, C. Ferraro, R. Lanotte, V. Luceri, A. Nardi, R. Pacione, P. Rutigliano, C. Sciarretta, F. Vespe, Comparison of Space Geodetic Data Analysis Results at the CGS, in Bjorn R. Pettersen (ed.), Proceedings of the 12th Working Meeting on European VLBI for Geodesy and Astronomy, Honefoss, Norway, 12-13 September 1997, ISBN 82-90408-41-2, 74, 1997

G. Bianco, R. Devoti, M. Fermi, V. Luceri, P. Rutigliano, C. Sciarretta, A contribution in the estimation of tectonic motion in crucial areas: the CGS96 SLR solution, Tectonophysics 294, 225-236, 1998

G. Bianco, R. Devoti, M. Fermi, V. Luceri, P. Rutigliano, C. Sciarretta, Estimation of Low Degree Geopotential Coefficients using SLR Data, Planet. Space Sci., 46 (11/12), 1633-1638, 1998

L.L.A. Vermeersen, R. Sabadini, R. Devoti, V. Luceri, P. Rutigliano, C. Sciarretta, G. Bianco, Mantle viscosity inferences from joint inversion of Pleistocene deglaciation-induced changes in geopotential with a new SLR analysis and polar wander, Geophysical Research Letters, 25 (23), 4261-4264, 1998

KEY POINTS OF CONTACT

Dr. Giuseppe Bianco
ASI - CGS, P.O. Box ADP, 75100 Matera - Italy
tel: +39-0835-377209
fax: +39-0835-339005
e-mail: giuseppe.bianco@asi.it

Dr. Vincenza Luceri
Telespazio SpA - ASI CGS, P.O. Box ADP, 75100 Matera - Italy
tel: +39-0835-377231
fax: +39-0835-334951
e-mail: cinzia.luceri@asi.it

7.1.2.5 GFZ Associate Analysis Center

Franz-Heinrich Massman, *GeoForschungs Zentrum Potsdam*

INTRODUCTION/DATA PRODUCTS PROVIDED

Besides its involvement in the SLR data acquisition through operation of the Potsdam station, The GeoForschungsZentrum Potsdam (GFZ) is actively contributing to the ILRS as an Associate Analysis Center with the following products:

- Routine generation and distribution of IRVs (actual satellite missions ERS-1, ERS-2 and GFZ-1, past missions: METEOR-3/7, D1-C, D1-D and MIR)
- Continuous time bias monitoring of the predictions (ERS-1, ERS-2, GFZ-1)
- Provision of Two-Line Elements (ERS-1, ERS-2, GFZ-1)
- Computation of improved Earth gravity field model (GRIM5, jointly with GRGS/CNES)
- Estimation of station positions and velocities (GRIM5, jointly with GRGS/CNES)

BACKGROUND

For almost ten years GFZ has been responsible for the operational, off-line, precision orbit determination of the ERS satellites in the framework of the German Processing and Archiving Facility (D-PAF) of the ERS ground segment of the European Space Agency (ESA). This includes the coordination and support of the ERS SLR tracking by SLR predictions, time bias monitoring, reports and maneuver information. The systematically generated precision ERS orbits (rapid, preliminary, precise) are ESA standard products and are available via the ERS order desk at ESRIN (Frascaty/Italy).

With the launch of GFZ-1 in April 1995 the activities were extended to GFZ's own satellite mission. Due to its orbital characteristics (lowest geodetic satellite, altitude decreasing from 390 km) it was a great challenge for all participants. Up to its predicted decay in June 1999 a large number of SLR returns were acquired and used for precise orbit determination as well as for Earth gravity modelling.

In continuation of a fruitful cooperation with GRGS/CNES, a new iteration of the GRIM Earth gravity field models has been initiated. This includes the reprocessing of about 15 satellites equipped with SLR, PRARE, DORIS and GPS on the basis of the GRIM5 standards. In 1999 the first resulting solutions were presented: GRIM5-S1 (satellite-only) and GRIM5-C1 (combined). Independent comparisons demonstrated the high quality of this solution. The available normal equations formed also the basis for an estimation of station coordinates and velocities.

FACILITIES/SYSTEMS

Section 1.2 (Satellite Mission Development and Operations, Oberpfaffenhofen near Munich) of GFZ and Section 1.3 (Gravity Field and Figure of the Earth, Potsdam) are responsible for the above mentioned activities. The computations are performed on a cluster of SUN workstations, which are also used within other projects. They include desktop stations up to Enterprise servers (3000, 3500) with multiple CPUs (6-8). For the gravity activities the massive parallel processor in Potsdam has also been involved (HP S2000, HP V2500, 16 CPUs each). The operating system was Solaris 2.5/2.6 and has recently been changed uniformly to Solaris 7, while the HPs are running with HP UX. All processing software (EPOS: Earth Parameter and Orbit System) was developed by team members and is the result of more than 10 years of operation experience. The software is written in Fortran 77 or Fortran 90, and a few modules are in C.

Current Activities

The operational activities for the ERS-1 and ERS-2 satellites are ongoing as both satellites are in good condition (as of the time of this writing) and SLR is needed for the precision orbit determination. The high solar activity and the maintenance of the Tandem configuration does require frequent maneuvers.

In view of the upcoming CHAMP satellite mission a corresponding orbit prediction system has been set up. SLR tracking at highest priority is requested during the first two weeks after launch scheduled for the end of April 2000. For the rest of the five year mission, SLR tracking priority can be relaxed as SLR then complements the onboard GPS tracking system. Mission goals are gravity recovery from GPS and SLR data and two color experiments. Acquisition data will be provided by GFZ.

In order to achieve further improvements in gravity field modelling additional SLR data from Geosat Follow-on, Sunsat, etc. will be processed and included in new solutions.

Key Points of Contact

Franz-Heinrich Massmann
GFZ Potsdam, Division 1
Section 1.2: Satellite Mission Development and Operations
c/o DLR Oberpfaffenhofen
82234 Wessling
Germany
Phone: (+49) 8153 28 1206
Fax: (+49) 8153 28 1585
E-mail: fhm@gfz-potsdam.de

Dr. Rolf Koenig
GFZ Potsdam, Division 1
Section 1.2: Satellite Mission Development and Operations
c/o DLR Oberpfaffenhofen
82234 Wessling
Germany
Phone: (+49) 8153 28 1353
Fax: (+49) 8153 28 1585
E-mail: rolf.koenig@gfz-potsdam.de

Future Plans

Future activities are concentrating on the CHAMP satellite mission. The acquired SLR, GPS and accelerometer data will be used to compute precision orbits and to derive improved (one order of magnitude) Earth gravity models every few months in order to monitor temporal variations.

The orbit predictions system will be migrated to the generation of acquisition data for the GRACE satellite scheduled for launch in 2001.

7.1.2.6 AUSLIG Associate Analysis Center

Ramesh Govind, *Australian Surveying and Land Information Group*

BACKGROUND/INTRODUCTION

The AUSLIG Associate Analysis Center has been routinely processing LAGEOS-1 and -2 data for satellite for orbit determination, station coordinates, Earth Orientation Parameters and SLR station performance monitoring. In addition, on an opportunity or project basis, Stella, Starlette, Etalon and GLONASS data is also processed. This work to-date has been reported in the attached list of publications. There is an ongoing emphasis on the co-location and combination of SLR with other space geodetic techniques. Recent activities have been the three epochs of observations and processing [1997, 1998 and 1999] for the Asia - Pacific Regional Geodetic Project (APRGP) of the Permanent Committee for GIS Infrastructure for Asia and the Pacific (PCGIAP). Twelve months of combined LAGEOS-1 and -2 solutions have been submitted to the IERS Time Series Pilot Project. Also, six months of GLONASS was processed as part of the IGEX-98 campaign.

FACILITIES/SYSTEMS

The current computation facilities in the AUSLIG Space Geodesy Analysis Center is comprised of four HP workstations [C160, C180, C360 and L2000]. The processing system uses the MicroCosm suite of programs for orbit determination and geodetic parameter estimation as the engine. NASA's SOLVE program is used for the combination solutions. A suite of programs have been developed in-house for analysis and re-formatting. Final results are provided in the SINEX format.

CURRENT ACTIVITIES

The current activities are:

- Participating and contributing to the three ILRS Analysis Working Group pilot projects [station coordinates and EOPs, Orbit comparison and the software/standards comparison].
- Continue submitting results to the IERS Time Series Pilot Project.
- At this stage there is a concerted effort to contribute a significant SLR solution (LAGEOS) to the ITRF2000.

FUTURE PLANS

- Continue submitting results to the IERS.
- Provide global solutions as a full analysis center to the ILRS when the AWG coordination structures are established.
- Extend routine processing and analysis to Stella, Starlette, Etalon, GLONASS and LEOs.
- Provide a station monitoring service.

RELATED PUBLICATIONS

Govind, R., J. Dawson, G. Luton and D. Sproule (1998): “Satellite Laser Ranging Solutions”, Proceedings, Workshop on Regional Geodetic Network, Working Group 1, Permanent Committee on GIS Infrastructure for Asia and the Pacific, Canberra, Australia, 2nd - 4th July, 1998.

Dawson, J., R. Govind, G. Luton, and D. Sproule: (1998) “Asia Pacific Regional Geodetic Project 1997”, presented Western Pacific Geophysics Meeting, Taipei, Taiwan, 21-24 July, 1998.

Govind, R., J. Dawson, G. Luton and D. Sproule: (1998) “Combination of High Precision Space Geodetic Techniques: The Asia and Pacific Regional Geodetic Project 1997”, Advances in Space Research, Vol.23, #4, pp 797-807, 1990, and presented 32nd COSPAR Scientific Assembly, Nagoya, Japan, July, 1998.

Govind, R., J. Dawson, G. Luton, and D. Sproule: (1999) “Combination of High Precision Space Geodetic Techniques”, Proceedings of the International Workshop on Geodetic Measurements by Collocation of Space Geodetic Techniques on Earth (GEMSTONE), Communications Research Laboratory, Tokyo, Japan, 25-28 January, 1999.

Govind, R., J. Dawson, and G. Luton: (1999): “Asia Pacific Regional Geodetic Project 1998 - GPS, DORIS and SLR Results and Analysis”, Proceedings, Workshop on Regional Geodetic Network, Working Group 1, Permanent Committee on GIS Infrastructure for Asia and the Pacific, Ho Chi Min City, Vietnam, 12th - 13th July, 1999.

Govind, R., J. Dawson, and G. Luton: (1999) “SLR GLONASS Orbit Determination”, presented (in proceedings), IGEX-98 Workshop, Nashville, Tennessee, 13th-14th September, 1999.

Govind, R., J. Dawson, and G. Luton: (1999) “A comparison of SLR and Microwave Determined GLONASS Orbits”, to be presented, The International Symposium on GPS - Application for Earth Sciences and Interaction with other Space Geodetic Techniques, Tsukuba, Japan, 18-22 October 1999.

KEY POINT OF CONTACT

Dr. Ramesh Govind
AUSLIG/Geodesy
PO Box 2, Belconnen, ACT 2616,
Australia.
Phone: 61 2 62014 371
Fax: 61 2 62014 366
E-mail: rameshgovind@auslig.gov.au

7.1.2.7 OCA/CERGA Associate Analysis Center

Pierre Exertier, *Centre de Recherche en Géodynamique et Astrométrie*

INTRODUCTION

Laser tracking tracking from regional networks of stations is an important means of controlling range biases. The International Laser Ranging Service (ILRS) has been organized and this report presents the participation of the OCA/CERGA Associate Analysis Center at the Grasse, France Observatory in this field.

For more than 20 years, the French geodynamic site located near Grasse, France has participated in the tracking of many geodynamic, geodetic, and oceanographic satellites. At Grasse there are three independent laser ranging instruments: a classical Satellite Laser Ranging (SLR) station, a Lunar Laser Ranging (LLR) station, and the French Transportable Laser Ranging Station (FTLRS).

The opportunity to have three independent laser stations located on the same site is unique for detecting errors and biases specific to each station. It also fulfils the purpose of the ILRS (International Laser Ranging Service), to control measurement accuracy and bias stability, and to improve efficiency.

For several years, in order to decrease the laser system biases, the hardware and the scientific and technical data analysis have been constantly upgraded. See the reports of Francis Pierron on SLR and the FTLRS stations and the report of F. Mignard concerning the tracking of high satellites (and the Moon) by the LLR station.

DATA PRODUCTS PROVIDED

LAGEOS and other satellites

For this purpose, since 1997, a collocation experiment has been carried out between the LLR and the SLR fixed stations on the LAGEOS 1 and 2 satellites. This kind of cross-analysis provides some evidence of the objective quality of the stations and their positioning, providing a possible detection of instrumental bias and seasonal signals with their geophysical interpretation.

We use the LAGEOS satellites (altitude of 6000 km) because they are the lowest targets accessible to the LLR station and the highest to the FTLRS. Moreover, they are routine targets for the SLR fixed station, which ranges to satellites at altitudes between 350 and 20000 km (from GFZ to the GPS and GLONASS constellations).

The dynamic orbit determinations on LAGEOS can also be used to estimate the data quality of the SLR and LLR stations. The mean value of the residuals can be computed for the whole international laser network or for individual stations such as the Grasse SLR and LLR. However at this stage, it is important to keep in mind that the LLR data have not been included in the orbit determination. The standard deviations of these residuals can also be computed in the same conditions. The arcs from 1998 have been evaluated and the following quantities have been computed:

- The mean value of the residuals for all of the 10-days arcs for the SLR and the LLR stations. They are (0. +/- 0.6) cm and (1.5 +/- 1.24) cm, respectively. The nominal value of the LLR bias is due, at this stage, to the non-adjustment of the LLR coordinates and to the fact that the LLR data are not included in the orbit computation.
- The mean value of the standard deviation for all of the 10-days arcs for the SLR and the LLR stations. They are (2.0 +/- 0.3) cm and (2.0 +/- 0.6) cm, respectively. For all the stations used in the orbit computation we get (2.2 +/- 0.6) cm.

These values show great stability of the data quality at the level of a few millimeters for all the stations considered, and specifically for the Grasse SLR and LLR ones. The 2.2 cm mean laser residual rms comes from: instrumental biases at each station, station coordinate errors, LAGEOS signature, tropospheric delay, and gravity field determination errors and non-gravitational modeling errors.

The station positions, and in particular the altitude, have been determined in each of the four seasons in 1998, as well as for an annual mean bias. In 1998, for the Grasse SLR and LLR stations, the mean annual biases were of (? 4.5 +/- 0.7) mm and (0.6 +/- 1.1) mm, respectively. These values demonstrate a very good stability at a few millimeters level along the year, what is satisfactory in terms of a SLR standard station.

Considerable progress has been realized since 1997 at the Grasse SLR fixed station, with a new photodiode system. The bias is much smaller than in the years before 1997 (0.5 cm instead of 3-4 cm) and there is now a very good stability (+/- 0.7 mm). As a result the photodetector in the FTLRS is also being upgraded.

GLONASS and GPS-35, -36 satellites

With the quality of the existing networks, and in part due to the action of the ILRS, it is possible to control the orbit quality for satellites like GPS, GLONASS (IGEX experiment). This is implicitly a key factor for precise positioning and for navigation.

One objective of the IGEX experiment was precise orbit determination and validation of GLONASS orbits by laser range observations. In this field, laser based orbit corrections (radial, tangential, and normal) have been systematically computed using a short-arc technique. The orbit corrections have been analyzed as a function of several parameters: date, orbital plane, satellite type and geographical area. The origin of the observed features have tentatively been investigated in terms of: non-gravitational forces, thermal equilibrium of equipment, reference systems, location of the retro-reflectors array. Further investigations will be needed to better understand the origin of various biases.

FACILITIES/SYSTEMS

In 1998, a local geodetic campaign was conducted at Grasse by IGN-F (French National Geographic Institute), to check the distances of all the calibration targets used by the laser stations. The consistency of the methods used is generally at the centimeter or sub-centimeter level, but improvements could still be made. The purpose was also to interconnect all the geodetic instruments, GPS, SLR, LLR, gravimeter. It is important to repeat periodically this kind of local geodetic connection.

A comparison with absolute gravity measurements was performed in 1998. The Geophysics Institute of Strasbourg carried out five campaigns in Grasse. Two reference stations (Grav. 1 and Grav. 2) were chosen to provide a good comparison between several measurements performed at the same period at close locations (the distance between the two points is of about 2 km). One station (Absol. Grav. 1) corresponds to a reference point located near the LLR pillar, and the other one (Absol. Grav. 2) is in a cellar. The variations measured in microGals can be converted in a conventional way into altitude variations (-0.296 =B5Gal correspond to 3 mm). The agreement between these gravimetric altitude variations and the altitude variations deduced from the laser positioning is quite satisfactory concerning the phase and the amplitude. On the other hand, there is a disagreement with the results obtained by the permanent GPS receiver. This could be due to a tropospheric effect but, there is not enough data to draw strong conclusions. However, it shows the importance of pursuing such experiments to better understand the origin of the observed seasonal variations. To support this work, a permanent DORIS beacon will be set up at the Grasse observatory in 2000-1.

The analysis of LAGEOS data, permanent GPS receiver measurements, and the absolute gravimetry measurements have permitted us to obtain technical improvements, orbitography and positioning quality control, and scientific results. More specifically, the Grasse Lunar Laser Ranging station bias of 9.87

cm, before 1997, has been confirmed by the LAGEOS observations. At the same time, the great stability of its bias since that time (+/-1.1 mm), as well as a mean bias very close to zero, have been shown. This data quality is very important for the future and for studying long term time varying phenomena.

FUTURE PLANS

The objective in the near future is to establish a permanent absolute geodetic observatory at Grasse with an absolute reference system (as stable as possible) to permit the control of altitude deviations (instrument, atmosphere) for oceanographic projects such as Jason and ENVISAT, both to be launched in 2000-1.

The SLR and LLR stations are the main systems, but special efforts have been made during the end of the 90s to combine different space geodetic and gravimetric techniques, such as SLR, GPS (Global Positioning System), DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite), GLONASS (GLObal NAvigation Satellite System), and an absolute gravimeter FG5. All these techniques are complementary and have a positioning accuracy at 1-2 centimeter or better. The use of these techniques, located in a number of fundamental geodetic stations, is a key factor for improving the absolute accuracy of geodetic products (i.e. positioning, orbit determination) at a global level. The aim of these collocations is also to identify systematics and instabilities in the measurements in order to improve the accuracy of each technique.

The collocation experiment on LAGEOS-1 and -2 will be extended into 2000, using the three laser ranging stations, including the renewed FTLRS.

7.1.2.8 NASA GSFC's/JCET Associate Analysis Center

Erricos Pavlis, *National Aeronautics and Space Administration*

INTRODUCTION

The Associate Analysis Center (AAC) at JCET/GSFC has been slowly coming on line with the activities we had originally proposed to ILRS. The delay is primarily the result of only partial funding of these activities by our sponsors. Despite these problems we have completed a substantial amount of the analysis that we intended to contribute to ILRS this year. We have participated in the IERS/ITRF Pilot Project for TRF definition and the ILRS Pilot Project for site and EOP SINEX file submission. This past year we submitted a preliminary solution to IERS and in 2000 we intend to contribute an iterated version for the new major TRF realization, ITRF2000.

BACKGROUND

The activities of the AAC are primarily focused on the analysis of SLR data from LAGEOS and LAGEOS 2, with analyses for SLR data obtained on additional satellite targets during specific campaigns of interest (e.g. SUNSAT, GPS, GLONASS/IGEX, etc.). The main products are the updated station positions and velocities and the Earth Orientation Parameters (EOP), x_p, y_p, and *LODR,* at daily intervals. In support of the ITRF Pilot Project we also form weekly solutions which are transformed into SINEX format for general distribution. 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. These series were used last year to estimate periodic signals at long and intermediate periods, primarily due to the seasonal redistribution of geophysical fluids in the Earth system.

FACILITIES/SYSTEMS

The AAC uses the computing facilities available to the Space Geodesy Branch at NASA Goddard, Code 926. These include a number of workstations, primarily HP 9000/735 and SUN Ultra-5_10, and the Cray J932 parallel processor for the multi-year solutions. The software used is NASA Goddard's GEODYN/SOLVE II package and a number of ancillary s/w used for the data handling/editing and the post-processing of the results.

CURRENT ACTIVITIES

At this time we are completing the combined analysis of the LAGEOS-1 and -2 SLR data set for the period from 1993 to present, in view of the upcoming submission to IERS' ITRF effort for the development of ITRF2000. We continue the generation of weekly solutions as a contribution to the IERS/ITRF Pilot Project and our own activity of monitoring the episodic and seasonal variations in the definition of the geocenter with respect to the origin of the conventional reference frame. We are also re-generating the complete series of the weekly SINEX files for the same period, following the ILRS adopted standards on the basis of the 1999 ILRS Pilot Project. A web site is soon to be operational to aid in disseminating these weekly files and other AAC products.

KEY POINT OF CONTACT

Dr. Erricos C. Pavlis
Joint Center for Earth System Technology, JCET/UMBC
NASA Goddard Space Flight Center
Space Geodesy Branch, Code 926
ESSB Bldg. 33, Rm G213
Greenbelt, Maryland
U S A 20771-0001
Phone: (301) 614-6119
Fax: (301) 614-6099
E-mail: epavlis@Helmert.gsfc.nasa.gov

FUTURE PLANS

In the future we will continue our LAGEOS-related activities with emphasis on the near-real-time generation of weekly products and their dissemination via the web. This year we will start generating a combination product on the basis of GPS and SLR SINEX files. This AAC will also expand its activities to include in its analyses the data of the new geodetic and oceanographic missions to be launched during 2000, CHAMP and JASON. With regard to the second one we have proposed to establish an absolute calibration site at Gavdos, Crete, Greece and in that capacity, we will participate with the SLR data analysis for the CAL-VAL activities during the first six months of the mission.

RELATED PUBLICATIONS

Pavlis, E. C., “JCET’s 1999 SLR-based Terrestrial Reference Frame”, *Eos Trans. AGU, 80(46)*, Fall Meet. Suppl., F262, 1999.

Pavlis, E. C., “Error Analysis for LARES”, Report to Dept. of Aerospace Engineering, Univ. of Roma ‘La Sapienza’, Rome, Italy, August, 1999.

Pavlis, E. C., “Geodetic Constraints on Mass Redistribution in the Earth System “, presented at the Joint Symposium *Insights into Earth System Science: Variations in the Earth’s Rotation and its Gravitational Field*, at the 22nd General Assembly of the *International Union of Geodesy and Geophysics*, July 19-30, 1999, Birmingham, UK.

Pavlis, E. C., “LAGEOS 1 and 2 Constraints on Mass Redistribution in the Earth System (1993-98)”, presented at the AGU Spring Meeting, *Eos Trans. AGU, 80(17)*, Suppl., S84, 1999.

Pavlis, E. C., “Fortnightly Resolution Geocenter Series: A Combined Analysis of LAGEOS 1 and 2 SLR Data (1993-96)”, in *IERS Technical Note 25*, Observatoire de Paris, April 1999.

Pavlis, E. C., “Geodetic Constraints on Mass Redistribution in the Earth System (1993-1998)”, Geophysical Res. Abstracts, 1(1), p225, EGS, March, 1999.

Pavlis, E. C., “Data Analysis for LARES”, Report to Dept. of Aerospace Engineering, Univ. of Roma ‘La Sapienza’, Rome, Italy, March, 1999.

7.1.2.9 IAA Associate Analysis Center

Zinovy Malkin, *Institute of Applied Astronomy of Russian Academy of Science*

INTRODUCTION/DATA PRODUCTS PROVIDED

The IAA (Institute of Applied Astronomy of Russian Academy of Science) Associate Analysis Center began its activity in 1994. It has been routinely processing LAGEOS-1 and -2 observations mainly for use in the IAA EOP Service. Both operational (daily) and final (monthly and yearly) ERP solutions are available on a regular basis.

Beginning from the IERS AR 1995, IAA final SLR submissions are used in the IERS CB combined solutions. Beginning in 1995, IAA operational SLR submissions are used in the IERS Bulletin A combination. For final solutions we process all available observations. Two final solutions are computed. The series EOP(IAA)L01 is computed using LAGEOS-1 observations only (from January 1983), and the series EOP(IAA)L02 is computed using LAGEOS-1 and -2 observations (from October 1992).

Due to limited resources, station coordinates and velocities are not adjusted regularly but are adopted from the IERS (now ITRF97).

FACILITIES/SYSTEMS

Three packages are used in the IAA (or planed for use) for processing of the SLR observations.

The program package GROSS (Geodynamics, Rotation of the Earth, Orbit determination Searching Software) developed by Z. Malkin is the main IAA package used for routine analysis of the SLR observations. It provides both multiarc and multisatellite solutions. The package is operated on a Pentium PC under MS DOsoftwareindows. The last version of GROSS meets IERS Conventions (1996). As an extension of the IERS Conventions, ocean loading in site displacement is computed using the CSR 3.0 model with a correction for the center of mass displacement computed by H.-G. Scherneck.

Operational calculations of EOP are being made automatically every day. Software used for operational computations includes both MS DOsoftwareindows (GROSS, data formatting, supplement service programs, archiving of results) and Unix (data exchange with world databases and analysis centers, ftp functions, etc.) components.

The software works as follows. Observational data and other relevant files from the Data Centers are automatically downloaded onto the Unix machine. GROSS picks up these data as an everyday scheduled task. Upon the completion of the computations the resulting file is transferred to the Unix machine to be automatically sent to users. In parallel, EOP files for general IAA use are updated along with corresponding data base on Windows and Unix machines. These data are also available via anonymous ftp.

Before and during computation GROSS quality controls input data to prevent submission of incomplete or incorrect data. Some configuration parameters needed for GROSS are also automatically adjusted to the amount and quality of input data.

A special operational strategy for calculations of EOP has been developed to limit the gap between the last observation and epoch of operational EOP to about 2 days (depends chiefly on availability of observational data in CDDIS).

To estimate UT, a free-running UT series is developed for the whole interval of observations and then it is corrected for long-term variations (with periods greater about half of a year) derived from comparison with the EOP (IERS) C04 series.

ERA (Ephemeris Research in Astronomy) is a problem-oriented programming system for ephemeris astronomy developed by the group of G. Krasinsky. The system is designed to support scientific research in astronomy and space science (ephemeris predictions, simulation of observation programs, comparison of positional observations with dynamic theories, etc.). ERA is operated on a PC under MS DOS. ERA supports ephemerides of all Solar system bodies, lunar and planet landers, artificial Earth satellites, and spacecraft.

This group has been developing algorithms and software for combined (on the observational level) processing of SLR and VLBI observations. The main goal is to use SLR data for densification of weekly UT1 and nutation series obtained from VLBI and to produce final daily series containing all five EOP.

The GRAPE package is intended for processing of the microwave and laser range observations of the GPS and GLONASS satellites. It consists of two main parts. The first part is based on the ITALAS package developed at the Institute of Theoretical Astronomy (which joined IAA in 1998) by the group Iskander Gayazov. It is used for preparation of satellite ephemerides used in the main part of the GRAPE package. The main part of the package was developed in Delphi under Windows.

This package uses third differences of phase observations for evaluation of satellite orbits, Earth Rotation Parameters (ERP), station coordinates and zenith troposphere delays. Some original algorithms for determination of cycle slips, phase ambiguities and troposphere delay modelling are used in the GRAPE package. At the moment only GPS observations are processed with GRAPE package. ERA and GRAPE packages operate on Pentium PC.

CURRENT ACTIVITIES

IAA Associate Analysis Center continues to:

- Regularly submit EOP operational and final solutions to the IERS.
- Develop the GROSS package, mainly for implementing advanced algorithms for the combination of SLR, GPS and VLBI EOP series.
- Develop ERA packages for combined processing of the SLR and VLBI observations. In 1999 the first yearly ERP series was produced using only SLR data and the first experimental combination SLR+VLBI results were obtained.
- Develop GRAPE package for processing of the microwave and laser range observations from GPS and GLONASS satellites. Experimental computation of orbits and ERP in a real-time regime (using GPS observations only) was begun and shows good quality results. The addition of microwave GLONASS and laser range observations on the GPS and GLONASS satellites are planned for 2000-2001.
- In 1999 the IAA AAC took part in the ILRS Analysis Working Group pilot project. Two ERP solutions obtained with GROSS and ERA packages and station position solution obtained with ERA package was submitted to the ILRS Analysis WG.

KEY POINTS OF CONTACT

IERS and ILRS related matters, EOP Service, GROSS package:

Zinovy Malkin malkin@quasar.ipa.nw.ru

GPS/GLONASS/SLR observations, ITALAS, GRAPE packages:

Iskander Gayazov gayazov@quasar.ipa.nw.ru

SLR/VLBI observations, ERA package

Nadejda Shuygina nvf@quasar.ipa.nw.ru

FUTURE PLANS

For 2000-2001 we plan to:

- Continue to regularly submit EOP operational and final solutions to the IERS and ILRS.
- Begin to regularly compute (fully independent of IERS data) EOP solutions based on a combination of SLR, GPS and VLBI data.
- Combine the microwave GLONASS and laser range observations on GPS and GLONASS satellites in 2000-2001.
- Begin to regularly produce station position and GPS/GLONASS orbit solutions (SLR only, GPS/GLONASS only and combined).

7.1.2.10 AIUB Associate Analysis Center

Tim Springer, *Astronomical Institute, University of Berne*

INTRODUCTION

The Center for Orbit Determination in Europe (CODE) is one of the Analysis Centers of the International GPS Service (IGS). CODE, located at the Astronomical Institute of the University of Berne, is a joint venture of the following institutes:

- Swiss Federal Office of Topography (L+T),
- French "Institute Geographique National" (IGN),
- German "Bundesamt fuer Kartographie and Geodaesie" (BKG), and
- Astronomical Institute of the University of Berne (AIUB).

Besides being one of the Analysis Centers of the IGS, CODE is also one of the Analysis Centers of the International GLONASS Experiment (IGEX), and one of the Associate Analysis Centers (AAC) of the International Laser Ranging Service (ILRS). In its role as AAC of the ILRS, CODE has provided (since December 1996) the SLR-GPS quick-look service using the SLR observations taken from the two GPS satellites PRN 5 and PRN 6. CODE also provides orbit predictions for all GPS and GLONASS satellites. These predictions are converted to IRVs by RGO and used by several of the (European) SLR tracking stations.

At CODE the main motivation to use the SLR observations for the GPS (and GLONASS) satellites is that these observations provide a unique opportunity to validate the quality of the IGS (and IGEX) orbit estimates. Because the IGS (and IGEX) orbits are based on microwave measurements only, the SLR observations provide a completely independent validation of the orbit quality. Due to the high altitude of the GPS satellites, the angle between the vector from the SLR observatory to the GPS satellite and the vector from the geocenter to the GPS satellite is 14 degrees at maximum. The SLR observations are therefore nearly in the radial direction, and thus provide mainly information concerning the radial orbit errors.

The orbit validation is based on the difference between the observed range (the SLR normal point measurement) and the computed range. The range is computed assuming both, the SLR station positions and the GPS satellite positions, are known. The SLR station positions are taken from the latest ITRF realization, whereas the orbit positions may be obtained from the IGS, in our case, the orbits of the CODE analysis center. The tropospheric delays are modeled using the Marini-Murray model in which the temperature, pressure, and humidity measurements, delivered with the SLR normal points, are introduced.

BACKGROUND

Besides the quick-look service we have analyzed all of the SLR observations from the GPS satellites observed in the time span from January 1995 to July 1999, and for the GLONASS satellites observed in the time span from day 283 in 1998 (start of the IGEX campaign) until day 149 in 1999.

The results of these OMC (Observed Minus Computed) analysis revealed that there is an average bias between the observed and computed SLR ranges! The bias estimate being -55 mm based on the GPS data and -42 mm based on the GLONASS data. The negative sign indicates that the observed SLR ranges are shorter than the computed ranges.

Secondly, the RMS of the OMC residuals, around the mean, is as low as 55 mm for the GPS data and 128 mm for the GLONASS data. This result is truly remarkable. It implies that the two independent techniques, microwave and SLR, agree at the level of a few centimeters. Most importantly it also shows that the (radial) orbit error of the IGS orbits is as small as 55 mm. This corresponds quite well to the RMS statistics of the weekly IGS orbit combinations. The higher RMS for the GLONASS results is caused by the lower quality of the IGEX orbits compared to the IGS orbits. This difference is mainly explained by the fact that the GLONASS microwave tracking network is quite poor compared to the current status of the IGS network. Considering this important limitation, the GLONASS orbits are in fact of a remarkable quality.

The fact that the observed bias is so similar for both satellite systems practically rules out the possibility of an error in the SLR reflector offset because it is unlikely that a similar error was made in computing the center of mass correction for the retroreflector arrays on both systems. We should note, however, that the GLONASS orbits are derived by fixing the GPS orbits. Therefore, the GLONASS orbits are not independent from the GPS orbits and the same might be true for the observed bias. We should also point out that the retroreflector arrays on both systems are very similar, the only difference being the size of the GPS and GLONASS retroreflector arrays. The observed bias might thus have something to do with the reflectors. However, given the small size of the reflectors, (height of only 37 mm) a 50 mm error is hard to imagine.

More information about this study may be found in “Modeling and Validating Orbits and Clocks Using the Global Positioning System.” [1]

Besides orbit validation, the SLR observations may also be used to study the attitude of the GPS satellites as a function of time during their eclipse phases. Furthermore, the combination of the observations from different techniques, microwave and SLR, will unify the terrestrial reference frame for both techniques and may lead to improved orbits of the microwave satellites. The unification of the terrestrial reference frame will be of advantage for all parameters common to both techniques, i.e., Earth rotation, station coordinates, and geocenter.

CURRENT ACTIVITIES

At CODE we monitor the SLR observations using our IGS rapid and final orbits. Because our daily IGS rapid orbits are available around 12:00 UTC, only 12 hours after the end of the observation day, they provide the possibility of giving very rapid feedback on the quality of the SLR observations. Because we think that this rapid turn-around is very useful for the SLR tracking stations, we have set up the SLR-GPS quick-look service.

Each day the SLR observations gathered over the last 6 days are evaluated using the CODE IGS Orbits. The last 4 days are analyzed using the CODE rapid orbits. The 2 older days are analyzed using the CODE final Orbits. The final orbits have an estimated precision of about 50 mm whereas the rapid orbit precision varies between 50 and 150 mm. The SLR-GPS quick-look results, covering 6 days, are distributed by e-mail every day provided that new data was available. Table 7.1.2.10-1 shows an example of the SLR-GPS quick-look report. Note that, in these reports, the “MEAN” will absorb possible range biases, to a large extent possible time biases, and part of the GPS orbit error. The “RMS” (around the mean) gives a reasonable representation of the noise of the SLR observations. However, in cases where a satellite eclipse event was tracked, the RMS will be larger than the noise of the observations. Furthermore, for long passes, the satellite orbit error will start to show up in the RMS.

Station ID	SAT PRN	Start Passage yy/mm/dd	hh:mm	Dur (min)	#OBS GOOD	MEAN (mm)	RMS (mm)	#OBS BAD	MEAN (m)	RMS (m)
7080 MLRS	6	00/03/01	02:47	7	3	-41	9			
7080 MLRS	6	00/03/03	01:14	157	8	-52	20			
7080 MLRS	6	00/03/06	02:29	22	6	-21	3			
7090 YARR	6	00/03/01	16:23	7	3	-135	0			
7090 YARR	6	00/03/03	18:28	143	9	-16	20			
7090 YARR	6	00/03/05	15:39	186	10	-61	15			
7090 YARR	6	00/03/06	16:10	125	5	-70	14			
7090 YARR	5	00/03/01	15:33	42	6	-54	6			
7090 YARR	5	00/03/03	18:09	7	3	-44	2			
7090 YARR	5	00/03/08	15:09	196	11	-38	8			
7090 YARR	5	00/03/06	13:39	211	9	-66	49			
7849 MSTR	6	00/03/01	19:13	24	5	-59	5			
7849 MSTR	6	00/03/02	18:32	61	8	-56	5			
7849 MSTR	6	00/03/05	18:52	24	3	-50	4			
7849 MSTR	5	00/03/01	15:52	25	6	-53	12			
7849 MSTR	5	00/03/02	17:28	34	5	-110	8			
7845 GRASSE	6	00/03/02	10:18	134	6	-10	8			
7845 GRASSE	6	00/03/03	11:14	12	4	0	4			
7845 GRASSE	6	00/03/06	10:14	126	7	5	45			
7845 GRASSE	5	00/03/02	09:54	9	3	-47	7			
7845 GRASSE	5	00/03/03	07:59	11	4	-67	3			
7845 GRASSE	5	00/03/06	08:39	11	4	-123	8			
7839 GRAZ	6	00/03/06	12:02	24	6	27	3			
					134	-46	39		0.0%	

Station ID	Station CDP number and first 4 characters of the station name
SAT PRN	The GPS Pseudo Random Noise (PRN) number (5 or 6 for SLR)
Start Passage	Start time of the SLR observation pass
Dur	Duration of the SLR observation pass
#OBS GOOD	Number of accepted SLR observations.
MEAN	Mean of the OMC residuals (in millimeters)
RMS	RMS of the OMC residuals around the MEAN (in millimeters)
#OBS BAD	Number of rejected SLR observations (OMC > 1 meter).
MEAN	Mean of the BAD OMC residuals (in meters)
RMS	RMS of the BAD OMC residuals around the MEAN (in meters)

Table 7.1.2.10-1: SLR-GPS quick-look report day 066, 2000

FUTURE PLANS

In the near future we hope to integrate data from the GLONASS satellites into our routine IGS processing. This will enable us to include the SLR data from the GLONASS satellites in our quick-look service. Because all GLONASS satellites are equipped with an SLR reflector array and are relatively easy to track, this will provide a useful enhancement of the present quick-look service.

REFERENCES

[1] "Modeling and Validating Orbits and Clocks Using the Global Positioning System," T.A. Springer, Ph.D. Thesis, University of Berne

7.1.2.11 BKG Associate Analysis Center

Bernd Richter, *Bundesamt fur Kartographie und Geodasie*

INTRODUCTION

Central task of the Bundesamt fur Kartographie und Geodasie (BKG) geodetic division is to provide and update the Geodetic Reference Networks of the Federal Republic of Germany including:

- Survey work (Station Wettzell - SLR, VLBI, GPS, GLONASS observations, survey campaigns, and other activities), and theoretical work for collection and preparation of survey data;
- Cooperation in bilateral and multilateral activities for definition and updating of global reference systems;
- Further development of the survey and observation technology used;

Representation of the relevant interests of the Federal Republic of Germany on an international level.

The BKG Associate Analysis Center routinely processes LAGEOS-1 and -2 data for satellite orbit determination, station coordinates, Earth Orientation Parameters and SLR station performance monitoring. In addition, special investigations have been made to study new laser ranging systems by collocation (e.g. TIGO) and to support the GLONASS IGEX campaign.

FACILITIES/SYSTEM

The available computation facilities in the BKG Potsdam Branch consist of HP workstations. Orbit and parameter estimations (station coordinates and EOP) are performed with UTOPIA (CSR, University of Texas). Moreover the BERNESE Software Engine is used for the network combination of various space techniques. In-house programs have been developed for station coordinate transformations, EOP series generations and to create updated SINEX files.

CURRENT ACTIVITIES

The BKG contributes to the ILRS Analysis Working Group pilot projects with respect to station coordinates and EOPs.

On an annual basis, station coordinates, velocities and EOPs are provided to the IERS office (in particular for the ITRF 2000).

The BKG solutions are no longer constrained by fixing parameters but rather by using a-priori sigmas to characterize the datum.

FUTURE ACTIVITIES

The BKG will continue its participation in future ILRS and IERS Time Series pilot projects. On a regular basis orbit determinations, positions, velocities, EOP solutions, geo-center and GM variations will be contributed to the IERS and other services.

7.2 LUNAR LASER RANGING

Lunar 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.

7.2.1 INTRODUCTION

Peter Shelus, *University of Texas*

In the simplest of terms, lunar laser ranging (LLR) is a modern and exotic form of astrometry. It consists of accurately measuring the round-trip travel time for a laser pulse that is emitted from an observing station on the Earth and returns, after being reflected off of a retroreflector array on the surface of the Moon. The analysis of this constantly changing distance, using several observatories on the Earth and several retroreflectors on the Moon, provides for a wide spectrum of terrestrial, lunar, solar system, and relativistic science [*Bender et a.l,* 1973; *Mulholland,* 1980; *Dickey et al.,* 1994]. But, even after more than 30 years of operation, LLR remains a non-trivial and technically challenging task. Signal loss, caused mainly by the inverse 4th power of the Earth-Moon distance but also the result of optical and electronic inefficiencies in the observing equipment, requires the detection of single photoelectron events. With the present laser firing rate of 10 hertz, at a station like the MLRS, fewer than 25 photoelectrons/minute are routinely obtained. Timing precision is measured in ten's of picoseconds with the total range accuracy being about an order of magnitude larger. Were the moon to be just 25% farther from the Earth than it is, this experiment probably could not be performed with present equipment. It is quite sobering to realize that it is more than a trillion times more difficult to range to the Moon than it is to range to Topex-Poseidon. At the present time, even though there are several tens of highly efficient artificial satellite ranging stations around the world, only two of them have the capability of ranging to the Moon. One of them is located in the United States, at McDonald Observatory. The other is in the south of France, near Nice, at the Observatoire de la Cote d'Azur.

The basic data that is gathered by LLR forms the foundation upon which a large number of astronomical disciplines depend. They provide for an invaluable multi-disciplinary analytical tool, the benefits of which are registered in such areas as the solid Earth sciences, geodesy and geodynamics, Solar System ephemerides, terrestrial and celestial fundamental reference frames, lunar physics, general relativity and gravitational theory. They contribute to our knowledge of the precession of the Earth's spin axis, the 18.6 year lunar induced nutation, polar motion and Earth rotation, the determination of the Earth's obliquity to the ecliptic, the intersection of the celestial equator and the ecliptic (the equinox), lunar and solar solid body tides, lunar tidal deceleration, lunar physical and free librations, as well as energy dissipation in the lunar interior. They determine Earth station and lunar surface retroreflector location and motion, the Earth-Moon mass ratio, lunar and terrestrial gravity harmonics and Love numbers, relativistic geodesic precession and the strong equivalence principle of general relativity.

REFERENCES

Bender, P. L., Currie, D. G., Dicke, R. H., Eckhardt, D, H., Faller, J. E., Kaula, W. M., Mulholland, J. D., Plotkin, H. H., Poultney, S. K., Silverberg, E. C., Wilkinson, D. T., Williams, J. G., and Alley, C. O., 1973, Science, 182, 229.

Dickey, J. O., Bender, P. L., Faller, J. E., Newhall, X X, Ricklefs, R. L., Ries, J. G., Shelus, P. J., Veillet, C., Whipple, A. L., Wiant, J. R., Williams, J. G., and Yoder, C. F. 1994, Science, 265, 482.

Mulholland, J. D., 1976, Sci. Appl. of LLR, (J. D. Mulholland, Ed.), Reidel, Dordrecht, Netherlands, 9.

7.2.2 ANALYSIS CENTERS

7.2.2.1 PARIS OBSERVATORY

Bernd Richter, *Bundesamt fur Kartographie und Geodasie*

INTRODUCTION

Paris Observatory Lunar Analysis Center (POLAC) is located in the Department of Fundamental Astronomy at the Paris Observatory and works in cooperation with the CERGA LLR team at Grasse, France. Its goals are to improve the analytical solutions of the orbital and rotational motions of the Moon, to determine the orientation of the ecliptic and to produce Universal Time series UT0-UTC.

BACKGROUND

For many years our team has been involved in celestial mechanics studies, especially in the development of analytical solutions of lunar and planetary motions for the publication of solar system bodies ephemerides. Since 1997, we have cooperated with IERS in the determination of the ecliptic dynamical celestial reference frame, and we now produce Earth rotation parameters.

FACILITIES

The computing equipment consists of individual microcomputers connected to the DANOF local network (UNIX system), the entire computer background being managed by the Data Processing Department of the Paris Observatory. The two operational LLR stations, Grasse (France) and McDonald (Texas), send us their observations directly by e-mail.

ACTIVITIES

LLR stations provide normal points which can be considered as observations of the light time between a terrestrial transmitter, a lunar reflector and a receiver on Earth. The LLR stations providing data for our analyses are: McDonald, Texas (3 different locations over the span 1969-1999); Grasse, France (2 successive instruments at the same location over the span 1984-1999); and Mount Haleakala, Hawaii (over the span 1987-1990). The lunar reflectors are Apollo 11, Apollo 14, Apollo 15 and Lunakhod 2.

Two kinds of analyses have been performed:

- Global analyses of all the observations available from January 1972 till March 1999. They have allowed us to fit several lunar motion parameters, and the orientation of the mean ecliptic of J2000.0 with respect to the mean Celestial Ephemeris Pole (MCEP) of J2000.0 and to the International Celestial Reference System (ICRS);
- Nightly analyses, using the results of the global analyses, for the determination of Earth orientation parameters. Values of UT0-UTC and Variation Of Latitude (VOL) have been estimated from January 1995 through December 1998 using the observations of the two active LLR stations: McDonald (MLRS) and CERGA (Grasse).

Basis of the analyses

We use the solution ELP2000-96 for the orbital motion of the Moon. It results from the improved analytical theory ELP2000-82B plus numerical complement fit to the numerical integration DE245 (JPL, Pasadena, USA) as described in [*Chapront and Chapront-Touzé,* 1997]. The adopted solution of the libration is Moons' theory [1982, 1984] with analytical and numerical complements as described in [*Chapront et al.,* 1999a]. Both solutions are referred to the mean ecliptic of J2000.0 in the inertial sense as defined by *Standish* [1981]. In the global analyses, these solutions allow to fit orbital parameters of the Moon including the tidal secular acceleration, parameters of the free libration, and parameters of the Earth-Moon barycenter motion.

The selenocentric coordinates of the lunar reflectors are fit in the global analyses. The coordinates of the LLR stations in the International Terrestrial Reference System (ITRS) are derived from ITRF94 [*Boucher et al.,* 1996] in the global analysis, and ITRF96 [*Boucher et al.,* 1998] in the nightly analyses. They are corrected for the Earth's deformations due to tides and pressure anomalies following the recommendations of the IERS Standards 1992 [*McCarthy,* 1992].

In the global analyses, the transformation from the terrestrial coordinates of the stations (ITRS) to their instantaneous equatorial celestial coordinates is computed with the IERS values (x, y, UT1) of the Earth Orientation Parameters (EOP series C04). In the nightly analyses the transformation is expressed by means of two fitted parameters UT0 and VOL. In both cases, a relativistic correction for the conversion of space coordinates in a terrestrial reference system (TCG time coordinate) to space coordinates in a barycentric system with TDB time coordinate [*Martin et al.,* 1985], is added. The short period variations in x, y, and UT1-UTC are taken into account by Ray's method [*McCarthy,* 1996].

In the nightly analyses and in the global analyses yielding the orientation of the ecliptic with respect to the MCEP of J2000.0, the rotation from the celestial instantaneous axes to fixed celestial equatorial axes uses analytical theories of the precession and nutation. The precession is given by the expressions of *Williams,* [1994] with corrections to the precession and obliquity constants introduced by means of the derivatives of *Simon et al.,* [1994]. Those corrections are fitted parameters in the global analyses. The difference between the actual value of the precession constant and the IAU 1976 value is introduced in the expression of the Greenwich Sidereal Time [*Aoki et al.,* 1982], following the conclusions of *Williams and Melbourne,* [1982]. The ZMOA 1990 solution [*Herring,* 1991] is adopted for the nutation. In the analyses yielding the orientation of the ecliptic in the ICRS, the precession is given by the IAU 1976 expressions [*Lieske et al,* 1977] and the nutation is computed by adding to the IAU 1980 expressions [*Seidelman,* 1982] the corrections $d\psi$ et $d\varepsilon$ provided by IERS (EOP series C04).

The rotation from celestial equatorial coordinates to ecliptic coordinates involve two parameters: ε, the inclination of the inertial mean ecliptic of J2000.0 (fixed by ELP 2000-96) on the equatorial reference plane, and ϕ, the angle separating γ^{I}_{2000} (the ascending node of the ecliptic on the equatorial reference plane) from the origin o of right ascensions in the equatorial reference plane. γ^{I}_{2000} is the origin of longitudes in the ecliptic. The positions of the equatorial reference plane and o result from the terrestrial coordinates of the LLR stations and their transformation to celestial equatorial coordinates. So do ε and ϕ, which are fit in the global analyses, and γ^{I}_{2000}.

In all the analyses, we take into account the relativistic time scale correction between the dynamical barycentric time TDB and the Terrestrial Time TT [*Fairhead and Bretagnon,* 1990]. The relativistic deflection of the light propagation in the frame of the General Relativity theory is given by an approximate formula [*Chapront et al.,* 1999b]. We use the tropospheric corrections formulated by [*Marini and Murray,* 1973]. A correction of 0.7 ns has been added to CERGA observations from 1997/01/13 till 1998/06/24 in order to take into account a calibration offset mentioned by F. Mignard and J.F. Mangin (CERGA).

Results of the global analyses

We give here the results obtained in 1999 for the orientation of the inertial mean ecliptic of J2000.0 with respect to the frame tied to the mean Celestial Ephemeris Pole of J2000.0 (MCEP) and to the International Celestial Reference System (ICRS).

ε(MCEP)	=	23°26'21.40532" ± 0.00007"	ϕ(MCEP)	=	- 14.9 mas ± 0.3 mas
ε(ICRS)	=	23°26'21.41096" ± 0.00006"	ϕ(ICRS)	=	- 56.7 mas ± 0.2 mas

The separation between the two origins of longitude, derived from the comparison of the fitted lunar mean longitudes at the mean epoch of observations, is

γ^{I}_{2000}(ICRS) γ^{I}_{2000}(MCEP) = 45.4 mas ± 0.6 mas.

γ^{I}_{2000}(MCEP) is the inertial dynamical mean equinox of J2000.0.

The fitted correction to the IAU 1976 value of the precession constant is:

$\Delta p = -3.43 \pm 0.4$ mas/yr.

The post-fit residuals RMS over the time span 1987-1999 is estimated to 0.33 nanosecond for the light time "transmitter-reflector-receiver", which corresponds to an accuracy of about 5 cm for the one way range station-reflector.

As an example, Figure 7.2.2.1-1 shows the LLR CERGA residuals for the time span 1995-1998.

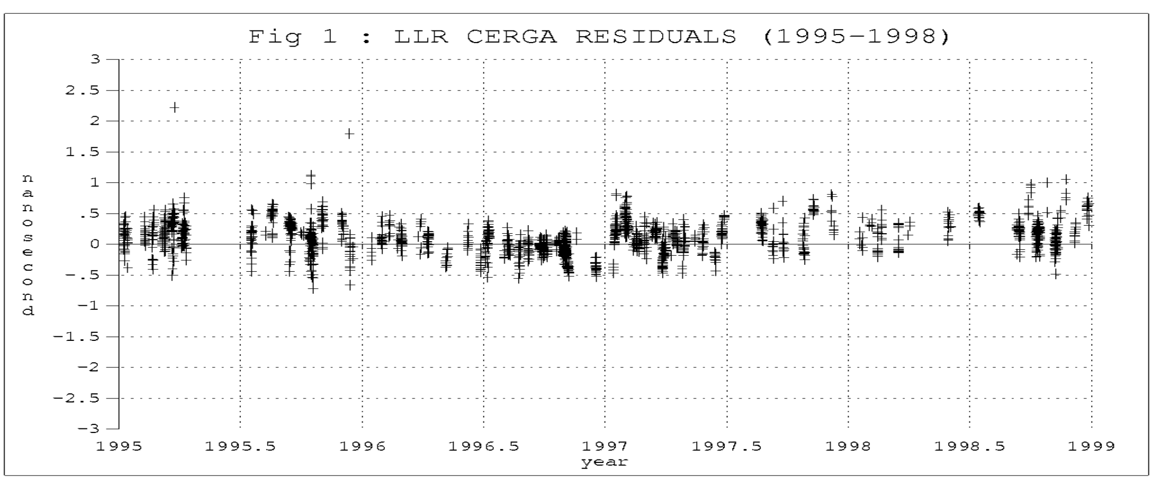

Figure 7.2.2.1-1 Determination of UT0-UTC and VOL

This determination is based on the analysis of a set of 2146 LLR observations (normal points) from Grasse (CERGA) and 1442 observations from McDonald (MLRS2) covering the time span from January 1995 till December 1998. The adopted coordinates of LLR stations, MLRS2 and CERGA, were derived from ITRF96 coordinates of the SLR stations at the same sites.

Disregarding negligible second order quantities, the determination of UT0-UTC and VOL are tied to the Earth rotation parameters UT1-UTC, x and y by the relations :

UT0-UTC = UT1-UTC + (x*sin(lambda) + y*cos(lambda)) * tan(phi)/(15*1.002737909)

VOL = x*cos(lambda) - y*sin(lambda)

UT1-UTC is measured in second of hour; (x, y) in second of degree; lambda is the station east longitude and phi is the geocentric latitude.

The couple of values (UT0-UTC, VOL) are determined by station and by reflector for the mean date of each night of observation. They are derived from the differences between observed and computed light times for each night/reflector by the least squares method with two iterations. No weights are assigned to the observations. The Apollo 15 reflector is the major contributor to the determination.

In the analysis, no *a priori* EOP values are introduced, but we take into account the variations of UT0-UTC and VOL during the night with the aid of approximate values of their derivatives estimated from IERS EOP during the previous lunation. We have rejected data from individual reflectors with less than 4 observations and those with just 4 observations in a night over a span shorter than 1.5 hour. We have also disregarded the results with formal uncertainties larger than 1 ms for UT0-UTC and 20 mas for VOL. These last circumstances are very rare.

Our numerical experiences show that an annual fitting of the lunar solution is sufficient to maintain this precision. Over the time span: 1995-1998, 323 values of (UT0-UTC, VOL) were produced, 172 values from CERGA observations and 151 values from MLRS observations. Figure 7.2.2.1-2 shows the differences between the UT1-UTC deduced from POLAC values (UT0-UTC, VOL) and those edited by IERS (EOP Series C04).

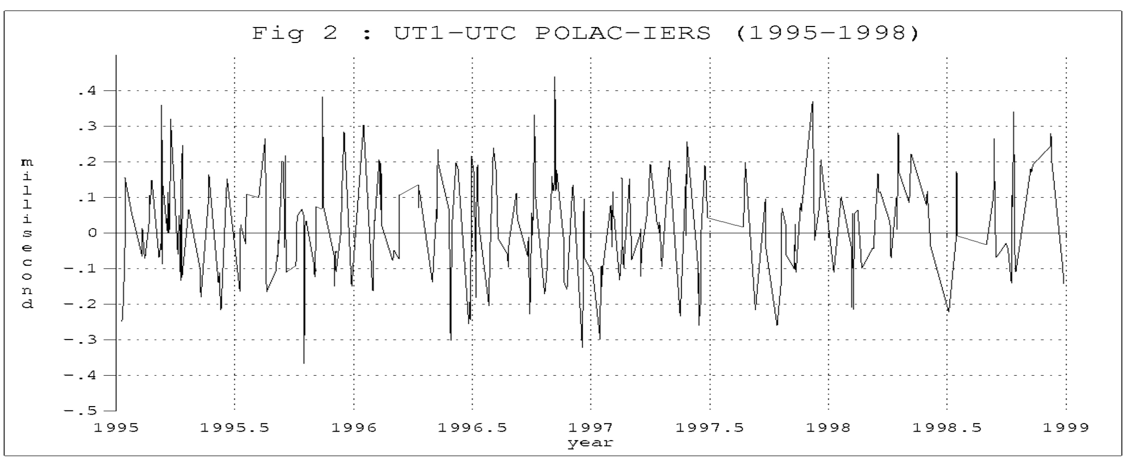

Figure 7.2.2.1-2 The precision of the determination is about 0.20 ms for UT0-UTC and 3.0 mas for VOL.

REFERENCES

Aoki S., Guinot B., Kaplan G.H. et al., Astron. Atrophys., 105, 359, 1982.

Boucher C., Altamini Z., Feissel M., Sillard P., IERS Technical Note n°20, Paris Obs, 1996.

Boucher C., Altamini Z., Sillard P., IERS Technical Note n°24, Paris Obs, 1998.

Chapront, J., Chapront-Touzé, M., Celest. Mech. 66, 31, 1997.

Chapront, J., Chapront-Touzé, M., Francou, G., Celest. Mech. 73, 317, 1999a.

Chapront, J., Chapront-Touzé, M., Francou, G., Astron. Astrophys. 343, 624, 1999b.

Fairhead L., Bretagnon P., Astron. Astrophys., 229, 240, 1990.

Herring, T.A., Proceedings of the 127th Colloquium of the IAU, J. A. Hughes, C.A. Smith and G.H. Kaplan eds, USNO, Washington D.C., p.157, 1991.

Lieske J.H., Lederle T., Fricke W., Morando B., Astron. Astrophys. 58, 1, 1977.

McCarthy D. D., IERS Technical Note n°13, Paris Obs, 1992.

McCarthy D. D., IERS Technical Note n°21, Paris Obs, 1996.

Marini, J.W. and Murray, C.W., NASA GSFC X-591-73-351, 1973.

Martin C.F, Torrence M.H., Misner L.W., J. Geophys. Res., 90, 9403, 1985.

Moons M., The Moon and the Planets, 27, 257, 1982.

Moons M., Celest. Mech., 34, 263, 1984.

Seidelmann P.K., Celest. Mech.. 27, 79, 1982.

Simon, J.L., Bretagnon, P., Chapront, J., Chapront-Touze, M., Francou, G., Laskar, J., Astron. Astrophys. 282, 663, 1994.

Standish, E. M., Astron. Astrophys. 101, L17, 1981.

Williams, J.G., Melbourne, W.G., O. Calame ed., High precision Earth precision and Earth-Moon dynamics, Reidel Publ. Comp., Dordrecht, p.283, 1982.

Williams, J.G., Astron. J. 108, 711-124, 1994.

KEY POINTS OF CONTACT

Authors: Jean Chapront, Michelle Chapront-Touze, Gerard Francou, Patrick Bidart

Address: Observatoire de Paris - Danof, 61 avenue de l'Observatoire, 75014 Paris, France

Contact: jean.chapront@obspm.fr

Server: Anonymous Ftp - danof.obspm.fr (directory: /pub/polac).

FUTURE PLANS

We shall continue to develop the lunar solutions. We plan to introduce the complete models recommended by the IERS Conventions of 1996, and expect to produce regularly values of UT0-UTC and VOL.

7.2.2.2 FESG/TUM

Jurgen Mueller, *Forschungseinrichtung Satellitengeodäsie*

INTRODUCTION/DATA PRODUCTS PROVIDED

At the FESG (Forschungseinrichtung Satellitengeodäsie = Research Facility for Space Geodesy), LLR data are analyzed once per year to provide a Set of Station Coordinates (SSC) in SINEX format as well as Earth Orientation Parameters (EOP) for the annual contribution to the ITRFxx and the IERS annual report, respectively. When solving for these parameters, a set of about 170 model parameters (without the EOPs) are estimated simultaneously in a so-called global standard solution. Thereby, the investigation of relativistic effects is of special importance.

Besides this routine procedure, further effects are investigated upon request, e.g. the correlation of some tidal parameters like h_2 or l_2 with the relativistic quantities (e.g. with the equivalence principle or Nordtvedt parameter η).

The parameter determinations are always based upon all LLR data available since 1970, about 13500 normal points which have an accuracy of about 1 cm in the Earth-Moon distance. The advantage of using data covering such a long time span (about 30 years) is that one is able to solve also for secular (e.g. the time variation of the gravitational constant dG/dt G^{-1}) and long periodic quantities (e.g. the coefficients of the 18.6 years nutation period). More details can be found in *Müller et al.* [1999].

BACKGROUND

The analysis of LLR observations started in the early 1980's when the basic modules of the LLR software were developed at the FESG. The whole software was intended to be consistent with Einstein's theory of gravity up to the first post-Newtonian level. In the Nineties, this software package was extended to be consistent with the *IERS Standards* [1989/1992] and the *IERS Conventions* [1996].

The main processes necessary for LLR analyses are the following ones:

- once per year (mostly in spring) the lunar observations from the last year are added and outliers eliminated;
- one software module computes the ephemerides of the main solar system bodies like Sun, Earth, Moon, planets and the major asteroids, covering the whole period since 1969 with intervals of about 8 hours;
- a second computer program calculates the dynamical partials, i.e. those which depend on the position of Earth, Moon and Sun (by far the most time consuming module);
- a third program performs the global parameter adjustment where improved values of the unknowns and the corresponding formal standard errors are obtained;
- the determination of VOL (variation of latitude caused by polar motion) and Earth rotation UT1 is performed by an additional module after the global parameter adjustment. There the post-fit residuals are analyzed.

Normally, the results can be improved by iterating steps b) through e) which is necessary because of the non-linear coupling of many model parameters (Figure 7.2.2.2-1 shows the post-fit residuals for 1999 where the final adjustment of VOL and UT1 was not performed yet).

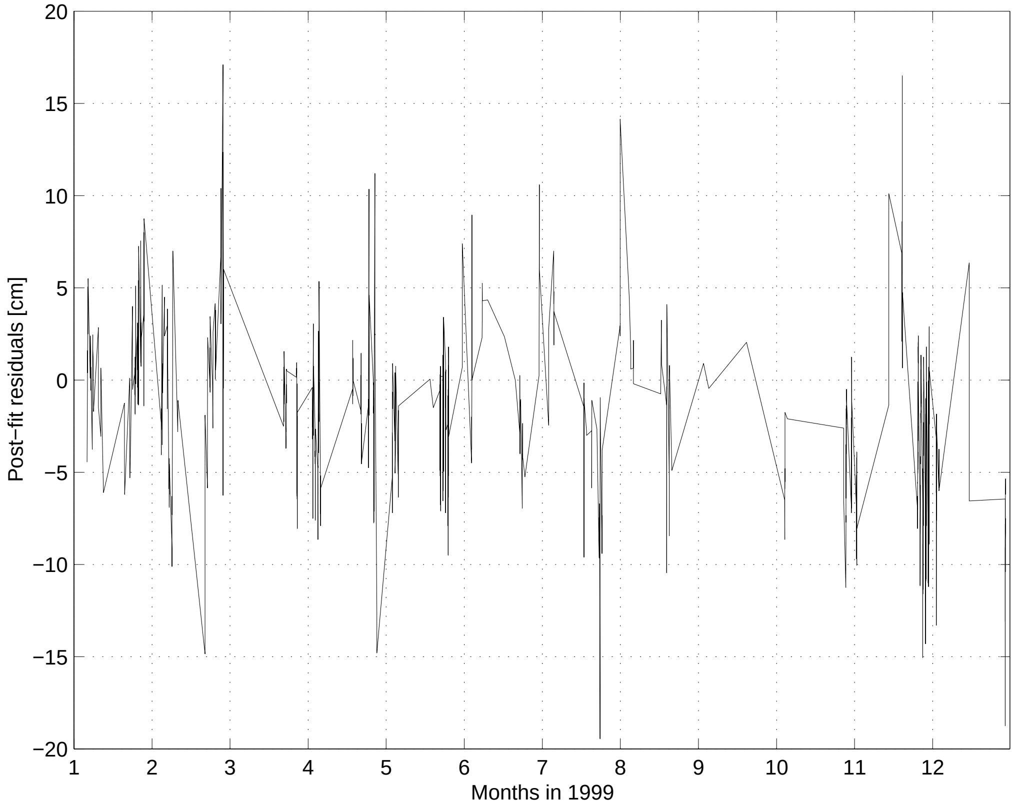

Figure 7.2.2.2-1: Post-fit residuals for 1999. The RMS is less than 4 cm.

In the global standard solution the solve-for parameters are geocentric coordinates of the observatories, selenocentric coordinates of the reflector arrays, physical librations of the Moon, initial values of the lunar orbit, initial values of the Earth orbit, lunar gravity field up to degree and order 3, the mass of the Earth-Moon system, the Love number of the Moon and a dissipative parameter, the lunar tidal acceleration (responsible for the increase of the Earth-Moon distance of about 3.8 cm/year), a correction to the luni-solar precession constant, the coefficients of the 18.6 years nutation period and others. The EOPs 'VOL' and 'UT1' are computed from the post-fit residuals using the daily decomposition method [*Dickey et al.,* 1985], i.e. correlations with the parameters of the standard solution are neglected. However, a new iteration with these improved EOPs may be started once again.

After the iterative procedure has converged, more tiny effects of special interest are investigated, e.g. quantities parametrizing relativistic effects like metric parameters γ and β, the geodetic precession of the lunar orbit, the Nordtvedt parameter (a test of the strong equivalence principle), the time variation of the gravity constant, the Yukawa coupling constant (a test of Newton's inverse square law for the Earth-Moon distance), the validity of the equivalence principle for dark matter assumed in the center of the galaxy or metric parameters indicating a possible presence of preferred frames or directions (in contradiction to special and general relativity).

FACILITIES/SYSTEMS

The software used for computing steps b) through e) as described in the last section, has been coded in FORTRAN from the very beginning. The main work has been done within three Ph.D. theses, written in German [*Gleixner,* 1986; *Bauer,* 1989; *Müller,* 1991]. The FORTRAN programs are running on a DEC Alpha work station. A C-version of the ephemeris program has also been written. In the last few years, a formulation of the whole LLR analysis package was developed in C^{++}. It was coded in another Ph.D.

thesis [*Reichhoff,* 1999], but could not be completed because our colleague died in April 1999 - a big loss for our group. The latter tool is running on a commonly used PC under UNIX. The standard solutions are presently computed using the FORTRAN software package.

The computer time including the calculation of the dynamical partials (which do not always have to be computed) takes about 1 hour per iteration for the whole period of 30 years, and below 20 minutes without calculating new partials.

CURRENT ACTIVITIES

At the moment, the LLR model is being improved with the help of a graduate student. The solid Earth tide model is being updated using the model of *Mathews et al.* [1997]. Along with the updated model, we are investigating the potential of LLR to determine tidal parameters. The capability of our recent LLR software to obtain a good result of e.g. the Love number h_2 (based upon the old model), is limited because the description of the effect does not consider the frequency-dependence in an appropriate way.

Then the velocities of the continental plates, on which the observatories are located, are estimated, where the best constraining procedure has still to be identified. The goal is to achieve sufficient quality of the LLR products, especially the SSC, that they can be used in the ITRF realizations without difficulty. In the last few years, the overconstraining of site velocities was often the reason for the rejection of the LLR result from the final ITRF solution. When computing the standard solution for the IERS Annual Report, the relativistic parameters are also estimated. In our most recent solution, given in Table 7.2.2.2-1, the realistic errors are indicated. These exceed the formal errors by a factor of 2 to 10, depending on the parameter.

Parameter	Results
difference of geodetic precession Ω_{GP} - Ω_{deSit} [″/cy] (1.92 ″/cy predicted by Einstein's theory of gravitation)	$(-2 \pm 10) * 10^{-3}$
metric parameter γ - 1 (space curvature; $\gamma = 1$ in Einstein)	$(4 \pm 5) * 10^{-3}$
metric parameter β - 1 (non-linearity; $\beta = 1$)	$(-1 \pm 4) * 10^{-3}$
Nordtvedt parameter η (violation of the strong equivalence principle)	$(8 \pm 9) * 10^{-4}$
time variable gravitational constant dG/dt G^{-1} [yr^{-1}] (-> unification of the fundamental interactions)	$(3 \pm 5) * 10^{-12}$
Yukawa coupling constant $\alpha_{\lambda=4*10^5 km}$ (test of Newton's inverse square law for the Earth-Moon distance)	$(2 \pm 2) * 10^{-11}$
special relativity ζ_1 - ζ_0 - 1 (search for a preferred frame within special relativity)	$(-5 \pm 12) * 10^{-5}$
influence of dark matter δg_c [cm/s^2] (assumed in the center of the galaxy; test of strong equivalence principle)	$(4 \pm 4) * 10^{-14}$
preferred frame effect α_1 (search for a preferred frame within general relativity)	$(-8 \pm 9) * 10^{-5}$
preferred frame effect α_2	$(-1.2 \pm 2.5) * 10^{-5}$

Table 7.2.2.2-1: Relativistic parameters and their realistic errors.

A further activity of the last year was a test whether the annual geocenter motion can be determined from the analysis of LLR data. We obtained good results, comparable to those of other techniques as given in *IERS Technical Note 25* [1999], whereas we did not achieve as good an agreement with the theoretical values as did SLR. We did obtain an improvement in the accuracy of the equivalence principle parameter η which was expected by Ken Nordtvedt [*private communication,* 1999], because there is a projection of the annual signal into the synodic one.

We performed a test where we fixed $GM_{Earth+Moon}$ taking GM_{Earth} from a current SLR solution. We obtained encouraging results, but these investigations are still under way. It is also a question of general strategy whether one should fix as many or as few parameters as possible.

To simplify the identification of the real lunar returns from the raw noisy measurements as obtained in Wettzell, we have started to use variable intervals in the histogram representation which can additionally be shifted by the half of the bin's width. This work is still ongoing.

KEY POINTS OF CONTACT

The FESG is the owner of the software, however, most of the analyses are performed by Jürgen Müller (Institute for Astronomical and Physical Geodesy, Technical University Munich) who is also member of the ILRS/AWG. The death of Burkard Reichhoff, who had coded the LLR software completely in C^{++}, was a harsh blow for the FESG activities. Furthermore the leadership of FESG changed in September 1999. Markus Rothacher, member of the IGS Governing Board, succeeded Manfred Schneider. Our LLR team is completed by Ulrich Schreiber, who struggles to get LLR returns in Wettzell, and Dieter Egger, who takes care of the lunar predictions and is a specialist on computer and software related topics.

In our work we orient ourselves at the recommendation of the ILRS/AWG and the IERS Conventions. Concerning relativistic topics, we have good cooperation with Ken Nordtvedt, David Vokrouhlicky (Univ. Prague) and Michael Soffel (Univ. Dresden). Concerning principle questions of LLR analysis, there is a good (e-mail) contact between all Lunar Analysis Centers and with the staff at the observatories. For example, the Grasse LLR Observatory changed its strategy for calculating the errors of the normal points in January 1999, and circulated this information well before that date so users could be prepared.

FUTURE PLANS

Our LLR plans comprise all activities from the investigation of the raw lunar observations to the computation of realistic errors of the estimated LLR parameters.

As mentioned above, we started to improve our software for the detection of the real lunar returns from the raw observations which are very noisy. We want to use the semi-train structure for separating the noise and the real measurements (two students are working on this topic). If we are successful we want to standardize and automate the computation of the normal points.

We are also trying to automate the procedure for the generation of the standard solution which is used for the ITRF and IERS annual submissions. These are the steps described in the 'Background' section. In this respect, we have to take care to ensure the consistency of the LLR system and LLR products with those of the other space geodetic techniques. As a by-product, we have to improve our modeling, e.g., of the lunar gravity field, the lunar tidal acceleration with more periods or atmospheric loading and so on.

We will continue the relativistic investigations which are mainly driven by Ken Nordtvedt at the moment, in so far as new ideas to be tested are concerned.

We want to make sure that the potential of LLR is further acknowledged as an important tool not only for relativity tests, but also for the determination of many classical parameters.

In any case we should be prepared for a renaissance of lunar missions like the planned Japanese mission SELENE II, where transponders are deployed on the surface of the Moon which should enable many pure SLR stations to observe the Moon. Moreover, in the case of co-location of microwave transponders, the connection to the VLBI system may become possible which will open a wide range of further activities (e.g. frame ties).

Unfortunately at moment, we have received almost no financial support for LLR analysis. However, we have great motivation and enthusiasm (mainly produced by the potential of good results), and we have the software in-house. So let's do it!

REFERENCES

Bauer R.: DGK C, No. 353, München 1989.

Dickey J, Newhall X., Williams J.: JGR, Vol. 90, No. B11, P. 9353-9362, 1985.

Gleixner H.: DGK C, No. 319, München 1986.

IERS Standards (1989), IERS Technical Note 3, ed. by D. McCarthy, Paris 1989.

IERS Standards (1992), IERS Technical Note 13, ed. by D. McCarthy, Paris 1992.

IERS Conventions (1996), IERS Technical Note 21, ed. by D. McCarthy, Paris 1996.

IERS Analysis Campaign to Investigate Motions of the Geocenter, IERS Technical Note 25, ed. by J. Ray, Paris 1999.

Mathews P., Dehant V., Gipson J.: JGR, Vol. 102, No. B9, P. 20,469-20,477, 1997.

Müller J.: DGK C, No. 383, München 1991.

Müller J, Nordtvedt K., Schneider M., Vokrouhlicky D.: BKG, Band 10, P. 216-222, 1999.

Reichhoff B.: DGK C, No. 512, München 1999.

7.2.2.3 JET PROPULSION LABORATORY

Jim Williams and Jean Dickey, *Jet Propulsion Laboratory*

INTRODUCTION/BACKGROUND/DATA PRODUCTS PROVIDED

Analyses of laser ranges to the Moon are utilized for a broad range of investigations: lunar science, gravitational physics, geodesy, geodynamics and astronomy. Unique contributions from LLR include detection of a molten lunar core; measurement of tidal dissipation in the Moon; an accurate test of the principle of equivalence for massive bodies (strong equivalence principle); and detection of lunar free librations. LLR analysis has provided tests of relativity, measurements of the Moon's tidal acceleration and the Earth's precession, and has provided orders-of-magnitude improvements in the accuracies of the lunar ephemeris and three-dimensional rotation. JPL has been active in all of these various LLR applications and supplies lunar and planetary ephemerides and lunar physical librations to the community.

CURRENT ACTIVITIES

Our LLR analysis efforts have been focused on gravitational physics, including tests of general relativity, and studies of the lunar interior. Part of Abstract #2018 of the Lunar and Planetary Science Conference XXXI, March 2000 is given below; the reader is referred to LPSC Abstracts for the full text.

LUNAR POWER DISSIPATED BY TIDES AND CORE-MANTLE INTERACTION

J. G. Williams, D. H. Boggs, J. T. Ratcliff, C. F. Yoder and J. O. Dickey
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA,
91109 (e-mail James.Williams@jpl.nasa.gov)

Introduction: Geophysical properties of the lunar interior are required to compute the dynamical contribution to the moon's heating. The heating is connected to development of solid convection in the mantle, fluid convection in the core, and generation of a lunar magnetic field.

Analysis of Lunar Laser Ranging data provides one opportunity to determine the moon's geophysical properties. Many lunar parameters, including bulk elastic and rotational dissipation parameters, are detected through their influence on lunar rotation. The Lunar Laser Ranging effort is reviewed in[1].

Dissipation Analysis: The present day 3.82±0.07 cm/yr expansion of the lunar orbit[1] is dominated by tidal dissipation on the earth, but is slightly affected (~1%) by dissipation in the moon. Dissipation effects in the moon are detectable through their influence on lunar rotation. Hence, sources of dissipation in the earth and moon are separable.

A study of dissipation signatures in the lunar rotation finds two sources of dissipation in the moon: solid-body tides and a molten-core/solid-mantle interaction[2, 3]. Tidal Q vs. frequency is determined; at 1 month the tidal Q is 37 and at 1 yr it is 60. The liquid core detection exceeds three times its uncertainty. The spin of the core is not aligned with the spin of the mantle and torque and energy dissipation arises from the velocity difference at the boundary. Yoder's turbulent boundary layer theory[4, 5] is used to compute the core radius. The core radius is equal to less than 352 km for molten iron and is equal to less than 374 km for the Fe-FeS eutectic. Independent evidence for a (solid or liquid) core is presented in6.

REFERENCES

[1] Dickey et al. (1994) Science, 265, 482-490.

[2] Williams J G et al. (1999) Abstracts of Lunar and Planetary Science Conference XXX, Abstract No. 1984.

[3] Williams J G et al. (2000) in preparation.

[4] Yoder C. F. (1981) Phil. Trans. R. Soc. London A, 303, 327-338.

[5] Yoder C. F. (1995) Icarus, 117, 250-286.

[6] Konopliv A. S. et al. (1998) Science, 281, 1476-1480.

RECENT ABSTRACTS

Williams, J. G., D. H. Boggs, C. F. Yoder, J. T. Ratcliff and J. O. Dickey, Lunar Dissipation in Solid Body and Fluid Core, Eos Transactions of the Amer. Geophys. Union 79, F546, 1998.

Williams, J. G., D. H. Boggs, J. T. Ratcliff, and J. O. Dickey, The Moon's Molten Core and Tidal Q, Abstracts of the Lunar and Planetary Science Conference XXX, abstract #1984, 1999.

J. G. Williams , D. H. Boggs, J. T. Ratcliff, C. F. Yoder and J. O. Dickey, A View of the Lunar Interior Through Lunar Laser Ranging, abstract for New Views of the Moon II, Flagstaff, Sept 22-24, 1999.

J. G. Williams, P. J. Shelus, D. H. Boggs, J. O. Dickey, J. T. Ratcliff, and J. G. Ries, The Multidisciplinary Lunar Laser Ranging Experiment, abstract for Fall AGU Meeting, December 13-19, 1999.

J. G. Williams, D. H. Boggs, J. T. Ratcliff, C. F. Yoder and J. O. Dickey, Lunar Power Dissipated by Tides and Core-Mantle Interaction, Abstracts of the Lunar and Planetary Science Conference XXXI, abstract #2018, March 13-17, 2000.

KEY POINTS OF CONTACT

Name	Email	Telephone No.
James G. Williams	James.G.Williams@jpl.nasa.gov	(818) 354-6466
Dale H. Boggs	Dale.H.Boggs@jpl.nasa.gov	(818) 354-1630
Jean O. Dickey	Jean.O.Dickey@jpl.nasa.gov	(818) 354-3235
J. Todd Ratcliff	James.T.Ratcliff@jpl.nasa.gov	(818) 354-0204

All Key Points of Contact can be reached at:

Jet Propulsion Laboratory
Mail Stop 238-332
4800 Oak Grove Drive
Pasadena, CA 91109-8099
FAX: (818) 393-6890

FUTURE PLANS:

Investigation of lunar science and relativity utilizing LLR data; LLR analysis and lunar ephemeris and libration development.

ACKNOWLEDGMENT:

This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

7.2.2.4 UNIVERSITY OF TEXAS

Judit Ries, *University of Texas*

INTRODUCTION

The University of Texas McDonald Observatory Lunar Analysis Center (UTXM) is operating within the Department of Astronomy of the University of Texas at Austin, in conjunction with the McDonald Laser Ranging Station (MLRS) near Ft. Davis Texas. The Center has been providing weekly/monthly Earth

Orientation Parameters (EOP) since 1989 and also provides predictions for lunar data acquisition. It also acts as data quality controller for MLRS. Our goals are to develop a technique to improve the quality of marginal LLR data and to improve the quality of our EOP series.

BACKGROUND

The LLR team in Texas has been involved with the acquisition and the analysis of LLR data since the birth of the technique. Before on site normal point production became a routine, the Austin team filtered the data and created and distributed the normal points. It was a natural step to start to use this data and produce an EOP series.

FACILITIES

The EOP series and the lunar orbits are computed on a Sun workstation using a UNIX operating system, at the Department of Astronomy, using. The main software is the MIT Planetary Ephemeris Program (PEP) for the integration of the lunar orbit and for parameter estimation. The Lunar data is provided by the MLRS crew through the Internet, and we directly receive OCA LLR data by e-mail, courtesy of the French LLR station at Grasse.

CURRENT ACTIVITIES

Laser ranging is the measurement of the round-trip travel time of a photon, which is emitted from an Earth-based laser and reflected from one of the corner cubes placed on the lunar surface. Travel times at MLRS can be measured to 50-psec resolution. Changes in travel the times, that is changes in the separation between the transmitter and the reflector, contain a great deal of information about the Earth-Moon system that can be retrieved by estimating model parameters.

The analysis process

Lunar normal points are available to analysts since September 1969. They were obtained by the McDonald Observatory 2.7m telescope (which ceased operation in 1985), the McDonald Laser Ranging Station (saddle site and Mt. Fowlkes site) near Fort Davis, Texas, the Haleakala Observatory on Maui, Hawaii (which ceased operation in 1990) and the Observatoire de Cote d'Azur station in Grasse, France. We include all this data in our analysis. There are also a few normal points from Wettzell (Germany) but due to the limited quantity, it is included only with zero weight. We estimate various global parameters for the whole span of the lunar data. However, after these adjustments, the nightly residuals still show some signature. Assuming this is due to UT1R error in the *a priori*, we estimate nightly UT0 and Variation of Latitude ($\Delta\phi$) corrections. (For our weekly/monthly EOP series we convert this into UT1, X and Y values, using the *a priori* polar motion values.)

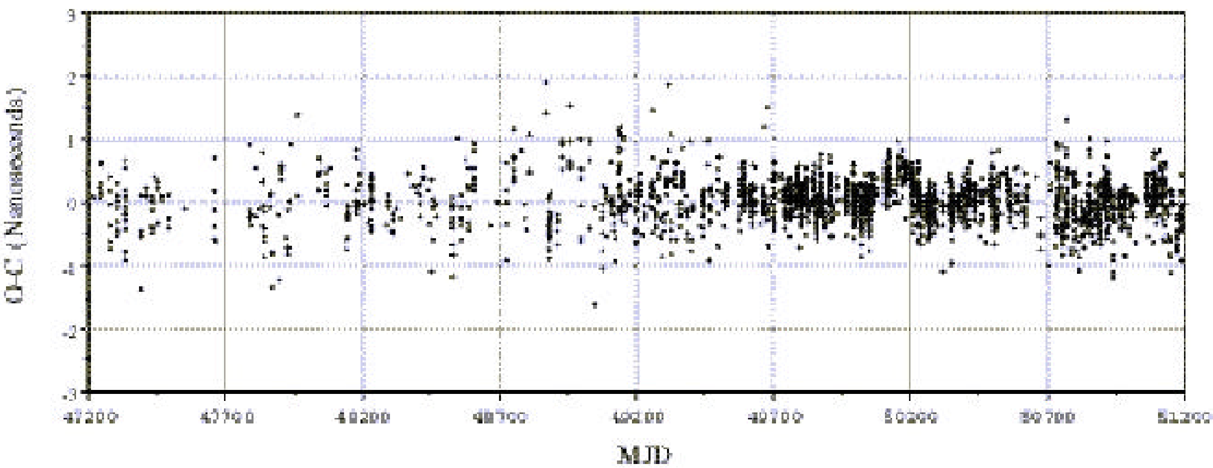

Figure 7.2.2.4-1. 2403 MLRS residuals (from all retro-reflectors) from February 1988 to December 1999

Our lunar orbit is based on the nbody740.2020 solar system ephemeris, provided by J. Chandler (CFA, Precision Astrometry Group). Using the LLR data, we adjust a number of global parameters. These include the GM of the Earth-Moon system, the orbit of the Moon, the EMbary orbit (with the exception of the node), lunar libration parameters, and third order gravitational coefficients of the Moon. The reflector and the station coordinates are also estimated with range biases for all the stations. The nutation amplitudes and the precession constant are also adjusted. Furthermore, we estimate a piecewise continuous linear spline for UT1R to model long period deficiencies in the *a priori* time series. The data is weighted according to the normal point uncertainty. The station assigned uncertainties are scaled by PEP. The resulting fit of the data from the Mt. Fowlkes site is shown on Figure 7.2.2.4-1. The mean of the data is $1.7x10^{-2}$ nsec with 0.37 nsec RMS about the mean. The nightly signature is due to UT1R error in the smoothed *a priori* series we use, which is a combination of early optical series and the modern LAGEOS based EOP series, provided by the Center for Space Research at UT. For nights with sufficient data we can remove this signal. The new mean is $-2.8x10^{-3}$, and the RMS is 0.28 nsec, illustrated on Figure 7.2.2.4-2. This corresponds to about 4.2 cm accuracy for the one way range.

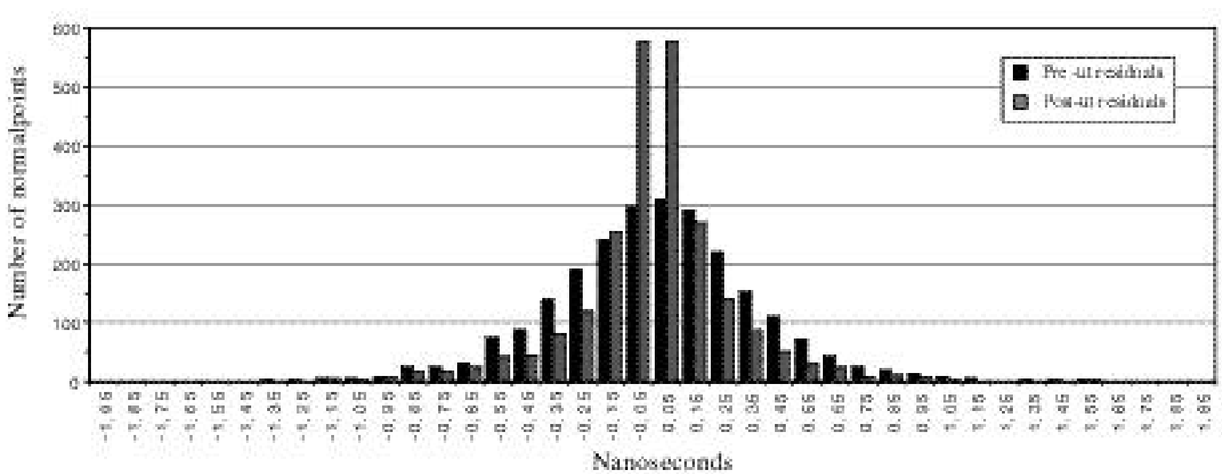

Figure 7.2.2.4-2 The distribution of the pre- and post UT0-UTC determination of MLRS residuals

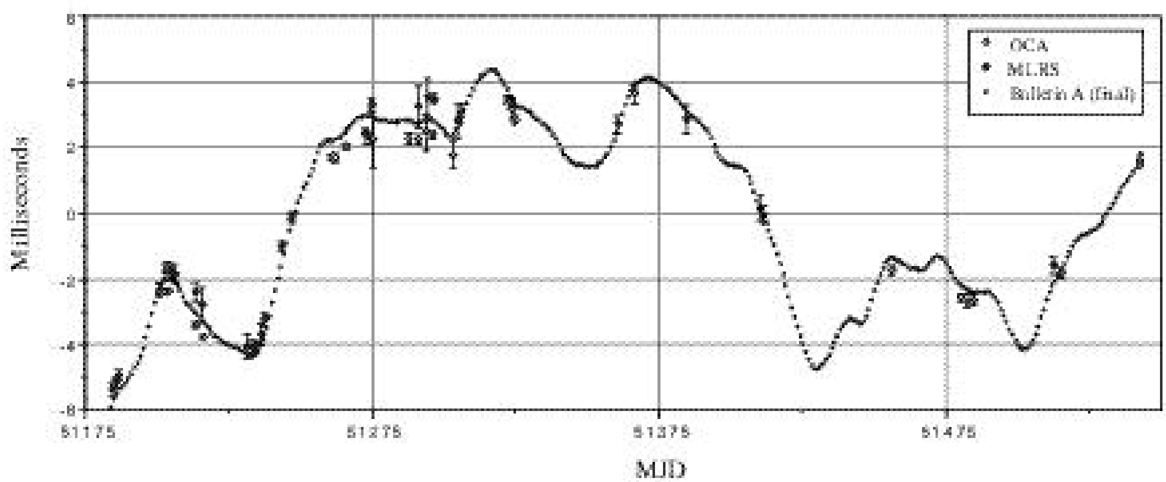

Figure 7.2.2.4-3. UT2-TAI with -1.013 msec/day slope removed (January 1 - December 31, 1999)

We provided a total of 54 UT0 -UTC values in 1999, 27 from OCA and 27 from MLRS reflector 3 (Hadley, Apollo 15), data. Only nights with at least 3 normal points and at least 1.5 hours span were accepted, and UT0 - UTC and $\Delta\phi$ were calculated using an iterative least square analysis. Figure 7.2.2.4-3 demonstrates the stochastic changes in the Earth rotation compared to a uniform time standard. It also compares our results with IERS Bulletin A EOP series. The actual products of our analysis are UT0 - UTC and $\Delta\phi$, which need to be converted using:

$$\text{UT0 - UTC} = \text{UT1 - UTC} + (X \sin\lambda + Y \cos\lambda) \tan\phi/15$$

$$\Delta\phi = X \cos\lambda - Y \sin\lambda$$

and

$$\text{UT2 - UT1} = 0.022 \sin(2\pi T) - 0.012 \cos(2\pi T) - 0.006 \sin(4\pi T) + 0.007 \cos(4\pi T)$$

$$T = 2000.000 + (\text{MJD} - 51544.03)/365.2422 \text{ (Besselian years)}$$

The corresponding units are seconds for UT0 - UTC, seconds of arc for X and Y, λ and $\Delta\phi$ are the station's East longitude and geodetic latitude.

RELATED PUBLICATIONS

Aoki, S., Guinot, G. H., Kaplan, H., Kinoshita, D. D., McCarthy, and P. K. Seidelmann, (1982). "The New Definition of Universal Time", Astron. Astrophys. 105, 359-361.

Eanes, R. J. and M. M. Watkins, CSR95L01 Solution, The 1994 IERS Annual Report, Observatoire de Paris, France, 1995.

Explanatory Supplement to IERS Bulletins A and B, March 1999

Jefferys, W. H. and J. Györgyey Ries, Bayesian analysis of lunar laser data, in Statistical Challenges in Modern Astronomy II, G. J. Babu and E. D. Feigelson (eds), 49-62, Springer Verlag, 1997.

Ricklefs, R. L. and P.J. Shelus, Poisson filtering of laser ranging data, in Proceeding of the Eighth International Workshop on Laser Ranging Instrumentation. Annapolis: NASA conference Publication 3214, 1992.

Stolz, A., P. L. Bender, J. E. Faller, E. C. Silverberg, J. D. Mulholland, P. J. Shelus, J. G. Williamson, W. E. Carter, D. G. Currie and W. M. Kaula, Earth rotation measured by lunar laser ranging, Science, 193, 997-999, 1976

UT0 and Variation of Latitude Determination from Lunar Laser Ranging Observations for 1969-1998,Ries, J. Györgyey, R. L. Ricklefs, P. J. Shelus, J. R. Wiant, 1998 IERS Annual Report, Observatoire de Paris, France, 1999.

KEY POINTS OF CONTACT

Author: Judit Györgyey Ries

Address: The University of Texas at Austin, Austin, TX 78712, USA

Contact: moon@astro.as.utexas.edu

FUTURE PLANS

We will continue to provide monthly and annual EOP series to the community, while improving the quality and the stability of our solution. We have shown with simulated lunar data that we can recover data considered marginal with the application of Bayesian statistics. We hope to work on applying this method to real data.