SECTION 7 - ANALYSIS CENTER REPORTS

7.1 SATELLITE LASER RANGING

7.1.1.0 ANALYSIS CENTERS INTRODUCTION

Peter Dunn, *Raytheon ITSS*

The Analysis Centers continuously refine their techniques for processing information from the Data Centers and regularly make the results of their analysis available to ILRS participants. The Centers deliver standard products to the Global Data Centers and to the IERS, among other recipients, and 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 has now completed the preparation of a new system based upon the ITRF2000 terrestrial reference frame on which to base their weekly analysis of LAGEOS-1 and LAGEOS-2. This information is also accessible, together with CSR 3-day EOP values via the web and anonymous ftp. They will continue to provide the CSR9501 system EOP values which NASA uses 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, LAGEOS-2 and ERS-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. During 2001, SLR data analysis activities at the ASI Space Geodesy Center "G. Colombo" (CGS) have continued to study tectonic plate motion, Earth rotation and polar motion, time variations of the Earth s gravitational field and satellite orbit determination. The realization of reference frames and the combination of geodetic solutions represented the primary interest of the analysis. The study of satellite rotation, in particular, by spectral analysis of the MLRO full rate data, has produced estimates of LAGEOS-2 rotation period and slow-down rate. 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 soon after the end of the observation day and thus can provide rapid feedback on the quality of the SLR observations.

The Central Laboratory of Geodesy (CLG) at the Bulgarian Academy of has developed a satellite orbit determination and parameter estimation software (SLRP). The Center employs the processor to provide global geodetic SLR solutions to the IERS and ITRF section of the IGN. Information about the CLG and the SLR analysis activity will be soon available on the web-server under construction in the Laboratory. CRL has developed the orbit analysis software package CONCERTO written in Java, which was used to conduct most of their 2001 activities. The Center has continuously been involved in the SSC/EOP pilot projects driven by the ILRS Analysis WG. Future plans include an extension of their satellite signature studies to derive systematic dependence of the center-of-mass corrections of spherical geodetic satellites.

The DGFI in Munich employs the software package DOGS (DGFI Orbit and Geodetic Parameter Estimation Software) for routinely high precision processing of SLR tracking data for station coordinates, EOP’s and geopotential coefficients. They plan to extend routine processing and analysis to other satellites, such as Ajisai and Starlette in the future. The Russian Academy of Science s IAA Associate Analysis Center continues to regularly submit EOP operational and final solutions to the IERS. Global fitting of the LLR observations have also been analyzed to determine corrections to UT0 and verify whether LLR is a viable component of EOP monitoring. The NASDA Associate Analysis Center has been routinely processing Ajisai, LAGEOS-1, LAGEOS-2 and LRE data for precise orbit determination, station coordinates, Earth orientation parameters and SLR station performance monitoring for some time. Plans are underway to establish a procedure for ADEOS-II in routine operation and preparation for ADEOS-II launch operation. 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 conducted an accurate calibration of the French Transportable Laser ranging station as well as the Grasse Lunar Laser Ranging station.

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, and continuously improves the GEOSAT software used for the analysis. 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 generating weekly SINEX following ILRS-adopted standards. The Department of Geomatics at Newcastle University has been active in space geodetic research for over a decade. Their current ILRS activities include precise orbit determination of altimetric and geodetic satellites utilizing SLR, DORIS, PRARE and altimetry in the form of single and dual satellite crossovers. Their combination solution approach for GPS and SLR coordinates is being extended to Earth rotation parameters. The Geoscience Australia Associate Analysis Centre has been routinely processing LAGEOS-1 and LAGEOS-2 data for satellite orbit determination, station coordinates, Earth Orientation Parameters and SLR station performance monitoring. In addition, on an opportunity or project basis, Stella, Starlette and Etalon data is also processed.

The automatic service at the NERC SLR facility at Herstmonceux and Monks Wood, UK was considerably upgraded during the year, to include more satellites and short-arc analyses for the whole Network. Their work suggests that an improvement in the quality of the precise orbits of the GLONASS satellites in particular could be achieved by incorporating SLR data into their derivation. The central task of the BKG geodetic division is to provide and update the Geodetic Reference Networks of the Federal Republic of Germany, and continues to participate in the ILRS pilot projects. Satellite orbits, station position and velocities, EOP solutions, geo-centre and GM variations are produced on a regular basis to contribute to the IERS and other services.

In 2001, the GeoForschungsZentrum (GFZ) Potsdam continued its ILRS activities of the previous years. The main focus was again on the routine provision of high quality predictions for the ERS-2 and CHAMP satellites. The launch of the GRACE satellite in 2002 will add two new satellites to the prediction work, and will allow a much more precise determination of the gravity field of the Earth. The Navigation Support Office of the European Space Operation Centre (ESOC) provides high-precision orbit data for ESA s Earth observation missions, such as ERS-1, ERS-2 and the future ENVISAT mission (launched March 1, 2002). Future plans include the processing of data for all current and future ESA satellites equipped with a LRR array (e.g. CryoSat, GOCE), and in test mode for a number of non-ESA LEO missions, such as Jason.

7.1.1.1 CENTER FOR SPACE RESEARCH (UT/CSR)

Richard J. Eanes, John C. Ries, Minkang Cheng, *University of Texas Center for Space Research*

CURRENT ACTIVITIES

Weekly EOP estimation and SLR Network Quality Control

Although our routine weekly analysis of LAGEOS-1 and LAGEOS-2 continues to use the CSR95L01 system of models and station positions for EOP estimation and SLR residual analysis, we have now completed the preparation of a new system based upon the ITRF2000 terrestrial reference frame. The improved station positions and models of the new system allow significant improvements in the quality of the resulting EOP and in our ability to detect small systematic errors in the ILRS normal points. We will soon begin to report results using the new system while continuing to provide 9501 system EOP to the TOPEX/Poseidon POD team during a short transition period.

As we developed plans for the new CSR system, the ILRS network successfully implemented an hourly distribution cycle for ILRS range normal points. This success convinced us that automation of the new system was feasible and that the improved timeliness of the hourly LAGEOS normal points might once again allow a significant contribution of SLR to the IERS rapid service product, Bulletin-A. Achieving this goal is difficult due to the high quality and timeliness of the IGS Rapid Service product and its automated use by USNO to compute daily EOP estimates and predictions. Based on successful tests of the new procedures made during the last two months, we are confident that the benefits of automation have justified the required effort and will soon begin daily distribution of EOP results in the new system

The automation is accomplished via sequences of Unix shell scripts activated using the Unix cron utility. First we download the most recent two days of hourly ILRS NP files from both the CDDIS and GFZ data centers. The hourly files are then supplemented with the daily files created at both ILRS data centers in order to minimize the chance of missing any data. When the update of our normal point archive is completed the main analysis script begins the required orbit computations. For our initial tests the analysis script was configured to process the data for three pairs of SLR targets (LAGEOS-1/2, TOPEX/Jason-1, and GRACE-1/2) at six hour intervals. If the need arises the procedure can be easily be extended to include other satellites. We believe that increased use of multiple targets will be one of the most productive ways to extend the set of useful ILRS products. A relevant example is the combined use of SLR data and GRACE data to obtain improved results for the variations of low degree gravitational coefficients (n=2,3,4). This will also allow the GRACE results to be tied in to the much longer record that SLR techniques have provided.

Using the CSR95L01 models, the weighted RMS of range residuals computed in 3-day arcs has typically been 15-25 mm in the last several years. Comparable fits in the new system are now between 6 and 12 mm as shown in Figure 7.1.1.2-1. Figure 7.1.1.2-2 illustrates one of the benefits of the improved system by documenting the detection of a small error in the time-tags of normal points from the Graz observed during a four-day span in early 2000. To our knowledge this problem has not been previously reported even though its impact (if not corrected) on our EOP product is easily noticed. Graz observations of LAGEOS-1 and LAGEOS-2 are given the largest possible weight in our analysis because of their abundance, regularity and high quality (Graz is, in our opinion, the SLR system least likely to have a problem). Sub-decimeter level problems at key stations can sometimes be quite difficult to distinguish after orbital and geodetic parameters are adjusted, hence any improved problem detection capability is valued.

The LAGEOS-1 spin-rate is now quite small, and large variations in the orientation of the spacecraft s spin axis are now common. As a result, modeling the LAGEOS-1 orbit at the sub-centimeter level is becoming increasingly more difficult. In fact, the short duration of nearly 20 mm RMS of LAGEOS-1 residuals (but not LAGEOS-2) evident in Figure 7.1.1.2-1 is due a 10 to 100-fold increase in the size of the average along-track acceleration which we routinely adjust every three days. This latest LAGEOS-1 acceleration anomaly only lasts a few days centered on April 05, 2002 just before the peak of the eclipse period. It is likely that this type of event occurs when the LAGEOS-1 spin axis and the Sun are aligned in a way that maximizes the size of the resulting thermal forces and fails to average down over each orbit. In response, we now estimate daily along-track acceleration corrections for LAGEOS-1. This unfortunate situation will probably only get worse and may soon require the development of a better parameterization of anomalous spacecraft accelerations.

The LAGEOS-1/2 near-real-time daily EOP solutions are easily better than the 3-day LAGEOS-1 (95L01) series we currently provide. The RMS difference between the new series and the IGS Rapid series is 0.2 mas for polar motion and 40 microsec for LOD which is comparable to the excellent operational series provided by IAA. For comparison, the RMS difference between IGS Rapid and Bulletin-A is below 0.1 mas for polar motion and 30 microsec for LOD. We preliminarily conclude that use of our new series will probably not significantly improve the excellent Bulletin-A polar motion result. On the other hand, we believe that the last few LOD estimates will help to improve the determination of the current trend in the UT1 error of the previous prediction. Many figures showing results obtained in tests of our new procedures can be downloaded via anonymous ftp from:

ftp.csr.utexas.edu in pub/slr/newops_gallery

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 approximately 2 cm in the radial direction. Studies have demonstrated that the SLR data contribute critically to the accuracy of the centering of the altimeter orbits with respect to the Earth s mass center, particularly along the Z-axis (along the Earth s spin axis). 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. We continue to exploit this capability for Jason-1 orbit verification, and this will be extended to ENVISAT orbit studies.

Terrestrial Reference Frame

We have continued to participate in the Analysis Working Group s POS+EOP pilot project devoted to improving the quality of SLR results related to the evolution of the terrestrial reference frame. In addition to providing the required sequences of SINEX files for use in comparisons with other the other analysis centers we have computed a series of monthly results going back to the LAGEOS-2 launch in late 1992. Figure 7.1.1.2-3 shows the Z-translation component of the Helmert transformation that best fits the differences between the monthly CSR solution and ITRF2000. The comparison suggests that the ITRF origin may be different from the actual center of mass by a small (~4 mm @ 1997.0) offset plus a trend of approximately 1 mm/y. Including more recent data increases the apparent drift to 1.4 mm/yr. Discrimination between step changes and a slow trend is, however, quite difficult. Either way, we conclude that fixing ILRS station positions to ITRF2000 (with no geocenter adjustment) will result in a terrestrial frame realization that differs from observational constraints by more than 1 cm in Z at the beginning of 2002. This highlights the continued importance of SLR in the maintenance of ITRF. By comparison, the differences in X and Y are only 0.2-0.3 mm/yr. The annual cycle in the Z-geocenter time series shown in Figure 3 is (on average) about 4 mm which is about the size expected due to seasonal mass redistribution between the Northern and Southern hemisphere.

Additional EOP and station position results can be found in the AWG pages of the ILRS Web site and at:

ftp.csr.utexas.edu in pub/slr/pos+eop

and other nearby directories.

FUTURE PLANS

We will strive to continue improvements in the automation of our SLR analysis applied to rapid-service EOP determination and network quality control. Increasing use of multi-satellite SLR analysis for monitoring the drifts in ITRF2000, temporal variations of low-degree geopotential harmonics and POD for altimetric satellite orbits is anticipated in the next year.

Analysis Working Group Members

Richard Eanes, Minkang Cheng, John Ries, Bob Schutz

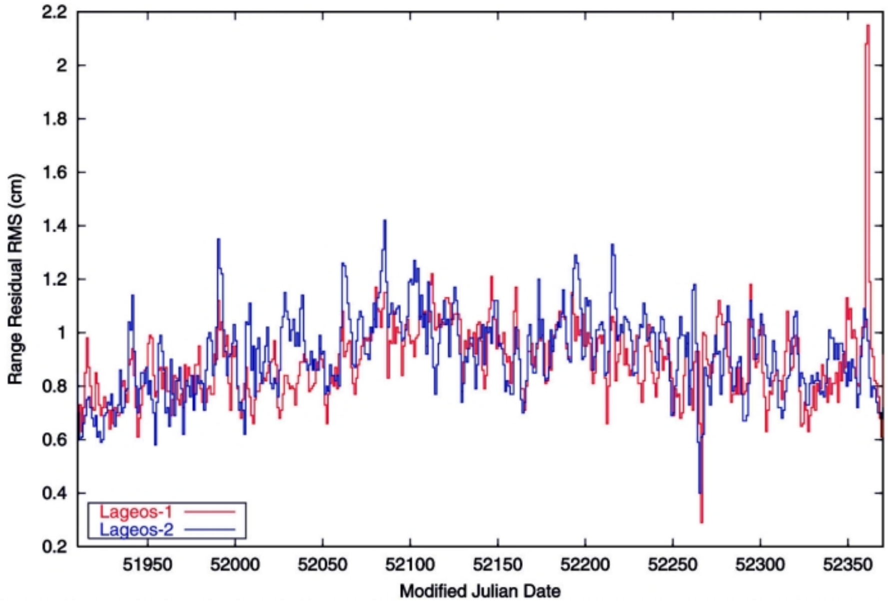

Figure 7.1.1.2-1. Typical range residual RMS for 3-day arcs from LAGEOS-1 and LAGEOS-2

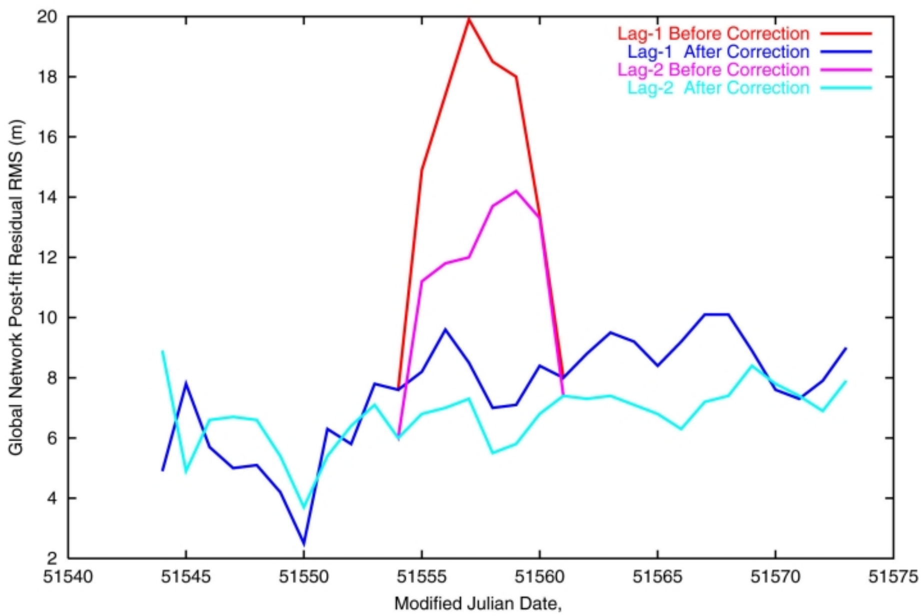

Figure 7.1.1.2-2. Effect of ~25 microsecond Graz time bias during 14-18 January 2000

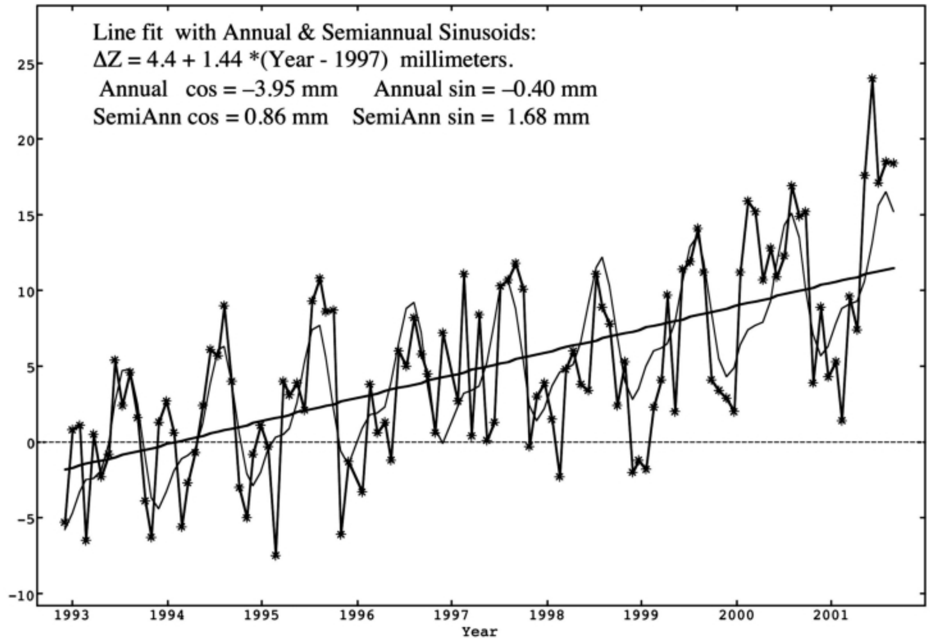

Figure 7.1.1.2-3. Z-translation which moves ITRF2000 toward CSR SLR monthly solutions.

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7.1.1.2 DELFT UNIVERSITY OF TECHNOLOGY

Eelco Doornbos, Ron Noomen, Remko Scharroo, *The Delft Institute for Earth-Oriented Space Research*

INTRODUCTION

The Delft Institute for Earth-Oriented Space Research (DEOS) at Delft University of Technology (DUT) has been active in the field of SLR analysis since about 1980. The current activities include (i) the LAGEOS quick-look analysis, (ii) LAGEOS crustal dynamics investigations, and (iii) ERS-2 orbit computations.

LAGEOS QUICK-LOOK ANALYSIS

The Quick-Look Data Analysis Center (QLDAC) has been operational at DUT/DEOS since the beginning of 1986. The main objectives are a semi real-time quality control of the global SLR observations on LAGEOS-1 and LAGEOS-2, and the production of Earth Orientation Parameters (EOPs), for inclusion in the IERS Bulletins A.

Being an operational analysis service, the QLDAC analysis system has run all through the year 2001. QLDAC benefitted from the reorganisation and automation of the analysis system, which took place at the end of 2000 and at the beginning of 2001: the old, menu-driven system was succeeded by a simpler and fully autonomous analysis system. For continuity reasons, the computation model basically follows the IERS 1996 Standards. Typically, an rms-of-fit of 33 mm on average was obtained for the 10-day arcs during 2001. As for the (near) future, QLDAC intends to introduce new elements in the operational analysis: (1) the use of internet to disseminate analysis results, (2) the replacement of the rather old model for station coordinates SSC(DUT)93L05 by ITRF2000, (3) the inclusion of models for ocean ands atmospheric pressure loading, (4) the addition of other satellites, probably the Etalons, and (5) the increase of the frequency of the analysis.

CRUSTAL DYNAMICS

The SLR observations on LAGEOS-1/2 are also used for crustal dynamics investigations. Here, it is extremely important to model the orbit of the LAGEOS spacecraft as well as possible. An element of the dynamic model for these vehicles which has gained significance during the last few years is the thermal forces (the pressure force exerted by the photons emitted by the hot components of the satellite surface). Since the rotation of LAGEOS-1 has almost stopped, these forces do no longer average out, and the result can easily deteriorate the quality of orbit solutions. DEOS has developed the preliminary LAGEOS Spin Axis Model (LOSSAM-1), which is based on (a development of) the theory on rotational dynamics available in literature and independent observations of the spin axis orientation and the spin rate coming from various data sources. To illustrate LOSSAM-1: the agreement between the spin-axis orientation observations and their model equivalents for LAGEOS-2 is about 0.4 degree.

ERS-2 NEAR REAL-TIME AND PRECISE ORBIT DETERMINATION

DEOS has been involved in the analysis of orbits and altimetry of the European remote sensing satellites ERS-1, ERS-2 and ENVISAT, since well before the launch of ERS-1 in 1991. In the routine orbit determination for ERS-2, SLR measurements are combined with altimeter heights and crossovers. This is done in order to compensate for non-gravitational force model errors with a parameterization of drag scale factors and empirical 1-cpr accelerations, which is not possible using SLR tracking alone. The orbits are computed at four distinct times with an increasing level of accuracy, in synchronization with the incoming altimeter data.

In an automatic process, near real-time altimetry is used together with SLR data to generate orbits for the entire previous day. These orbits are included in the NOAA ERS-2 RGDR altimeter product at approximately 9:20 UTC daily. The first human intervention takes place in the editing of SLR residuals for the production of the so-called fast delivery orbits, every Tuesday and Friday afternoon. These orbits are computed in arcs of 5.5 days and form the basis for the preliminary and precise orbits. These are identical to the fast-delivery orbits, except for the inclusion of the preliminary and final altimetry data from ESA s OPR products. Since these products have a lag-time of about one month and three months, respectively, the resulting orbits also benefit from any corrections to the geophysical quantities (EOPs and solar/geomagnetic indices) and updates in the SLR data.

The radial accuracy of the DEOS orbits for ERS-2 has been estimated at approximately 10 cm for the near real-time orbits to 5 cm for the precise orbits. In 2001 it has not always been possible to reach the highest level of orbit accuracy. This is due mainly to the high solar-activity levels, which have made atmospheric drag forces large and unpredictable at times. In addition, the failure of several gyros onboard the spacecraft have forced ESA engineers to devise a new method for attitude determination, which had to be calibrated. During these periods, the satellite has shown deviations from its nominal attitude, which has a negative influence on the surface force model accuracy, as well as on the altimeter data that is used in the orbit determination. DEOS continues to investigate possible further improvements in the orbit determination accuracy of ERS-2.

Also, in 2001, DEOS has been heavily involved in preparations for the processing of SLR, DORIS and altimeter observations of ENVISAT, which was launched on March 1, 2002. These preparations include, amongst others, the development of a state-of-the-art model for surface forces affecting spacecraft dynamics.

The ERS-2 orbits of course are used for scientific investigations (sea-level variations, ice cap elevation changes), but this is beyond the scope of this report.

7.1.1.3 Mission Control Center (MCC) Analysis Center

Vladimir Glotov, *Russian Mission Control Center*

Introduction

The SLR data Analysis Center is a part of the MCC Navigation and Coordinate-time Service. MCC has certain technical capabilities and its own software for the precise data processing (Figure 7.1.1.3-1).

Facilities/Systems

There are three branches of our software used for routine service by the MCC Analysis Center. The first is STARK, initially prepared as general software for usual missions with high accuracy. The other software, POLAR, is much more complicated and used for determination of highly accurate orbits, Earth Orientation Parameters (EOP), station coordinates and performance, etc. The new software STARK-AUTO&STARK-SYSTEM were written combining DEC FORTRAN and C++ Builder and directed toward automation of the operations and different kind of the precise tracking data (SLR, "phases" and code navigation GPS/GLONASS data etc.) processing. All software packages run on standard IBM compatible Pentium computers. Special calculation methodology allows reduced computation time without loosing accuracy. So, even though the software is suited for the PC, it imposes no limitations on precise data processing.

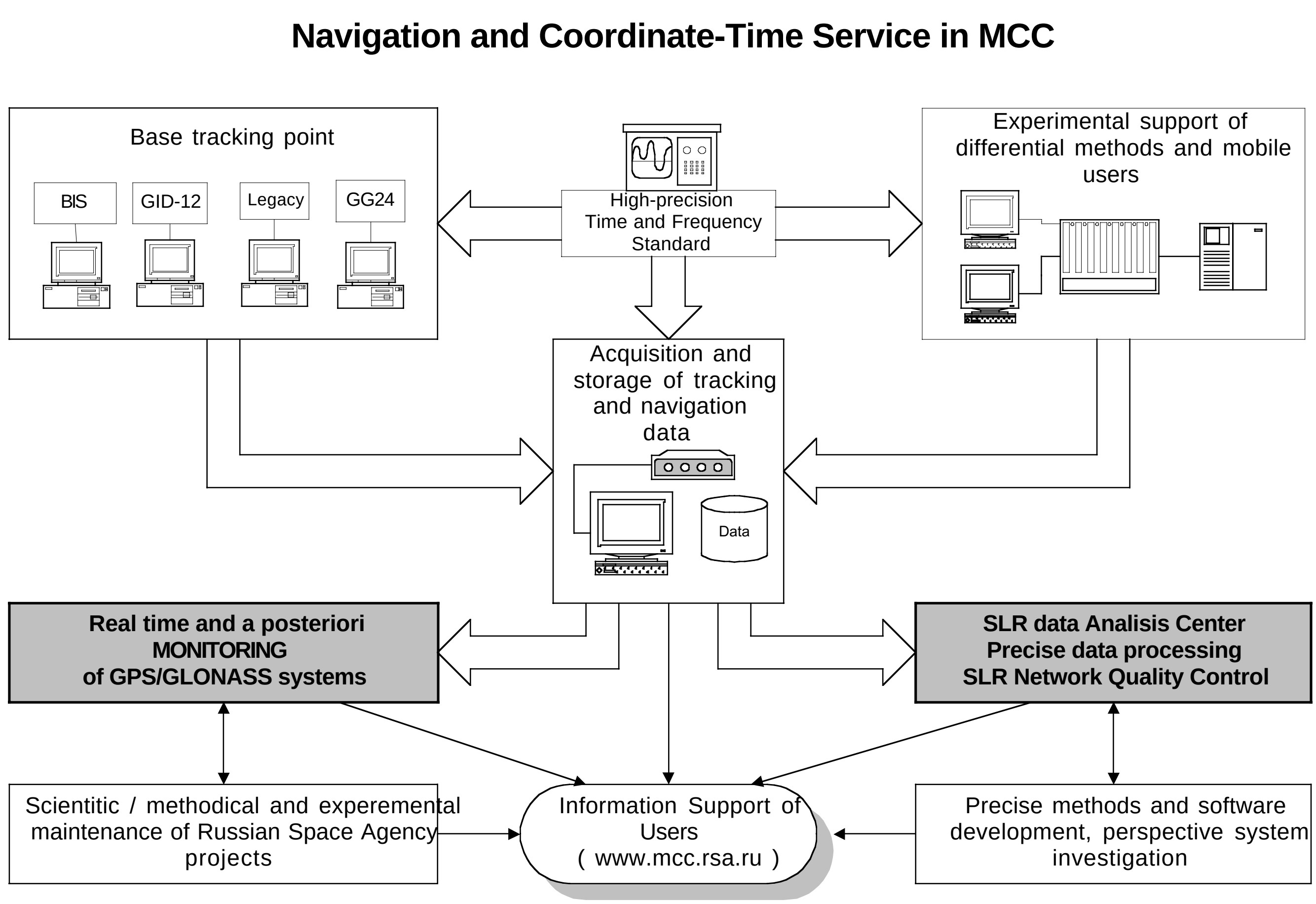

Figure 7.1.1.3-1. Technical capabilities and MCC activities related to the precise navigation issues

CURRENT ACTIVITIES

In 1993, MCC started routine determination of Earth Orientation Parameters (EOP) in cooperation with IERS. Based on the LAGEOS satellites SLR data, EOP are sent weekly to the Central (Paris) and Rapid (Washington) IERS Bureaus. 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 MCC started a regular service of assessing SLR stations performance. All the data of LAGEOS-1 and -2 has been analyzed to get values of time and range biases and RMS. The routine service requires two levels of data filtering: automatically exclude outliers and wrong sessions and manually check and correct results.

Since 1995, the MCC has permanently supported orbit determination of GLONASS satellites based on SLR data. For this work, a GLONASS solar pressure model was developed. Orbits for GLONASS satellites (in SP3 format) are regularly sent to the CDDIS for the determination of the final orbits based mainly on the "phase" GLONASS data. Due to limited number of measurements, MCC currently determines eight day GLONASS orbits with SLR data with four day time offset between the solutions. The central four middle days from each arc are then used for the generation of the SP3 formatted orbits.

KEY POINTS OF CONTACT

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

7.1.2 Associate Analysis Centers:

7.1.2.1 ASI/CGS Associate Analysis Center for ILRS

G. Bianco, R. Devoti, V. Luceri, P. Rutigliano, C. Sciarretta, *Agenzia Spaziale Italiana*

Introduction

During 2001, SLR data analysis activities at the ASI Space Geodesy Center "G. Colombo" (CGS) have been directed, as in the past, to the study of tectonic plate motion, Earth rotation and polar motion, time variations of the Earth s gravitational field and satellite orbit determination. The realization of reference frames and the combination of geodetic solutions represented the primary interest of the analysis.

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

http://geoday.mt.as.it

Current Activities

- International Terrestrial Reference System (ITRS) maintenance: the production of IERS oriented products (global SSC/SSV and EOP time series) is regularly performed to assure the CGS contribution to the reference frames establishment.
- ILRS AWG Pilot project: submission of coordinate/EOP solutions following the pilot projects requirements and comparison/combination of the submitted solutions.
- Satellite rotation: the spectral analysis of the MLRO full rate data, over a 3 year time span, produced estimates of LAGEOS-2 rotation period and slow-down rate, now available to the scientific community.
- Geodetic solution combination: the combination algorithms are defined with the aim to build a unique SSC/SSV solution for the Mediterranean area, taking into account all the available solutions from different analysis groups.

Data Products Provided

- Coordinates and velocity fields (SSC/SSV) of the global SLR tracking network, from LAGEOS-1 and -2 data, submitted to IERS for the ITRF2000 frame realization
- Long series (1984-2000) of Earth Orientation Parameters (EOP), from LAGEOS-1 and -2 data, submitted to IERS for the 2000 Annual Report;
- 1-day estimated EOP, from LAGEOS-1 and -2 data, routinely provided to IERS for the monthly Bulletin˚B;
- Solution of SSC and EOP time series, estimated using LAGEOS-1 and -2 data, for the ILRS AWG pilot project on coordinate and EOP combination;
- Solution of SSC and EOP time series, estimated using LAGEOS-1 and -2 and Etalon-1 and -2 data, for the ILRS AWG pilot project following the ILRS Etalon campaign;
- Combined solution of SSC and EOP time series, estimated by different analysis centers, for the ILRS AWG pilot project on coordinate and EOP combination;
- Estimation of tectonic movements and strain-rates in the Mediterranean area combining SLR, GPS and VLBI results obtained at CGS;
- Time series of LAGEOS-2 rotational periods computed from MLRO data.

FUTURE PLANS

- ILRS AWG: investigation on the use of Etalon data for EOP, GM, gravity and participation to its new pilot project on "benchmarking and orbits" for comparison of the different analysis software.
- IERS Combination Research Centers: participation to the "IERS ERP alignment campaign" through submission of SLR solutions and comparison of submitted solutions. A large involvement in all the CRC activities is planned.
- A revised solution of geopotential zonal drifts will be implemented with updated data set and a new analysis strategy.
- CHAMP orbit determination: in response to the CHAMP AO, the CGS submitted a proposal, including orbit determination with SLR, that was accepted by the CHAMP Science Board
- Satellite rotation: further investigations on LAGEOS rotation with the use of the MLRO streak camera and new analysis methods on the ranging data LLR data analysis activities will soon start together with the MLRO lunar tracking.

MOST RECENT PUBLICATIONS

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KEY POINTS OF CONTACT

Dr. Giuseppe Bianco
Agenzia Spaziale Italiana, 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

7.1.2.2 ASTRONOMICAL INSTITUTE OF THE UNIVERSITY OF BERN (AIUB)

U. Hugentobler, H. Bock, D. Ineichen, *Astronomical Institute of the University of Bern*

CURRENT ACTIVITIES

The Center for Orbit Determination in Europe (CODE) is located at the Astronomical Institute of the University of Berne and is a joint venture of the Swiss Federal Office of Topography (L+T), Wabern, the Bundesamt f r Kartographie und Geod sie (BKG) in Frankfurt, Germany, the Institut G ographique National (IGN) in Paris, France, and the Astronomical Institute of the University of Berne (AIUB). CODE is one of the eight Analysis Centers of the International GPS Service (IGS) since the start of the IGS in June 1992. Precise orbits for the GPS satellites, orbit predictions, Earth orientation parameters, station coordinates and velocities, satellite and station clock corrections, troposphere parameters, and ionosphere models are computed and delivered every day based on the observations of the IGS network of GPS stations. In the framework of the International GLONASS Experiment (IGEX) CODE delivered precise orbits for the GLONASS satellites from January 1999 to June 2000.

As an Associate Analysis Center (AAC) of the International Laser Ranging Service, CODE provides a SLR-GPS quick-look service since December 1996. It is based on the residuals of the SLR observations taken from the two GPS satellites PRN 5 and PRN 6 with respect to the CODE IGS final and rapid orbits as computed from microwave observations. Each day the SLR observations gathered over the last six days and downloaded from CDDIS are evaluated. The last four days are analyzed using the rapid orbits and the two older days using the final orbits. Comparison between the orbits from the different IGS analysis centers regularly show an internal consistency of about 2 cm RMS (1-dim) for the CODE final orbits and 3 cm RMS for the CODE rapid orbits. The external accuracy, as confirmed by SLR observations, is of about 5 cm RMS. The SLR-GPS quick-look results, covering six days, are distributed by e-mail to the SLR Report mail exploder every day — provided that new data was available — giving rapid feedback on the quality of the SLR observations. Since day 016 of year 2002 the quick-look residuals are referred to ITRF2000. Because no GLONASS orbits based on microwave observations are currently computed at CODE the quick-look service is restricted to the two GPS satellites PRN˚5 and 6.

CODE also provides daily orbit predictions for all GPS and GLONASS satellites spanning a time interval of five days. For the GPS satellites, the predictions consist of an extrapolation of the CODE rapid orbits which are based on microwave observations spanning three days. The GLONASS predictions are based on the broadcast messages collected over four days. The predictions are usually available at noon of the day after the last observations used. They are converted from the standard IGS orbit format (SP3) to IRVs by the National Environment Research Council (NERC) and used by several of the (European) SLR tracking stations.

FUTURE PLANS

Although not currently combining SLR and microwave observations, the main interest of CODE on SLR data — the validation of orbits based on microwave observations — is unchanged. In the future, we plan to use SLR observations not only to GPS and GLONASS but also to low Earth orbiters carrying GPS receiver and SLR retroreflectors — such as CHAMP, GRACE, JASON, GOCE — for an independent verification of GPS based precise orbit determination techniques.

7.1.2.3 BUNDESAMT F R KARTOGRAPHIE UND GEOD SIE (BKG)

Bernd Richter, *Bundesamt f r Kartographie und Geod sie*

INTRODUCTION

The central task of the BKG geodetic division is to provide and update the Geodetic Reference Networks of the Federal Republic of Germany including

- Survey work (Station Wettzell, TIGA / Chile, O Higgins / Antarctica - SLR, VLBI, GPS, GLONASS observations, survey campaigns, and other activities), and theoretical work for collection and preparation of survey data, also with
- Cooperation in bilateral and multilateral activities for definition and updating of global reference systems in the framework of ILRS , IVS , IGS, IERS and
- Further development of the surveying, observation and analysis technology used as well as representation of the relevant interests of the Federal Republic of Germany on an international level.

The BKG Associate Analysis Centre processes routinely Lageos-1 and Lageos-2 data for satellite orbit determination, station co-ordinates, Earth Orientation Parameters and SLR station performance monitoring. In addition, special investigations have been made to support the ILRS WG pilot studies.

FACILITIES / SYSTEM

During 2001, the computer hardware changed, and the operating system changed from UNIX to LINUX. In addition, the in-house-network changed and a new firewall protection was installed. As a consequence, routine analysis work stopped during the transition phase, which unfortunately lasted for the entire year.

CURRENT ACTIVITIES

The BKG contributed to the ILRS Analysis Working Group pilot projects with respect to station co-ordinates and EOPs taking data from LAGEOS and Etalon.

Due to the hardware and OS changes the structure of the in-house SLR data base was reorganised as well as the related programs and scripts.

Theoretical and practical investigation were performed to study the stability of the global network. If any single network solutions are to be used for further combinations (multi-satellite techniques) it is important that the datum can be removed from the estimated covariance matrix without numerical deterioration of the network. The a priori sigmas of the station co-ordinates and EOP and the strength of these constraints have a large influence upon the solution. Mathematical tools are being developed to check the datum of SLR networks.

FUTURE ACTIVITIES

The BKG will continue to participate in the ILRS pilot projects. Satellite orbits, station position and velocities, EOP solutions, geo-centre and GM variations will be produced on a regular basis to contribute to the IERS and other services.

7.1.2.4 CENTRAL LABORATORY OF GEODESY (CLG)

Ivan Georgiev and Javor Chapanov, *Central Laboratory of Geodesy at Bulgarian Academy of Sciences*

INTRODUCTION/DATA PRODUCTS PROVIDED

The Central Laboratory of Geodesy (CLG) at the Bulgarian Academy of Sciences has involved in space geodetic research in the last 20 years. Submission of global geodetic SLR solutions — coordinates (SSC) and velocities (SSV) and Earth Orientation Parameters (EOP) to the IERS and ITRF section of the IGN are in progress from 1993. The analysis has been made by the Satellite Laser Ranging Processor (SLRP) — a satellite orbit determination and parameter estimation software package, developed at the Laboratory. Information about the CLG and the SLR analysis activity will be soon available on the web-server under construction in the Laboratory.

CLG Associate Analysis Center provided the following data products:

- Submission of a global SLR solution (station coordinates and velocities and EOP) for ITRF.
- Geogravitational parameter GM and selected set of geopotential coefficients and ocean loading parameters from LAGEOS-1 and LAGEOS-2 tracking data.
- Low degree zonal rates from the analysis of LAGEOS-1 (1984-2001) and LAGEOS-2 (1993-2001).
- Global tectonic plate motion.
- Range- and time-biases for the SLR tracking stations.

CURRENT ACTIVITIES

- Reprocessing SLR tracking data of LAGEOS-1 and LAGEOS-2 with the updated and modified software version SLRP 4.0.
- Continuing to produce the IERS and ITRF oriented products — SSC, SSV and EOP.
- Research activities of the low degree zonal drifts of the geopotential, geocenter variations and SLR reference frame.
- Global tectonic motion with emphasize for the Mediterranean.

FUTURE PLANS

- Including in the analysis tracking data from the Etalon satellites.
- GPS/GLONASS orbit determination from SLR tracking data.
- Continue the SLR IERS and ITRF products submission.
- Participate in the future ILRS pilot projects.

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CLG KEY POINT OF CONTACT

Dr. Ivan Georgiev
Central Laboratory of Geodesy
Acad. G. Bonchev Str. Bl. 1
Sofia 1113, Bulgaria
Phone: + 359 2 979 2453
Fax: + 359 2 72 08 41
E-mail: ivan@argo.bas.bg

7.1.2.5 COMMUNICATIONS RESEARCH LABORATORY

Toshimichi Otsubo, *Communications Research Laboratory*

INTRODUCTION

In August 2001, the ILRS Governing Board approved CRL as an Associate Analysis Centre (AAC) of the ILRS. This is the first AAC report from us. We have researched satellite laser ranging analysis since mid-nineties including Otsubo s two-year visit to Natural Environment Research Council (NERC) in the UK, and our research will continue as ILRS AAC activities.

CRL has developed the orbit analysis software package *concerto* written in Java, which was used to conduct most of our 2001 activities.

CURRENT ACTIVITIES

- SSC and EOP: CRL has continuously been involved in the SSC/EOP pilot projects driven by the ILRS Analysis WG. We submitted the SSC/EOP solutions to the 4th (Nice) and 5th (Toulouse) ILRS AWG pilot projects. Our 10-year SSC solution also contributed to the ITRF2000 solution released in April 2001.
- Weekly quality check: We developed an automated system to check the station quality using seven geodetic satellites (Stella, Starlette, Ajisai, LAGEOS-1, LAGEOS-2, Etalon-1 and Etalon-2. Analyzing various satellites makes it easier to find possible problems at stations. The analysis reports are being updated weekly at our ftp and Web site:

  ftp://ftp.crl.go.jp/mt/cybernetics/slrqc/   http://www.crl.go.jp/hk/slr/bias
- Satellite spin: With a continuous collaboration with NERC, we analyzed the photometer data obtained at the Herstmonceux station and estimated the spin rate and the spin axis evolution of LAGEOS-2 during 2000-2001.

FUTURE PLANS

- Further development of the *concerto* software package to adapt various data types.
- Satellite signature studies to derive systematic dependence of the center-of-mass corrections of spherical geodetic satellites.

Recent Publications

T. Otsubo, H. Kunimori, K. Yoshihara and H Hashimoto, Optical response of the H2A-LRE satellite, SPIE Symposium on Remote Sensing (Toulouse), SPIE Proceedings Series 4546, 44-48, 2001.

T. Otsubo, G. M. Appleby and P. Gibbs, GLONASS laser ranging accuracy with satellite signature effect, *Surveys in Geophysics*, 22, 6, 507-514, 2001.

7.1.2.6 DEPARTMENT OF GEOMATICS, NEWCASTLE UNIVERSITY

Philip Moore, *Newcastle University*.

The Department of Geomatics has been active in space geodetic research for over a decade. Within the remit of the ILRS our current activities include:

Precise orbit determination of altimetric and geodetic satellites utilizing SLR, DORIS, PRARE and altimetry in the form of single and dual satellite crossovers. Effort is continually devoted to development of the in-house orbit determination software package *Faust*. The use of crossovers as an additional tracking type allows estimation of an extended state vector to the extent that accuracy of the lower altimeter satellites (ERS-2, GFO) is now not far short of the most precise altimeter orbit of TOPEX/Poseidon. Applications include gravity field enhancement and studies of stability of the altimetric range.

Precise orbits of LAGEOS 1 and 2 are used to determine station coordinates of the SLR tracking network. The weakly constrained solutions are use to estimate seasonal variability in the geocentre for comparison against comparable results from geophysical models. In addition to geocentre displacement the effects of loading and gravity field variations from the mass distributions have been included.

GPS pseudo-range and phase data from GPS onboard the CHAMP satellite has been used to compute orbital positioning in a reduced dynamic procedure within JPL s software suite *GIPSY-OASIS* . Overlaps provide a check on internal precision while SLR has been used as the independent check on the accuracy of orbits determined. Cartesian positioning from GPS and accelerometer data is being used to enhance the Earth s gravity field with applications aimed towards temporal variability.

The Department of Geomatics of Newcastle University is a Global Network Associate Analysis Center for the IGS producing weekly combination station coordinates for the IGS network. This rigorous approach is being applied to SLR coordinates to produce solutions superior to the individual submissions from the ILRS Analysis and Associate Analysis Centres. The combination solution approach for GPS and SLR coordinates is being extended to Earth rotation parameters.

Further information, including ERS-2 orbits are available at:

http://geomatics.ncl.ac.uk/research/research.htm

POINT OF CONTACT

P Moore
Department of Geomatics, Newcastle University
Newcastle, NE43 7RU, UK
Tel: + 44 (0)191 222 5040
email Philip.moore@ncl.ac.uk

7.1.2.7 DEUTSCHES GEOD TISCHES FORSCHUNGSINSTITUT (DGFI)

Horst M ller, Detlef Angermann, Rainer Kelm, *Deutsches Geod tisches Forschungsinstitut*

INTRODUCTION/DATA PRODUCTS PROVIDED

Since 1980 DGFI has been involved in SLR data analysis. Our software package DOGS (DGFI Orbit and Geodetic Parameter Estimation Software) is the basis for routinely high precision processing of SLR tracking data for station coordinates, EOP's and geopotential coefficients. More information on DGFI, the activities within ILRS and SLR analysis results are available at the DGFI Web-server at: http://www.dgfi.badw.de.

DGFI Associate Analysis Center provided following data products:

- Participating in the ILRS Analysis Working Group pilot projects 4 and 5A: solutions (station coordinates and EOP«s) and comparison/combination of results.
- Time series for station coordinates, terrestrial reference frame parameters (origin and scale) and J2.

CURRENT ACTIVITIES

- Reprocessing of all available LAGEOS-1 and LAGEOS-2 SLR tracking data since 1981 for a new station coordinate and velocity solution
- Researching activities related to the accuracy and long-term stability of station coordinates and velocities, SLR reference frame (origin, scale), GM, geocenter variations and EOP«s.
- Processing of Etalon SLR data.
- Combining miscellaneous station coordinate solutions as ITRF analysis center.
- Researching activity on combination of solutions from all space techniques within the scope of a ITRF combination research center.

One of our recent projects was the analysis of the long-term stability of various space techniques on the basis of weekly solutions. Figure 7.1.2.7-1 shows the weekly transformation parameters for a combined LAGEOS-1 and -2 solution with respect to ITRF2000. The translation parameters show a significant annual signal of 3 mm in X and Y and 4.5 mm in Z, but no secular motion. The scale shows a good longterm stability with a noise of below 1 ppb. This result proofs the significant contribution of SLR for the realization of a global reference frame.

FUTURE PLANS

- Continue submitting solutions within future ILRS pilot projects
- Analyze SLR data (bias parameter and station quality)
- Combine space techniques for ITRS realizations.
- Extend routine processing and analysis to other satellites (Ajisai, Starlette, etc.).
- Submit SLR products to the ILRS routinely to the ILRS (e.g. station coordinates and EOP«s on a monthly basis, multi-years solutions for station coordinates and velocities, range and time-biases for SLR tracking stations) to become an operational ILRS analysis center.

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Kaniuth, K., H. M ller, W. Seem ller , Displacement of the space geodetic observatory Arequipa due to recent Earthquakes, Zeitschrift f r Vermessungswesen, Germany, accepted, 2002.

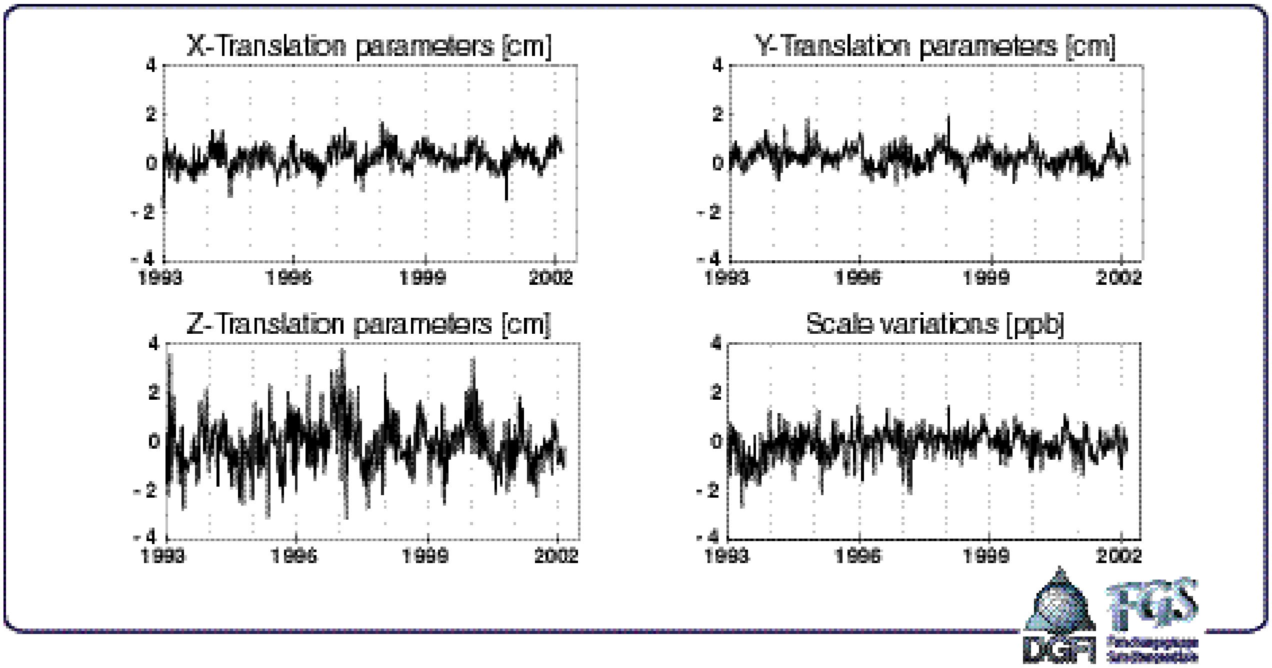

Figure 7.1.2.7-1. Transformation parameters between weekly LAGEOS-1 and -2 combined coordinate solutions and ITRF2000

KEY POINTS OF CONTACT

Horst M ller,
Deutsches Geod tisches Forschungsinstitut
Marstallplatz 8
D-80539 M nchen, Germany
Phone: +49-089-23031217
Fax: +49-089-23031240
E-mail: horst.mueller@dgfi.badw.de

Detlef Angermann
Deutsches Geod tisches Forschungsinst itut
Marstallplatz 8
D-80539 M nchen, Germany
Phone: +49-089-23031217
Fax: +49-089-23031240
E-mail: angerman@dgfi.badw.de

7.1.2.8 EUROPEAN SPACE OPERATIONS CENTER (ESOC)

John Dow and Ren   Zandbergen, *ESOC*

INTRODUCTION

One of the tasks of the Navigation Support Office of the European Space Operation Centre (ESOC) is to provide high-precision restituted orbit data for ESA s Earth observation missions, e.g. ERS-1 before its demise, ERS-2 and the future ENVISAT mission (launched March 1, 2002). To achieve this high precision, processing and application of SLR data is one of the requirements. The restituted orbits are based on automatically retrieved quick look laser ranging data, reprocessed fast-delivery altimeter height measurements, and for ENVISAT also DORIS measurements. This task not only supports the provision of the routinely determined and predicted orbits for operational purposes and use in fast-delivery products of the scientific instruments on these missions, but also the computation of monthly sea level anomaly solutions from altimeter data. To accomplish this task, a batch least squares orbit determination sequence including the retrieval and pre-processing of tracking data, and the generation of residual and orbit comparison plots, is run automatically. Five day arc orbit solutions are generated every three days, with a delay of typically one week to allow collection of most of the laser tracking. After each solution, updated reports are made available on the Navigation Support Office s web site (http://nng.esoc.esa.de), and the solution is used as a reference against which the accuracy of the routinely determined orbit is checked.

FACILITIES/SYSTEMS

This activity is carried out using the precise orbit determination (POD) system of ESOC that has evolved out of the routine orbit determination software. While the routine system was frozen at the start of the ERS-2 mission (1995), the POD system has been constantly improved. This system is also being used initially for ENVISAT, but will be replaced by the newly-developed Navigation Package for Earth Observation Satellites (Napeos), after its POD capabilities have been validated.

The computation facilities are mainly SunBlade 1000 workstations that operate under Solaris 8.0.

CURRENT ACTIVITIES

The operational activities for the ERS-2 satellite are on-going as the satellite is still in good shape, although being operated (successfully) in a gyro-less AOCS mode. Therefore, SLR tracking data are still required for the precise orbit determination of ERS-2.

The new generation of orbit determination, prediction and control software Napeos, developed by the team in preparation of ENVISAT and other future Earth Observation missions, will support both the routine operational and high-precision orbit determination of ENVISAT. Since Napeos is already qualified for operations support, the main development effort is being put in the improvement of the high-precision computations, including support of all observation types currently used for geodetic applications.

KEY POINTS OF CONTACT

John Dow
Head of Navigation Support Office
ESA/ESOC, Robert-Bosch Strasse 5
D-64293 Darmstadt, Germany
Tel: +49 6151 902272
Fax: +49 6151 902271
Email: John.Dow@esa.int

Ren Zandbergen
Navigation Support Office
ESA/ESOC, Robert-Bosch Strasse 5
D-64293 Darmstadt, Germany
Tel: +49 6151 902236
Fax: +49 6151 902271
Email: Rene.Zandbergen@esa.int

FUTURE PLANS

SLR data processing will be performed for all current and future ESA satellites equipped with a LRR array (e.g. CryoSat, GOCE), and in test mode for a number of non-ESA LEO missions, such as Jason. In addition, ESOC is responsible for providing the SLR station predictions for ENVISAT and other future ESA satellites.

7.1.2.9 FORSVARETS FORSKNINGSINSTITUTT (FFI)

Per Helge Andersen, *The Norwegian Defence Research Establishment*

INTRODUCTION

FFI has during the last 19 years developed a software package called GEOSAT (Andersen, 1995) for the combined analysis of VLBI, GPS, SLR and other types of satellite tracking data (DORIS, PRARE and altimetry). The observations are combined at the observation level with a consistent model and consistent analysis strategies. The data processing is automated except for some manual editing of the SLR observations.

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

ANALYSIS STRATEGY

Presently, the most important stochastic parameters of the global level state vector are the following: radio source coordinates (1d resolution) of sources with structure index 3 or 4, geocenter coordinates (three day resolution), Earth orientation parameters (one day), the C21 and S21 gravity coefficients (six day), satellite independent SLR ranging biases (15 day), solar radiation pressure scaling and an empirical drag of the LAGEOS satellites (three day), and GPS receiver antenna eccentricity vectors (station dependent time resolution to account for instrumental changes). The reason for including the two gravity coefficients is to account for the fact that errors in the gravity field will map into the estimates of polar motion derived from satellite tracking data. In order to be consistent with VLBI, which is almost independent of gravity, these parameters must be estimated. The arc length of the GPS and LAGEOS satellites is one day.

The main constant parameters of the global state vector are monument coordinates and velocities, GPS and/or SLR eccentricity vectors relative to the station monument if it ia a collocated station, radio source coordinates, relative zenith delay between VLBI and GPS at collocated stations (to account for differences in antenna heights), VLBI antenna axis offsets, and GPS satellite transmitter phase center Z-coordinate offset and nadir-dependent variation (relative to the satellite body-fixed reference frame). The commonly adopted Z-coordinates for the effective phase center of the GPS transmitter antennas are probably have a 1-2 meter error. Results show that the Z-coordinate, as a function of the nadir angle, can be determined to a formal precision of some centimeters (1 sigma). Using the IGS z-coordinate values will result in a scale inconsistent with SLR and VLBI by several ppb. This means that most, but not all, of the error in the GPS phase center offset is absorbed by the estimated clock and ambiguity parameters. However, the phase center variation as a function of the nadir angle is not absorbed by the estimates of any of the parameters. The phase center variation is within approximately 20 mm. One value is estimated for each of the Block II/IIA and Block IIR satellite types. Individual estimates for the different satellites of a specific type show remarkable similarities regarding the nadir dependency.

The status of the analyses is that approximately 3214 daily SLR arcs (with LAGEOS I & II data from 1 Jan 1993 to 31 Dec 2001) have been processed where approximately 744 arcs are combinations with VLBI and approximately 200 arcs are combinations with VLBI, GPS and SLR. Typically, 60 GPS stations are included in each arc. These 3214 arcs have been combined into a global solution using the CSRIFS program. A program called CSRIFS-IERS reads the output of CSRIFS and estimates a time dependent transformation from the internal terrestrial and celestial reference frames to an ITRF reference frame (presently ITRF-2000) and an IERS Celestial reference frame (presently ICRF-95.ext). Since the estimated Earth orientation parameters in principle are 100 % consistent with the internal reference frames the time dependent transformation parameters can be applied to transform the EOP estimates to IERS for comparison with the IERS EOP products. A possible inconsistency between the IERS reference frames and the IERS EOP estimates should in principle be detectable. The CSRIFS-IERS automatically generates SINEX files for the terrestrial and celestial reference frames and the EOP s. These files can be directly submitted to the IERS Product Centers.

During the last year the following improvements have taken place in the GEOSAT software:

- the DE405 planetary ephemerides have been implemented.
- perturbations from the planets Mercury, Mars, Uranus, Neptune and Pluto have been included.
- the IERS-2000 VLBI observation model has been implemented.
- the Mendes *et al*. SLR refraction model has been implemented.
- the following GPS satellites have been down-weighted: PRN 2, 15, 17, 21, and 23.
- a constant GPS satellite phase center offset (Z-coordinate) for each of the Block II/IIA and Block IIR satellite types has been estimated.
- nadir-dependent GPS satellite phase center variations for each of the satellite types have been estimated.

All improvements listed above have been applied in the analysis of the 3214 arcs.

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7.1.2.10 GEOFORSCHUNGSZENTRUM (GFZ) POTSDAM

Franz-Heinrich Massmann, *GeoForschungsZentrum*

DATA PRODUCTS PROVIDED

In 2001, the GeoForschungsZentrum (GFZ) Potsdam continued its ILRS activities of the previous years. The main focus was again on the routine provision of high quality predictions for the ERS-2 and CHAMP satellites. While for the ERS satellite a prediction interval of about two weeks was used with daily updates with time bias functions, for the LEO satellite CHAMP, a prediction generation up to three times per day was established to optimally support the community. The following table summarizes the delivered products.

The orbit prediction products enabled ILRS stations to track both satellites with excellent results. In total 37 stations reported 4196 successfully tracked passes for ERS-2 (111 less than 2000) and 26 stations delivered 1564 passes for the CHAMP satellite.

Table 7.1.2.15-1: ERS-2 and Champ products.

	ERS-2	CHAMP
Orbit Predictions	85	753
Time Bias Functions	276	-
Drag Functions	276	-
Two-Line Elements	85	753
SAO Elements	75	753
Total	797	2259

FURTHER ACTIVITIES

In addition to the operational products mentioned above, the systematic generation of the ERS-2 preliminary and precise orbits based on SLR and PRARE data under ESA contract was continued.

The CHAMP SLR data allowed excellent quality control within the precision orbit determination (POD) process, when computing the orbits based on GPS-SST data from CHAMP. Modeling improvements were easlily seen, especially after introduction of a new global Earth gravity model EIGEN-1, which was determined from GRIM5 normal equations plus several months of CHAMP GPS-SST data. The routine provision of radio occultation data from the GPS receiver onboard of CHAMP resulted in a more rapid generation of Rapid Science Orbits (goal: every three hours).

In view of the upcoming GRACE satellite mission the prediction system was reconfigured, because GFZ will provide predictions for these satellites too.

FUTURE PLANS

The launch of the GRACE satellite in 2002 will add two new satellites to the prediction work, and will allow a much more precise determination of the gravity field of the Earth. As for CHAMP, the SLR measurements will continue to be an important quality control component.

7.1.2.11 GEOSCIENCE AUSTRALIA

Ramesh Govind, *National Mapping Division/Geodesy, Geoscience Australia*

BACKGROUND/INTRODUCTION

The Geoscience Australia Associate Analysis Centre has been routinely processing LAGEOS-1 and LAGEOS-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 and Etalon data is also processed. This work to-date has been reported in the publication list available on:

http://www.auslig.gov.au/geodesy/techrpts/techrpts.htm.

There is an ongoing emphasis on the co-location and combination of SLR with other space geodetic techniques. The annual activities of observations and processing [since 1997], for the Asia — Pacific Regional Geodetic Project (APRGP) of the Permanent Committee for GIS Infrastructure for Asia and the Pacific (PCGIAP) continues. A new combination solution comprising of four annual campaigns of SLR, VLBI and GPS is currently being finalized. An eight year solution of LAGEOS-1 and LAGEOS-2 results were submitted to the IERS as a contribution for the IERS analysis campaign to align EOP to ITRF2000.

Facilities/Systems

The current computation facilities in the Geoscience Australia Space Geodesy Analysis Centre comprises of four HP workstations [C160, C180, C360 and 2XL2000]. 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 has 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 ILRS Analysis Working Group pilot projects (station coordinates and EOPs, Orbit comparison and Benchmarking).
- Continuing monthly solutions for LAGEOS-1 and LAGEOS-2. The results both as a time series and as SINEX files are available from

  http://www.auslig.gov.au/geodesy/sgc/product.htm.
- Continuing 3-day day arc LAGEOS-1 and LAGEOS-2 station time and range bias based on ITRF2000 set of station coordinates are now available from the above web page.
- Developing the processing software to estimate LOD and pole rates, and inclusion of new tropospheric mapping functions.

Future Plans

- Plans are to continue to provide both the one-month and the three day arc LAGEOS-1 and LAGEOS-2 solutions.
- Provide global solutions as a full analysis centre to the ILRS when the AWG coordination structures are established.
- Extend routine processing and analysis to TOPEX/Poseidon, Jason-1 for altimeter calibration / validation experiments.
- Compare the SLR solutions for LEOs with the GPS and DORIS determined solutions.
- Continue to provide a station monitoring service using the 3-day arc solutions described above.
- Compare and combine individual SLR solutions submitted by the various analysis centres.
- Contribute by submitting solutions to the IERS SINEX combination campaign.

Related Publications

The key publications appear on AUSLIG s Space Geodesy Analysis Centre Web page at:

http://www.auslig.gov.au/geodesy/techrpts/

KEY POINT OF CONTACT

Dr. Ramesh Govind
National Mapping Division/Geodesy
Geoscience Australia
PO Box 2, Belconnen, ACT 2616,
Australia.
Phone: 61 2 62014 371
Fax: 61 2 62014 366
Email: rameshgovind@auslig.gov.au

7.1.2.12 INSTITUTE OF APPLIED ASTRONOMY (IAA)

George Krasinsky, Zinovy Malkin, Nadia Shuygina, Ekaterina Aleshkina, Tamara Ivanova, *Institute of Applied Astronomy*

In 2002, two research groups were involved in independent analysis of satellite and laser ranging data applying two different software packages (ERA and GROSS).

Studies with the ERA package (Krasinsky G.A., Shuigina N.V., Aleshkina E. Yu., Ivanova T.V. referred as IAAK group).

- SLR observations of LAGEOS-1, LAGEOS-2, Etalon-1, Etalon-2 have been processed in the frame of AWG Pilot Project positioning + Earth orientation and submitted to AWG. The approach proposed by AWG was expanded by experiments with combine processing of the SLR observations with VLBI observations of NEOS-A program for the same time interval. In this way the contribution of SLR data not only to determination of the pole coordinates and LOD but also to evaluation of time variations of Celestial Pole could be provided. Kalman filtering was used for modeling of fast changing parameters of VLBI techniques so for modeling the time variations of the all five Earth s orientation parameters. It appeared that in this way some fine effects in the variations of EOPs might be studied. As an example in Fig 1 the obtained time behavior of UT on 28-day interval is presented. The separated points correspond to the least squares solution method obtained in accordance with the recommendations of AWG.
- Database of all SLR observations of Etalon-1, Etalon-2 has been constructed (about 100000 entries) for the planning study of time variations of lower harmonics of geopotential. A preliminary analysis of the dataset by confronting with ephemeredes is carried out.
- LLR observations 1970-2001 have been processed in the two modes: making use of the ephemeredes DE405 and ephemerides obtained by numerical integration in the frame of the ERA package with a new model taking into account an impact of a number of seleno-dynamical parameters. Estimated parameters include lunar Love numbers h_2, l_2, k_2, the tidal lag δ for which statistically significant estimates have been obtained: h_2=0.0861±0.0035, l_2=0.0426±0.0027, k_2=0.0285±0.0008, δ =2.0559±0.008°. Analysis of the residuals has revealed a sharp change of their time behavior after March 1998 that could not be modeled in other way but including corrections to the coordinates of the lunar reflectors after this date as independent solve-for parameters. As the corrections to coordinates of the reflectors appear to be rather close it is conjectured that near this date a jump of a few centimeters on the position of lunar barycenter with respect to the lunar crust had occurred at this date. For more details see the paper (Krasinsky G.A., 2002).
- Following the global fitting of the whole set of LLR observations 1970-2000, the post-fit residuals for 1995-2000 were analyzed to determine corrections to UT0 and verify whether LLR is a viable component of EOP monitoring.

Computation of EOP with GROSS package (Z.Malkin).

- The group of Lab of Space Geodesy and Earth Rotation continued everyday operative processing of LAGEOS-1 and LAGEOS-2 observations with the GROSS package with delay about two days. A new version of our software implements most of the recommendations of the IERS Conventions (2000) and some other improvements. In result, accuracy of EOP solutions became about 20% better.
- Two final SLR EOP series were computed and submitted to the IERS 2001 Annual Report: EOP(IAA)02L01 computed using LAGEOS-1 observations only (from January 1983), and the series EOP(IAA)02L02 is computed using LAGEOS-1 and LAGEOS-2 observations (from October 1992).

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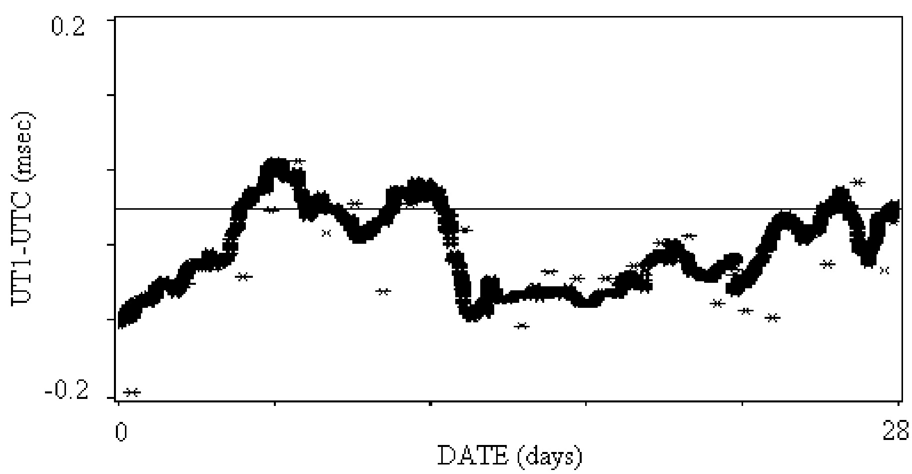

Figure 7.1.2.12-1. UT1-UTC obtained from combining processing of SLR and VLBI data with ERA package.

7.1.2.13 JOINT CENTER FOR EARTH SYSTEMS TECHNOLOGY/GSFC (JCET/GSFC)

Erricos Pavlis, *Joint Center for Earth Systems Technology, University of Maryland*

INTRODUCTION

The AAC at JCET/GSFC continued to support the activities of ILRS and several of its Working Groups during the year 2001. We continued to participate in the IERS/ITRF Pilot Project for TRF definition and the ILRS Pilot Project for the standardization of the SLR data analysis and its products for site and EOP in the form of SINEX file submissions. This past year we submitted to IERS a complete nine year solution based on LAGEOS-1 and LAGEOS-2 data. In addition to these solutions, we have generated solutions that include data from the Etalon-1 and -2 satellites during the period April 1-December 31, 2001 as part of a new Pilot Project of the ILRS AWG.

BACKGROUND

The activities of the AAC are primarily focused on the analysis of SLR data from LAGEOS-1 and LAGEOS-2, with analyses for SLR data obtained on additional satellite targets during specific campaigns of interest (e.g. GPS, GLONASS, Etalon-1 and -2, CHAMP, etc.). The main products are the updated station positions and velocities and the Earth Orientation Parameters, x_p, y_p, and *LODR,* as well as their rates x_p-*dot* and y_p-dot, 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 examined in terms of their spectral content by estimating periodic signals at long and intermediate periods. Comparing them to those obtained from primarily geophysical model predictions, we conclude that they are primarily due to the seasonal redistribution of geophysical fluids in the Earth system.

FACILITIES/SYSTEMS

These are the same as for last year.

CURRENT ACTIVITIES

We continue the generation of our 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 continuing our support for the ILRS Pilot Project, by including EOP rate estimation, utilization of the new mapping function for atmospheric delay, and the analysis of tracking data from Etalon 1 and 2, and the orbit and s/w benchmarking projects. We have also completed a reanalysis of the 9-year series using the new mapping function to identify its impact on the deliverable products. This constitutes our contribution to the IERS for the year 2001 report.

KEY POINT OF CONTACT

Dr. Erricos C. Pavlis (same information as last year)

FUTURE PLANS

ILRS-related activities continue, with emphasis on the near-real-time generation of weekly products and their dissemination via the web. We will also expand our activities to include the data of the new geodetic and oceanographic missions launched during 2001-2002, (e.g. CHAMP, Jason, ENVISAT and GRACE A & B). With regards to the second one and our European Union project GAVDOS to establish an absolute altimeter calibration site at Gavdos/Crete, Greece, we will participate with the SLR, GPS and DORIS data analysis for the CAL-VAL activities during a six month on-site campaign.

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Pavlis, E. C. Satellite Laser Ranging constraints on global mass transport in the Earth system, presented at the *European Geophysical Society (EGS) General Assembly*, Nice, France, March, 2001.

Pavlis, E. C. Combination and evaluation of satellite laser ranging contributions towards a single ILRS product, presented at the *European Geophysical Society (EGS) General Assembly*, Nice, France, March, 2001.

Pavlis, E. C. Earth orientation from satellite laser ranging (SLR): quality, content and resolution, presented at the *European Geophysical Society (EGS) General Assembly*, Nice, France, March, 2001.

Pavlis, E. C. and V. B. Mendes Validation of improved mapping functions for atmospheric corrections in laser ranging, presented at the *European Geophysical Society (EGS) General Assembly*, Nice, France, March 2001.

Pavlis, E. C. and L. Iorio, The impact of tidal errors on the determination of the Lense-Thirring effect from satellite laser ranging , *International Journal of Modern Physics D* , 11, 4, pp. 599-618, 2001.

7.1.2.14 NATIONAL SPACE DEVELOPMENT AGENCY OF JAPAN: (NASDA)

Takashi Uchimura, *Flight Dynamics Group, NASDA*

INTRODUCTION

The NASDA Associate Analysis Center has been routinely processing Ajisai, LAGEOS-1, LAGEOS-2 and LRE data for precise orbit determination, station coordinates, Earth orientation parameters and SLR station performance monitoring since 23rd August. In addition, on an experiment basis, GPS satellite data is also processed using SLR data and RINEX data. On the other hands, we compared our orbit determination results and prediction results with NERC and HTSI s one as an evaluation of processing accuracy in NASDA. In addition, we prepared for the launch of ADEOS-II satellite. A Major event in 2001 was the launch of LRE (Laser Ranging Equipment) payload by H-IIA launch vehicle No.1 from Tanegashima Space Center. The LRE mission is to help evaluate the H-IIA rocket trajectory, calibration of SLR station from a target which spans a large range of satellite altitude (LRE eccentricity is 0.73), and satellite spin evolution vs. BK7 degradation. We have continued to determine the LRE orbit and have provided IRVs to ILRS station as often as possible.

In the ADEOS-II mission, it became clear that there were visibility problems for ADEOS-II SLR tracking. A detailed analysis of the ADEOS-II satellite, showed that there were some obscured view angles caused by GLI (Global Imager: Optical sensor) for which no SLR returns are possible. We analyzed the following items for ADEOS-II and reported these results at ILRS General Assembly in Nice, France on April 25, 2001.

- SLR restriction area analysis
- Station visibility analysis
- Orbit determination analysis
- Study of SLR operation method

FACILITIES/SYSTEMS

The precise orbit determination system, GUTS , develop ed by NASDA will be improved in two steps. The first step has been completed and is in operation as an experimental OD system for ADEOS-II. The second step for ALOS is now being developed in addition four GPS stations and one SLR station. This system will be performed automatic operation from obtain observation data, orbit determination of several satellites and to deliver orbital information to user. This system is to be main system for precise orbit determination in NASDA and will improved until the 1st quarter of 2003.

CURRENT ACTIVITIES

- Processed Ajisai, LAGEOS-1 and LAGEOS-2 data for orbit determination and generate IRVs on an routine basis. We evaluated orbit determination results and prediction results with NERC and HTSI s one.
- Processed GPS satellite data (QLNP and RINEX) for precise orbit determination and the evaluation of GUTS own system.

- Estimated individual station coordinates, Earth orientation parameters and SLR station performance monitoring when we determined orbit of operation satellites. The results of SLR station performance monitoring is available from http://god.tksc.nasda.go.jp/slreport/
- Comparison of Earth gravity model (JGM-3 vs EGM96) for precise orbit determination using Ajisai and LAGEOS.
- Orbit analysis for LRE which includes station visibility, link budget, orbit determination accuracy and orbit prediction accuracy.
- LRE launch operation. The comparison result (Position difference) between Two Line Elements (TLE) and orbit determination result using SLR is shown in figure 7.1.2.1-14.

FUTURE PLANS

- Establish operation procedure of ADEOS-II in routine operation and preparation for ADEOS-II launch operation.
- Continue to provide IRVs of Ajisai, LAGEOS-1 and LAGEOS-2.
- Continue to process Ajisai, LAGEOS-1, LAGEOS-2 and GPS data for the following estimation; Station coordinates, Earth orientation parameters and SLR station performance monitoring, Solid Earth tide, Coefficient of Earth Gravity Model.

RELATED PUBLICATIONS

The key publications appear on NASDA associate analysis center Web page at:

http://god.tksc.nasda.go.jp/aac/top.html

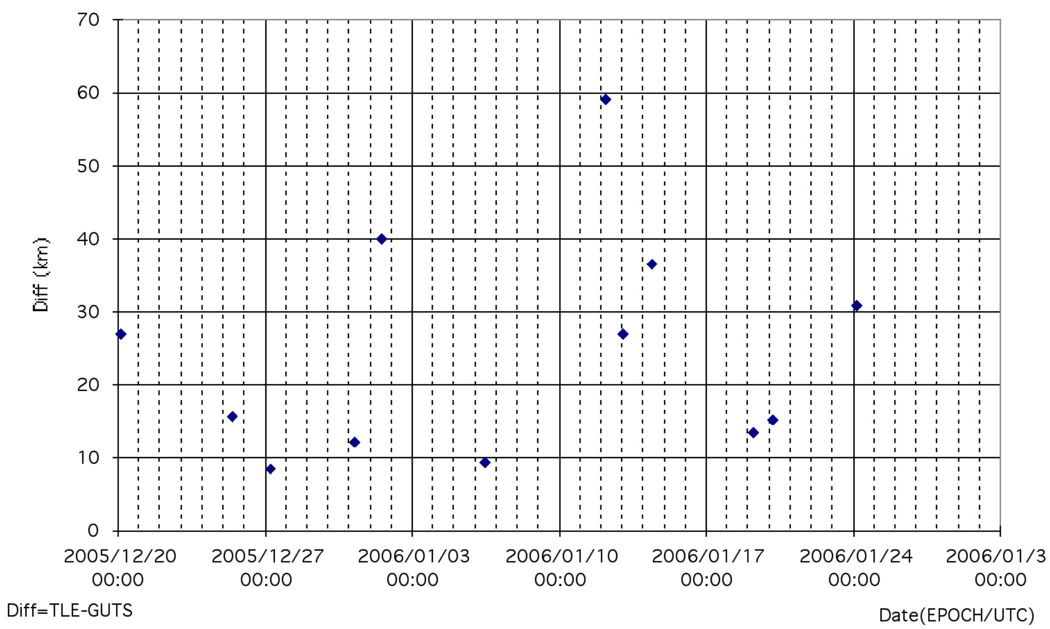

Figure 7.1.2.14-1: LRE Orbit comparison result between TLE and SLR POD (3D position)

KEY POINT OF CONTACT

Takashi Uchimura
Flight Dynamics Group,
Satellite Mission Operations Department,
Office of Satellite Technology,
Research and Applications,
National Space Development Agency of JAPAN

Tel +81 298 68 2624
Fax +81 298 68 2990
e-mail: uchimura@eoc.nasda.go.jp

7.1.2.15 NATURAL ENVIRONMENT RESEARCH COUNCIL (NERC), SPACE GEODESY FACILITY, UK

Graham Appleby, Philip Gibbs and Roger Wood, *NERC*

DAILY QUALITY MONITOR

Our automatic service was considerably upgraded during the year, to include more satellites and short-arc analyses for the whole Network. Long-arc (six-day) results are computed for each ILRS station and shown as residuals from fitted orbits for both LAGEOS and both Etalon satellites on a single plot. Post-fit residual mean and sigma values give an indication of the relative station bias and precision of the data for each satellite during the period, as well as showing current network productivity. For most satellites, short-arc solutions are carried out for all arcs that are tracked pseudo-simultaneously by at least two ILRS stations. The best stations are used to determine small corrections to global long-arc orbit determinations and then residuals are computed for all stations. The results can reveal subtle system changes that occasionally occur during a pass, such as variation of measured range with return signal strength, as well as small errors in the (ITRF2000) values of the station coordinates. All these results are presented daily at:

http://nercslr.nmt.ac.uk/

GLONASS/GPS ORBITAL DETERMINATION

We have continued our study to use SLR observations of the ILRS-campaign GLONASS and GPS satellites to check the quality of the available microwave-based orbital solutions. The SLR observations are used both to generate independent orbits for comparison with the microwave orbits, and in a direct comparison to the positions of the satellites given by the microwave orbits. For the GPS satellites (GPS-35 and -36) the results confirm that on average the satellites are some 40 mm closer to the Earth than is implied by the microwave-based orbits, given of course the accuracy of available data for the location of the on-board retro-reflector arrays. For the GLONASS satellites, after taking into account ranging-system dependent effects due to the large reflector arrays, we find that radial errors are on average close to zero, but that large systematic, possibly seasonal, errors of magnitude up to 30 cm can occur. Unfortunately this work does not impact on the question of the location of the phase centres of the satellites microwave transmitters since the microwave-based orbits are very insensitive to this parameter. The work does, however, suggest that an improvement in the quality of the precise orbits of the GLONASS satellites in particular could be achieved by incorporating SLR data into their derivation.

ILRS ANALYSIS WORKING GROUP PILOT STUDY (POS+EOP)

Effort continues to improve and automate much of the SATAN SLR processing software in order to take part in this pilot project. The analysis was extended during the year to include both LAGEOS and Etalon data and to include solutions for rates of change of Earth rotation parameters, as agreed by the AWG. Monthly LAGEOS solutions for 1999 and LAGEOS+Etalon solutions for 2001 were submitted for subsequent comparison and combination.

SATELLITE PREDICTIONS

Daily and medium-term IRVs along with hourly time bias functions are automatically generated for most of the laser-tracked satellites using up-to-date SLR data. For the designated GLONASS satellites we compute daily IRVS in collaboration with the CODE, Berne, group. All the predictions are available through EDC and on our own anonymous ftp site (mtuftp.nmt.ac.uk; directory nercslr/current), acting as a backup for the official HTSI IRVs.

PHOTOMETRIC OBSERVATIONS OF LAGEOS

In a continuing collaboration with Toshi Otsubo of the Communications Research Laboratory in Japan, we routinely collect ’flash’ photometric data during all nighttime ranging sessions to LAGEOS-1 and -2. The data are processed on-site to determine spin rates for both satellites and precise spin axis orientation results for LAGEOS-2.

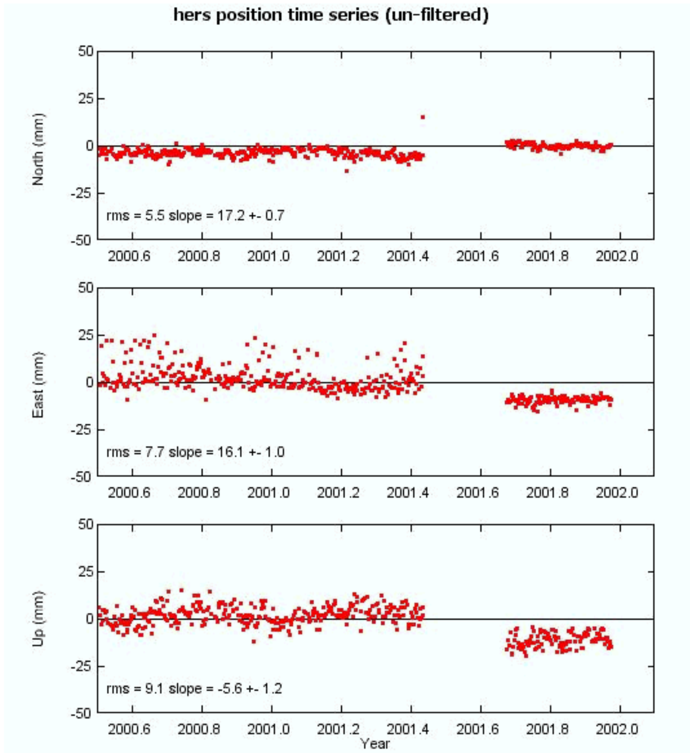

Figure 7.1.2.15-1. Position of Hersmonceux GPS Receiver from SOPAC.

GPS ANSLYSIS

From June 2001 the Ashtech Z18 dual GPS/GLONASS receiver has been contributing regular 30 second sampled data daily to IGLOS. In addition a local archive of one second sampled data is being maintained.

Following the reinstallation of the repaired Ashtech antenna in 2001 August, HERS Z12 data have shown a marked improvement in quality, as shown in the daily coordinates time-series plots below (from Scripps Orbit and Permanent Array Center, San Diego). Data are again being submitted hourly and daily to IGS in the normal way. Daily quality checking software has been developed on site, which will aid in detecting such hardware failures in the future.

RELATED PUBLICATIONS

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System Performance Assessment from NERC Simultaneous Arc Analysis; V.Husson, P.Stevens & G.Appleby.

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Abstract in *Geophysical Research Abstracts, volume 3, 2001*. Monitoring GPS and GLONASS microwave orbits using SLR; G.M.Appleby & T.Otsubo.

ACKNOWLEDGEMENTS

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

7.1.2.16 OCA/CERGA ASSOCIATE ANALYSIS CENTER

Pierre Exertier, Jo lle Nicolas, Pascal Bonnefond, David Coulot, *Centre d'Etude et de Recherche en G ody-namique et Astrom trie, GRASSE — FRANCE*

INTRODUCTION

Besides its involvement in the SLR data acquisition through operation of the Grasse stations (SLR, LLR (high altitude satellites and Moon), and FTLRS deployed in the Corsica island since January 2002, the OCA/CERGA is actively contributing to the ILRS as an Associate Analysis Center (AAC).

We have participated (1) in the analysis of SLR data for calibration/validation (CAL/VAL) activities (TOPEX/Poseidon project in view of Jason-1, GPS, CHAMP, etc.), and (2) in the analysis of LAGEOS-1 and -2 SLR data for carefully analyzing site coordinate time series - in addition to instrument stability including uncertainties relative to atmospheric propagation.

FACILITIES/SYSTEMS

The current computation facilities in the OCA/CERGA consist of two Compaq (DEC-Alpha) workstations. The processing system uses the GINS (GRGS/CNES) software for orbit determination and a suite of locally developed programs for space geodesy analysis.

Concerning geodetic techniques, our AAC is supporting several instruments in collaboration with CNES (Toulouse) and IGN (Paris). These instruments are :

- three laser ranging stations: SLR, FTLRS, and LLR, and
- one permanent GPS receiver.

BACKGROUND

The activities of the OCA/CERGA AAC are primarily focused on the analysis of SLR data from altimeter satellites such as TOPEX/Poseidon (T/P). We have developed a short arc orbit technique for orbit validations and positioning-collocation experiments (geometric approach). This method is based on rigorous adjustment criteria, which can be applied to the entire laser network. These developments and capabilities have been put on a dedicated web site in order to permit the quasi-immediate and continuous validation of T/P orbits. This site can be used to evaluate results of the overall mission; local radial, tangential, and normal orbit residuals; and SLR residuals, eventually per station, are also presented.

After the long phase of improvements, the French Transportable Laser Ranging Station (FTLRS) began observations in its new configuration in summer 2001. In order to validate the new performances of the FTLRS, we used the unique opportunity of having three independent laser ranging stations very close one to each other (about 20 m): a classical satellite laser ranging station (SLR), the French Lunar laser ranging station (LLR), and the FTLRS. Therefore, we performed a collocation experiment between these three instruments from September to December 2001.

This collocation experiment is based on common observations between the three stations on LAGEOS—1 and —2 satellites (altitude of about 6000˚km).

Our analysis, based on all the common normal points, gave us a value of the relative range biases between these three instruments for the two LAGEOS satellites.

- The bias between the Grasse SLR fixed station and the FTLRS is of 4.6 mm on LAGEOS—1 and of 5.7 mm on LAGEOS—2.
- The biases between the Lunar Laser Ranging station and the FTLRS are of 18.6 mm and 18.4 mm for LAGEOS—1 and —2 respectively.
- The range measurement differences between the Lunar Laser Ranging station and the fixed Satellite Laser Ranging station are 13.9 and 12.1 mm respectively.

Combining these LAGEOS—1 and —2 solutions (weighted by the number of normal points), we determined the following relative range biases between the stations: 5.4 mm between the SLR station and the FTLRS, 18.5 mm between the LLR and the FTLRS, and of 13.1 mm between the LLR and the SLR stations. There are technological explanations for the 1 cm difference in the range measurements between the two Grasse fixed stations. The explanation is probably linked to a difference in terms of detection level (multi-photon for the SLR and single photo-electron for the LLR) which may introduce a difference in the satellite signature correction, and may be linked to the systematical LLR return detector center-edge effect on LAGEOS satellites (of about 60˚ps which corresponds to a range of about 9˚mm).

We can so conclude that the improvements of the FTLRS were successful and that the FTLRS seems to be better than the Grasse SLR fixed station. We will have confirmation of this with the analysis of the data of the 2002-campaign performed in Corsica for the Jason-1 CAL/VAL experiment.

CURRENT ACTIVITIES

- Combination of SLR, GPS and gravimetry time series. Analysis of possible regional sources of seasonal variations of g and of the positioning vertical component,
- CAL/VAL activities, see on : http://grasse.obs-azur.fr/cerga/gmc/calval/alt/
- Realization of the Jason-1 CAL/VAL campaign which has been carried out in Corsica (the official site of CNES),

FUTURE PLANS

The OCA/CERGA AAC will continue to develop the same kind of laser data analysis. Our activities for 2002-2003 will be centered on:

- Jason-1 CAL/VAL campaign (realization and data processing).
- realization of the EU GAVDOS project in Crete

Figure 7.1.2.16-1. Laser Ranging at the Grasse Site.

RELATED PUBLICATIONS

Exertier Pierre, Pascal Bonnefond, Jo lle Nicolas, and Fran ois Barlier, *Contributions of Satellite Laser Ranging to past and future radar altimetry missions*, Surveys in geophysics, vol 22(5-6), 491

KEY POINT OF CONTACT

Dr. Pierre Exertier
OCA/CERGA
Avenue Nicolas Copernic
06130 Grasse
France

Tel: +33-(0)439405386
Fax: +33-(0)493405333
e-mail: Pierre.Exertier@obs-azur.fr

7.2 LUNAR LASER RANGING

7.2.1 INTRODUCTION

Peter Shelus, *University of Texas at Austin*

Lunar laser ranging (LLR) is one of the more modern and exotic forms of astrometry. It measures the round-trip travel time of a laser pulse that is emitted from a station on the Earth and returns, after being reflected off of a retroreflector array on the Moon. The analysis of this constantly changing distance, using several stations on the Earth and several retroreflectors on the Moon, provides a diversity of terrestrial, lunar, solar system, and relativistic results. After almost 35 years of operation, LLR remains a technically challenging task. With several tens of highly efficient artificial satellite ranging stations around the world, only two of them have the capability of routinely 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. A third station, the MLRO, in Matera, Italy is on the verge of becoming operational in LLR. A totally new LLR station is being constructed at the Apache Point Observatory in New Mexico in the USA.

The data that is gathered by the LLR stations form a foundation upon which a large number of astronomical disciplines rely. They provide a valuable 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.

7.2.1.1 Paris Observatory Lunar Analysis Center (POLAC)

Jean Chapront, M. Chapront-Touz , G rard Francou, *Observatoire de Paris*

Introduction

The lunar analysis center POLAC is a part of the Department of Fundamental Astronomy at Paris Observatory (DANOF). Beginning in 2002, the work of POLAC will be transferred to the new department SYRTE (SYst me de R f rence Temps-Espace). We work in cooperation with the LLR team of CERGA at Grasse (France). For many years our team has been involved in celestial mechanics studies, especially in the development of analytical solutions for lunar and planetary motions for our publication of solar system bodies ephemerides. Since 1997, we have cooperated with the IERS and our main goals are: to improve the analytical solutions of the orbital and rotational motions of the Moon, to determine the orientation of the dynamical celestial reference frame, and to produce Earth rotation parameters, Universal Time (UT0-UTC) and variation of latitude (VOL) series.

Activities

An analysis of Lunar Laser Ranging (LLR) observations from January 1972 to April 2001 was performed, and a new solution for the lunar orbital motion and librations named S2001 was constructed. The solution methodology was modified by incorporating improvements to the statistical treatment of the data, new nutation and libration models, and the addition of the position of the observing stations to the list of the fitted parameters.

The most recent results concern:

- the secular acceleration of the Moon's mean longitude due to the tidal forces, (table 7.2.1.1-1)
- the correction to the IAU76 luni-solar constant of precession (table 7.2.1.1-2).

In addition to the positioning of the dynamical reference system with respect to the ICRS, a fit of the positions and velocities of the LLR stations was done.

The total post-fit residuals fit (root mean square error) is within two to three centimeters in the lunar distance for recent observations provided by the two modern instruments: MLRS2 for McDonald and YAG for the CERGA. The following tables present some of our results.

Table 7.2.1.1-1: Tidal acceleration of the lunar mean longitude (in arcsecond/cy^2) compared with the Jet Propulsion Laboratory values.

Sources	Value	Publication
S2001	-25.858	2001
JPL DE405	-25.826	1998
JPL DE403	-25.580	1995
JPL DE200	-23.895	1982

Table 7.2.1.1-2: Correction to the IAU 1976 precession constant Δp in (in arcsecond/cy) and offsets of Celestial Ephemeris Pole at J2000.0 $-\psi \sin\varepsilon$ and $\Delta\varepsilon$ (in arcsecond).

Method Source	Δp	$\psi \sin\varepsilon$	$\Delta\varepsilon$
LLR S2001	0.302±0.003	0.0177±0.0004	0.0054±0.0002
VLBI Fukushima	0.297±0.004	0.0167±0.0005	0.0049±0.0003

The uncertainties are formal errors

Table 7.2.1.1-3. Time distribution of the post-fit residuals (rms)

Observatory and *instrument*	Time Interval	S2001 rms	N
McDonald	1972-1975	43.5	1487
Telescope 2.70 m	1976-1979	27.7	1035
and *MLRS1*	1980-1986	29.1	990
CERGA *Rubis*	1984-1986	18.7	1165
Haleakela	1987-1990	6.3	451
McDonald	1987-1991	5.8	232
MLRS2	1991-1995	4.6	586
	1995-2001	3.3	1669
CERGA	1987-1991	5.3	1574
Yag	1991-1995	3.9	2044
	1995-2001	3.0	3273

N is the number of LLR normal points involved.

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POINTS OF CONTACT

Authors: Jean Chapront, Michelle Chapront-Touze, Gerard Francou
Address: Observatoire de Paris (SYRTE), 61 avenue de l'Observatoire, 75014 Paris, France
Contact : jean.chapront@obspm.fr

7.2.1.2 FORSCHUNGSEINRICHTUNG SATELLITENGEOD SIE (FESG) / INSTITUT F R ERDMESSUNG (IFE)

J rgen M ller, *FESG/IFE*

STATUS

At the FESG (Research Facility for Space Geodesy), the LLR data have been analyzed in March 2001 to provide a set of station coordinates (SSC) in SINEX format as well as Earth orientation parameters (EOP) for the IERS annual report. The parameter determination was based upon all LLR data available since 1970, about 14,350 normal points.

The investigation of tidal effects has been finished (first results were shown in the ILRS annual report 2000) and the main results have been published; see M ller and Tesmer (2002) and M ller et al. (2002).

We have improved the software for the detection of the real lunar returns in the very noisy, raw observations at Wettzell. To improve the visibility of the LLR measurements in the noise, a semi-pulse pattern was incorporated in the transmitted signal (and thus in the received time series). This specific feature could be used to detect the real lunar returns in the raw observations by applying a correlation procedure. Figure 7.2.1.2-1 shows the improvement in the processed data. On the left hand side, the original observations are indicated in the usual histogram representation, where no lunar returns can be identified at all. On the right hand side, the resulting post-correlation histogram based upon the same observational data as before, is shown. The lunar returns are clearly visible now. For more details see Meyer et al. (2002).

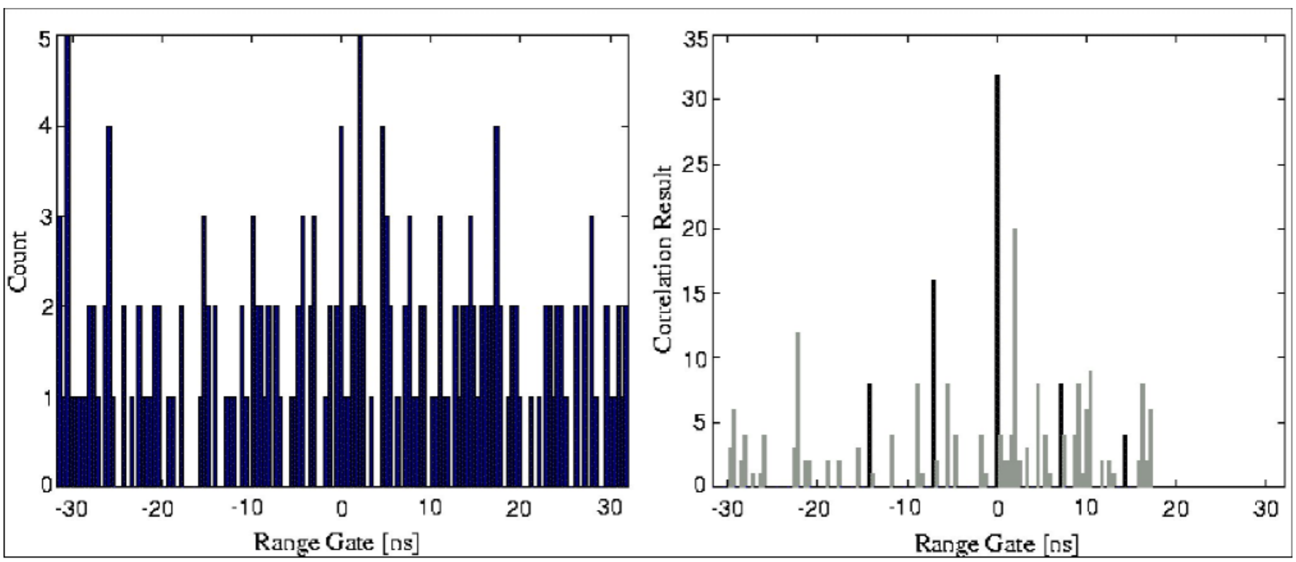

Figure 7.2.1.2-1: Comparison of LLR observations before and after applying the correlation procedure.

CURRENT ACTIVITIES AND FUTURE PLANS

In October 2001, J rgen M ller moved from the Technical University Munich to the Institute of Geodesy (Institut f r Erdmessung) at the University of Hannover, where the LLR activities will be continued in cooperation with the FESG. As a first step, the software has been implemented on a PC. Now the fine-tuning of the software is under progress, to be able to provide the LLR parameters with highest accuracy.

Moreover, we plan to prepare a further version of the LLR software package for implementation at Wettzell, which shall be used for the calculation of the normal points as well as for the computation of the standard LLR products, i.e. EOPs and station coordinates.

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KEY POINT OF CONTACT

Prof. Dr.-Ing. J rgen M ller
University of Hannover
Institut f r Erdmessung
Schneiderberg 50
30167 Hannover, Germany
e-mail:° mueller@ife.uni-hannover.de
phone: ++49 (0)511-762-3362
fax :°°°° ++49 (0)511-762-4006

7.2.1.3 *JET PROPULSION LABORATORY (JPL)*

J. G. Williams, D. H. Boggs, J. O. Dickey, and J. T. Ratcliff, *Jet Propulsion Laboratory*

STATUS

Analyses of laser ranges to the Moon are used for a variety of investigations: lunar science, gravitational physics, geodesy, geodynamics and astronomy. Lunar Laser Ranging (LLR) analyses provide determinations of the Moon's tidal acceleration, orbit, three-dimensional rotation (physical libration), and tidal deformation, determinations of fundamental constants and the Earth's rotation, orientation, precession, station locations and motions, and tests of gravitational physics. 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.

ACTIVITIES

Lunar laser ranges (LLR) are regularly received from the Observatoire de la Cote d'Azur (Grasse 7845) and McDonald Observatory (7080) sites. Four lunar retroreflector arrays are ranged, but about 80% of the data comes from the largest array at the Apollo 15 site. Global solutions for a number of parameters fit range data from recent years with a weighted rms scatter of 17 mm. The ranges are processed at frequent intervals for Earth rotation information and the resulting sequences of UT0 and variation of latitude values for the two stations are input to the JPL Earth rotation filter. Tables of Earth rotation derived from a combination of techniques are available at the ftp site:

ftp://euler.jpl.nasa.gov/keof/combinations

Files and documentation for lunar and planetary ephemerides and lunar physical libration are available to the scientific community at the web site http://ssd.jpl.nasa.gov/horizons.html.

The tidal acceleration of the Moon has been computed for several ephemerides based on iterated solutions. The acceleration in mean longitude due to dissipative effects is -25.7 arcs/cent^2, of which -26.0 arcsec/cent^2 is due to tides on Earth and +0.3 arcs/cent^2 is due to tidal and fluid core dissipation in the Moon. The tidal increase in semimajor axis is 38 mm/yr.

Dissipation in the Moon is investigated in (Williams, 2001). The solid-body tidal Q is low and has a weak dependence on tidal period. A fluid core is indicated with a size about 20% of the Moon's dimension. An oblate core-mantle boundary (CMB) can influence the determination of the Love number k_2. Preliminary attempts allowing for CMB oblateness give a lunar Love number k_2=0.0266, with uncertainty 0.0027 (5). A low velocity zone may be present above the core.

Uncertainties continue to tighten for tests of gravitational physics. The Earth and Moon are accelerated alike in the Sun's gravitational field to within 1.5 parts in 10^{13} (Anderson, 2001). This equivalence principle test is sensitive to differences between Earth and Moon due to both composition and gravitational self-energy. Tests of the relativistic geodetic precession and the Parameterized Post Newtonian (PPN) beta and gamma agree with Einstein's General Relativity (Williams, 2002). The equivalence principle test limits the beta uncertainty to 0.0005 (Anderson, 2001). The gravitational constant G has no detectable rate for dG/dt / G within 1.1x10^{-12} /yr (Williams, 2002).

FUTURE PLANS

Data analysis models will be improved and lunar laser ranges will be processed. Earth rotation results will continue to be generated. Investigation of lunar science and gravitational physics will continue along with lunar ephemeris and physical libration development. Ranges from several sites on the Earth to the several retroreflectors on the Moon are valuable. We will process data from sites with existing and future (Murphy, 2001) lunar capability.

RECENT PUBLICATIONS

J. D. Anderson and J. G. Williams, Long-Range Tests of the Equivalence Principle, Classical and Quantum Gravity, 18, 2447-2456, 2001.

J. G. Williams, D. H. Boggs, C. F. Yoder, J. T. Ratcliff, and J. O. Dickey, Lunar Rotational Dissipation in Solid Body and Molten Core, J. Geophys. Res. Planets, 106, 27933-27968, 2001.

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ABSTRACT

J. G. Williams, D. H. Boggs, J. T. Ratcliff and J. O. Dickey, Lunar Love Numbers and the Deep Lunar Interior, abstract #2033 of the Lunar and Planetary Science Conference XXXIII, March 11-15, 2002.

KEY POINTS OF CONTACT

Name	e-mail	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

7.2.1.4 UNIVERSITY OF TEXAS MCDONALD OBSERVATORY LUNAR ANALYSIS CENTER (UTXM)

Judit Ries, *University of Texas at Austin*

STATUS

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 monthly Earth Orientation Parameters (EOP) from 1989 through 2000, switching to annual production in 2001, and also supplies predictions for lunar data acquisition and carries out internal quality control.

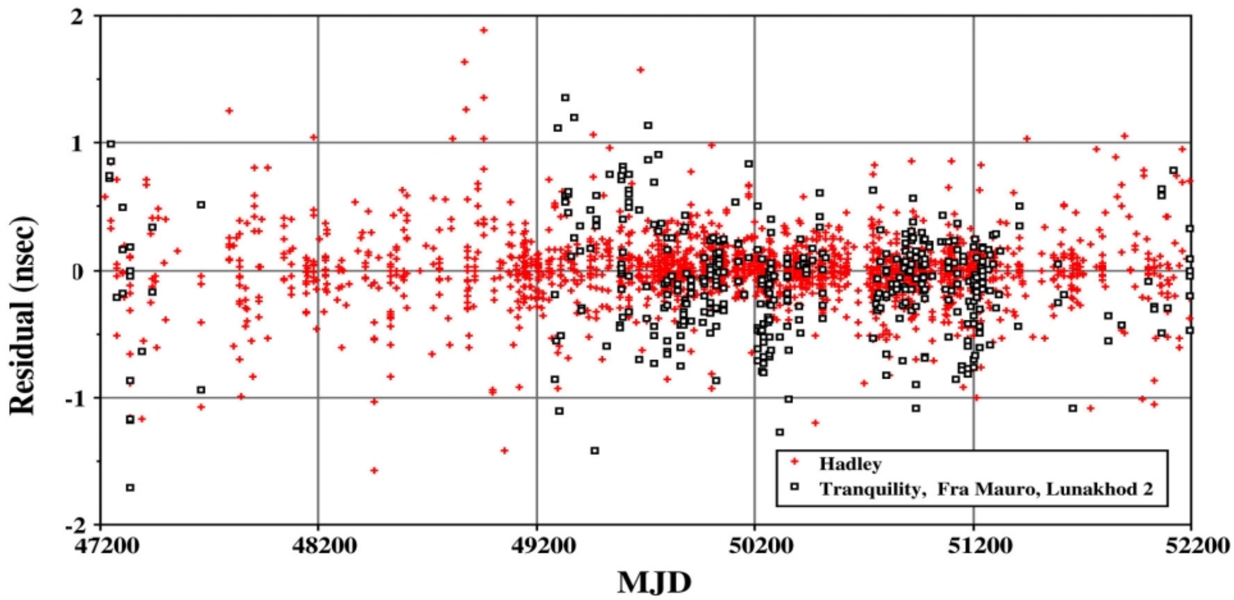

Figure 7.2.1.4- 1. Residuals for 2578 MLRS normal points including all retro-reflectors February 1988 to December 2001

CURRENT ACTIVITIES

- Using all available the LLR data, we adjust a number of global parameters of the Earth Moon system and station and reflector parameters. We assume that the remaining nightly signature is due to UT1R error in the smoothed a priori series we use. For nights with sufficient data we can remove this signal. The residuals show a normal distribution with a mean of 1.15×10^{-2} nsec, and 0.22 nsec weighted RMS. The fit to the data from the Mt. Fowlkes site is shown on Figure 7.2.1.4-1. (The slope of the linear fit to the residuals is practically zero, 1.1×10^{-5} nsec/day).
- We have calculated a total of 34 UT0 - UTC values in 2001, 26 from OCA and 8 from MLRS reflector 3 (Hadley, Apollo 15), data, based on 382 normal point provided by the two active stations. 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.
- We converted the UT0 and variation of latitude estimates to UT2-TAI using the a priori polar motion values to compare our results with IERS Bulletin A EOP series, as seen on Figure 7.2.1.4-2.

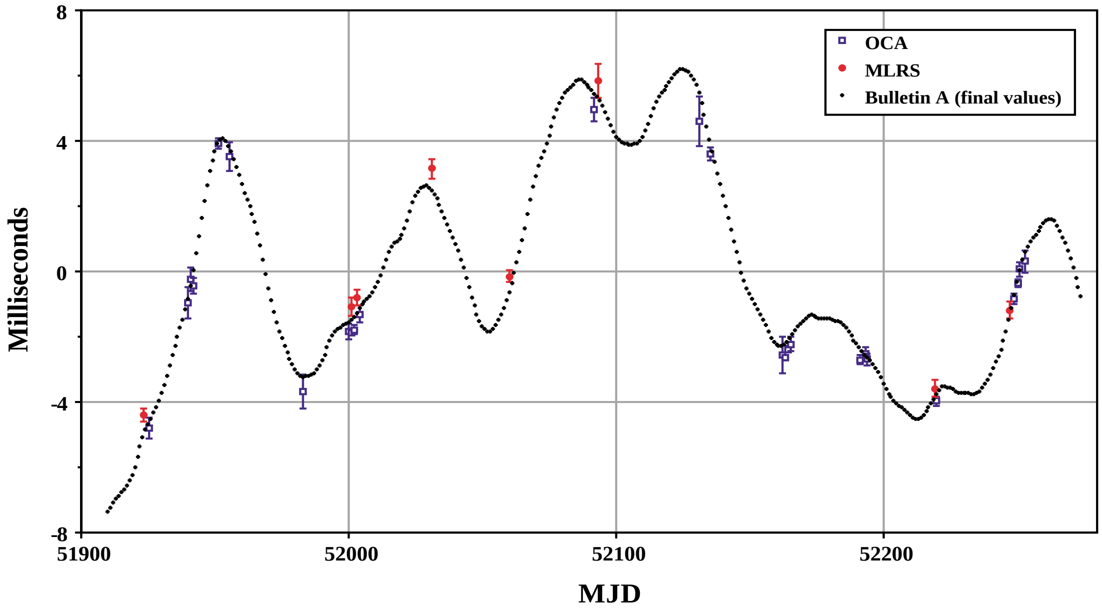

Figure 7.2.2.4-2. UT2-TAI with -0.589 msec/day slope removed (January 1 — December 31, 2001)

FUTURE PLANS

We will continue to provide annual EOP series to the community, while improving the quality and the stability of our solution. We hope to work on the simultaneous processing of LLR data and SLR data as the second step in truly unifying laser data handling.

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KEY POINT OF CONTACT

Author : Judit Gy rgyey Ries
Address : The University of Texas at Austin, Austin, TX 78712, USA
Contact: moon@astro.as.utexas.edu

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