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INTERNATIONAL LASER RANGING SERVICE

2005–2006

REPORT

October 2007

Edited by C. Noll and M. Pearlman

Goddard Space Flight Center
Greenbelt, MD 20771

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PREFACE

This 2005-2006 volume is the fifth published report for the International Laser Ranging Service (ILRS). This edition once again concentrates on achievements and work in progress rather than ILRS organizational elements. The 2005-2006 ILRS report is structured as follows:

- Section 1 – ILRS Organization, reviews the service and its role in space geodesy.
- Section 2 – ILRS Tracking Network, ILRS Tracking Network, provides the current status and recent performance statistics of the international stations supporting the ILRS and offers a perspective on site surveys and system collocations. An update on field engineering activities is also provided.
- Section 3 – ILRS Missions and Campaigns, gives information about many of the current and future missions supported by the ILRS.
- Section 4 – Infrastructure, details recent activities tackled by the ILRS Central Bureau, including Web site improvements and data center developments.
- Section 5 – Tracking Procedures and Data Flow, discusses satellite predictions, ILRS tracking priorities, recent developments in the area of dynamic priorities, and the flow of on-site normal points and full-rate data.
- Section 6 – Emerging Technologies, includes information about high repetition rate lasers and systems, detectors, timers and frequency standards, multi-wavelength ranging, and other hardware that will help advance the accuracy and automation of laser ranging systems. Also included are new applications for the SLR technique.
- Section 7 – Analysis Activities, reviews the recent developments in the ILRS Analysis Working Group including the three pilot projects begun in 2002, Computation of Station Positions and EOPs, Orbits, and Software Benchmarking.
- Section 8 – Modeling, discusses recent advancements in refraction modeling and satellite center of mass corrections.
- Section 9 – Science Report examines the ILRS role in the ITRF, its synergy with the other geodetic techniques, and some interesting applications for both SLR and LLR.
- Section 10 – Meetings and Reports, reviews ILRS-related meetings in 2005-2006 and reports issued by the service over that period.
- Section 11 – Bibliography, lists some of the papers and presentations about SLR and LLR science and technology made during 2005-2006.
- Section 12 – AC, AAC, and Lunar AAC Reports, presents individual summaries from ILRS analysis and associate analysis centers.
- Section 13 – Station Reports, includes information received from the stations contributing to the ILRS network.
- Appendix A – ILRS Information, lists organizations participating in the ILRS and defines acronyms used in this report.

This report is also available through the ILRS Web site at URL
http://ilrs.gsfc.nasa.gov/reports/ilrs_reports/ilrsreport_2005.html.

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A complete list of ILRS associates can be found on the ILRS Web site at
http://ilrs.gsfc.nasa.gov/contact_ilrs/ilrs_netdir.html.

Acknowledgement

The editors would like to acknowledge the essential contributions from our ILRS colleagues to this 2005-2006 edition of the ILRS report.

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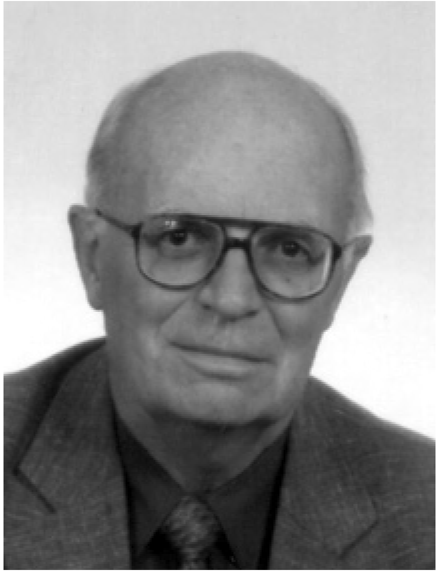


Professor Karel Hamal, 1932—2007
Czech Technical University, Prague

The ILRS community was very sad to learn of the passing of Professor Karel Hamal on Thursday, February 8, 2006, at the age of 74. Since 1987, Karel had held the prestigious position of Professor in Quantum Electronics within the Faculty of Nuclear Sciences and Physical Engineering, Department of Physical Electronics at the Czech Technical University (CTU) in Prague.

Karel received his Engineering Diploma (equivalent of an MS) in Electrophysics from MTA Brno in 1955. After spending his early technical career working on microwave systems and radar for the Tesla Radio Communication Company, he joined CTU in 1962 where he became interested in the new field of laser physics and later earned his CSc (equivalent of Ph.D.) and Doctor of Science degrees in Technical Sciences in 1967 and 1979 respectively.

Karel was an early and active proponent of Satellite Laser Ranging for Earth science in Europe. Under Karel's able technical leadership, the first of the Soviet INTERKOSMOS network stations began successful operations in Ondrejov, Czechoslovakia in 1972. He and George Weiffenbach were the original organizers of the SLR Workshop series; Karel sponsored the second SLR workshop in Prague in August 1975. First generation INTERKOSMOS stations were later deployed internationally at several Soviet AFU 75 optical camera sites, including sites in Bolivia, Cuba, and India. During the early 1990's — under a joint program between the Smithsonian Astrophysical Observatory, the Technical University of Prague, the Soviet Academy of Sciences, and the Helwan Institute for Astronomy and Geophysics — Karel led the establishment of a much needed centimeter accuracy SLR station on the African continent in Helwan, Egypt. In 2002, the ILRS presented Professor Hamal with one of only two "SLR Pioneer Awards" to date in recognition of his early technical and programmatic leadership in developing and deploying the INTERKOSMOS systems, which enabled a truly global satellite laser ranging network in support of Earth science.

During his long tenure at CTU, Karel established a world-class laboratory in Prague, which collaborated with researchers around the globe. In the process, he educated generations of students and researchers both at home and abroad and left his mark on SLR stations from the Americas to Asia and Australia. Over three decades of SLR workshops, Karel and his team presented papers on picosecond lasers, nonlinear optics, fast photon-counting detectors, precision timing, multiwavelength ranging, atmospheric propagation experiments, and calibration standards. In addition to SLR, Karel's laboratory routinely made important and original technical contributions to a number of other disciplines, including plasma physics, atmospheric lidar, and the applications of lasers to medicine. In the late 1990's, two deep space probes carried his laser ranging and photon counting devices toward the planet Mars and another two space missions under development in Europe and China will be launched into Earth orbit soon.

The ILRS wishes to dedicate this report to the memory of Professor Karel Hamal, in grateful recognition of his many technical and programmatic contributions to SLR, which spanned four decades. He will be missed by his SLR colleagues around the world.

John J. Degnan

Introduction

THE INTERNATIONAL LASER RANGING SERVICE 2005-2006

According to the brochure *CDDIS, NASA's Archive of Space Geodesy Data* "the ILRS is operational since 1998 collects, archives, and distributes global satellite and lunar laser ranging data and their related products. The ILRS provides products important to the IERS".

Let us look in more detail at some of these contributions. The ILRS contributions are of crucial importance for the definition of the datum parameters of the ITRF (International Terrestrial Reference Frame). It is undisputed that only the ILRS is capable of providing a meaningful realization of the geocenter, nominally the origin of the ITRF, through the observation of specially designed geodetic satellites like LAGEOS-1 and -2, Etalon-1 and -2, and others. The ILRS furthermore contributes to the definition of the ITRF scale – to what extent this should be the case is currently an issue of heated debate among analysts in space geodesy. It is, however, clear from the measurement type point of view (see remarks below) that SLR must continue contributing to this datum parameter, as well. The ILRS of course also contributes to the establishment of the Earth Rotation Parameters (ERPs) and the ITRF network of fundamental stations. In summary, one can say that the ILRS is badly needed to monitor the geometric properties of the Earth together with other mature space geodetic techniques VLBI (Very Long Baseline Interferometry) and GNSS (Global Navigation Satellite Systems).

Prior to the launch of CHAMP in the year 2000, SLR was the only technique capable of providing an accurate global gravity field with a rather high spatial resolution. Today, the SLR-derived gravity field is still used to determine the orbits of the GNSS satellites. With the advent of the dedicated gravity field missions CHAMP, GRACE, and GOCE (early in 2008), Low Earth Orbiters (LEOs) equipped with continuously operating GPS receivers, (ensembles of) accelerometers, and, in the case of GOCE, ultra-precise satellite-to-satellite measurements, the temporal and spatial resolution of the gravity field determination and the accuracy of the coefficients have dramatically improved.

Does this development imply that SLR was ruled out early in the 21st century as an indispensable tool for gravity field determination? The answer to this question is clearly "no". Whereas the SLR technique cannot provide the high spatial and temporal resolution of gravity field determination (mainly due to the lack of continuous observation), the technique is and will remain indispensable in three respects: (a) as a very objective, accurate, and direct calibration tool to validate LEO orbits (established by GPS point positioning) by ranging to the LEOs, (b) to define the lowest degree and order coefficients of the gravity field including their time variation, and (c) to validate the gravity fields resulting from new space missions. The recent developments are, in a way, parallel (or analogous) to the development of GNSS for the purpose of defining and maintaining the ITRF: The importance of SLR for the determination of the low degree and order terms of the gravity field are caused on one hand by the comparatively poor performance of accelerometers in the low frequency domain and, on the other hand, by the simple, but extremely powerful concept of cannonball satellites to diminish teh effects of and model non-gravitational forces (or to make the residual effects easy to account for in the analysis).

This brings me to one more important aspect of laser ranging: It is the only technique, which is not based on the microwave part of the electromagnetic spectrum, which means that atmospheric refraction may be taken into account on the (sub-)cm level using simple meteorological measurements at the SLR/LLR observatories and appropriate atmospheric models. Also, SLR and LLR measure directly the round-trip travel times of signals using the same timing device for both transmission and reception – which avoids the cumbersome clock synchronization problem of other techniques. Therefore SLR/LLR provides not only measurements of a high precision, but also of high accuracy in space geodesy. SLR/LLR measurements are unambiguous, almost unaffected by atmospheric refraction (after appropriate reduction), and the scale of the measurements is uniquely defined by the speed of light. This makes SLR very attractive for calibrating GNSS-derived products (in particular orbits). In the years covered by this report we learned a great deal about the signature of systematic errors of GNSS orbits using SLR ranges to these satellites. We would know even more, and it would be much easier to study and (hopefully) remove the systematic errors of GNSS-derived orbits, if SLR measurements were not only available to two GPS satellites (of the same type, in the same orbital plane) and to a subset of GLONASS satellites, but ideally to all GNSS satellites used for precise positioning. There are strong scientific arguments to equip all GNSS satellites with laser reflectors. Co-location of observation techniques is not only important for the terrestrial network(s), but also in space! This aspect of laser ranging is extremely important. It is, for example, exploited to calibrate altimetry missions, but should be used (as indicated above) for a much broader class of satellites.

So far, I uniquely discussed the benefits of SLR. We must also recognize the deep scientific impact of LLR. If you consult the two-volume work *Methods of Celestial Mechanics* written by the author of this introduction you can see that the area/mass ratio of the Moon is about seven orders of magnitude smaller than for the best available geodetic satellites (LAGEOS-1 and -2). This makes the Moon an almost perfect probe in the gravity field of the Earth, the Sun, and the other bodies of our planetary system. Currently the Moon is the only target accessible to precise ranging. I am somewhat concerned that LLR is currently performed on a rather moderate level. This of course reduces the scientific return. I hope that the revitalized (political and) scientific interest in our "cosmic companion" will cure this problem. It would be fascinating and extremely rewarding if new technologies, such as those based on optical transponder technology, would render ranging to the Moon and to neighbouring planets accessible to other than "only" the specialized LLR observatories.

Let me congratulate the ILRS community not only for its very successful worldwide laser operations and its implementation of new technologies to improve ranging capabilities, but also for keeping the interest in this fascinating technique stimulated, through the timely publication of this biannual report and by organizing the various ILRS workshops. On the occasion of my participation in the 15th International Workshop on Laser Ranging in Canberra in October 2006, I was able to see that the community is, what it always was: a group of very creative and innovative scientists and engineers working to the benefit of space geodesy.

Let me conclude with the standard SLR/LLR salute: ***Many happy returns!***

Gerhard Beutler
President of IAG
Astronomical Institute
Bern, Switzerland

Chairman's Remarks

The ILRS bi-annual reports as well as the proceedings of the International Laser Ranging Workshops are the main publications for the timely announcement and description of the activities of the International Laser Ranging Service. In particular the reports offer the participants the opportunity to present their inputs on procedures and to discuss their ideas and innovations on equipment. The reports usually include performance information prepared by the ILRS Central Bureau.

Several significant events impacted the ILRS during the past two years:

- The two stations, Arequipa and Haleakala (Maui), were temporarily closed by NASA for budgetary reasons in 2004 and again reopened in late 2006; Haleakala was newly equipped with the transportable TLRS-4 system previously upgraded at Goddard Space Flight Center;
- A new Chinese SLR station was installed at San Juan, Argentina, and in 2006 very quickly became one of the most productive stations of the network, a most welcome improvement to the network geometry and performance, especially of the southern hemisphere;
- Most of the stations migrated to the new consolidated prediction format by the end of 2006. The change introduced a significant improvement in the quality of predictions facilitating acquisition especially on difficult targets;
- A number of ILRS stations implemented the new restricted tracking procedures and successfully demonstrated their new capability to track vulnerable satellites, such as ICESat and ALOS.

Under the IAG, the Global Geodetic Observing System (GGOS) has been organized as a project to enhance the cooperation among the measurement services and strengthen the outreach and better educate the user community and the funding agencies on the importance of the geodetic infrastructure to Earth science and applications. The ILRS strongly supports the GGOS project in its role of making government and large institutions (especially space and geodetic agencies) aware of the importance of high-quality geodetic services as basis for all global and regional geo-reference activities including global change.

In October 2006 we again enjoyed a well-organized International Laser Ranging Workshop, this time in Canberra, Australia. I would like to express my thanks to the organizers and sponsors, Geoscience Australia and Electro Optics Systems (EOS) for this wonderful and very beneficial event.

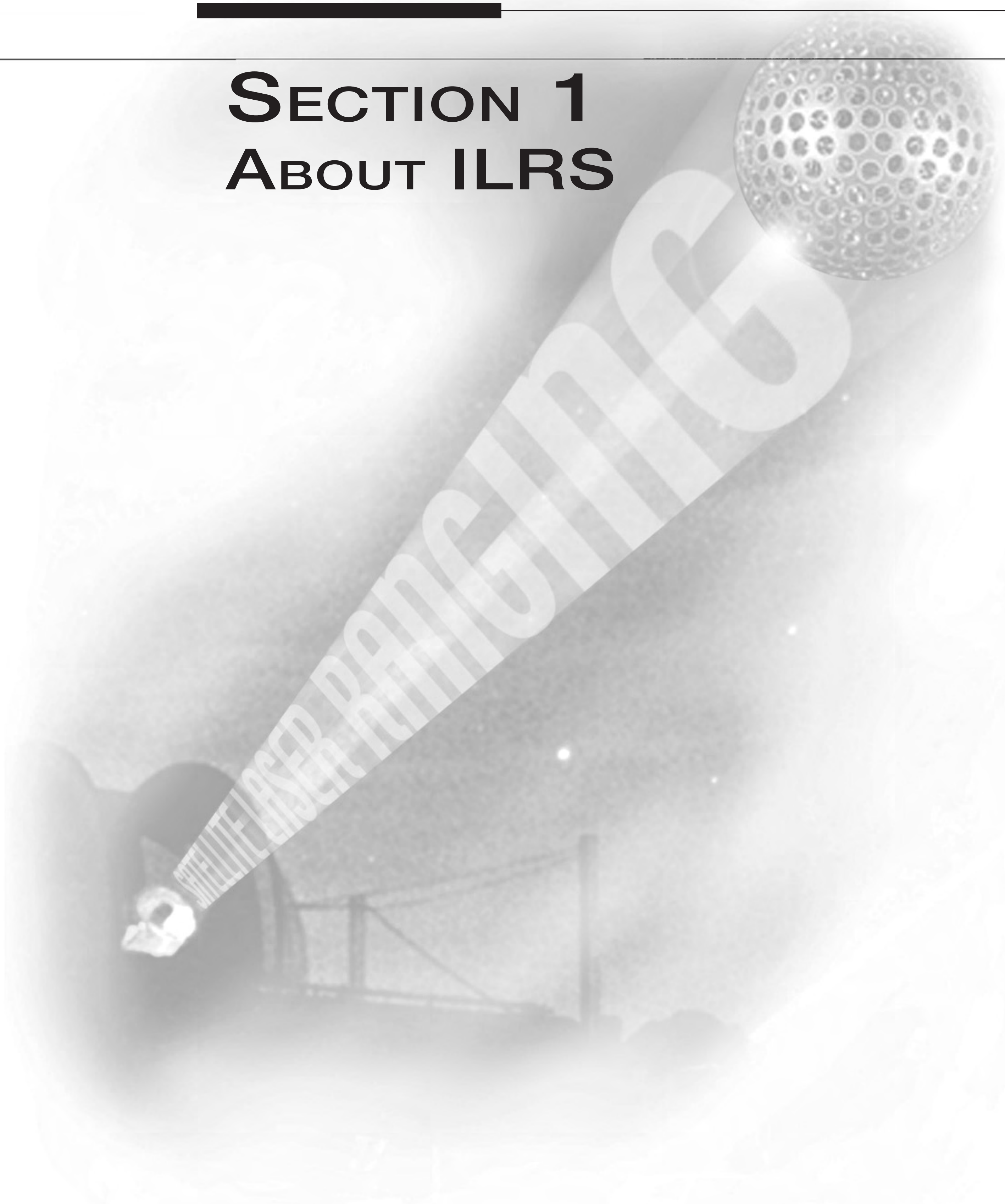
It has become a tradition now to have a smaller, more dedicated workshop in the years between the big workshops. RGO organized the Herstmonceux workshop in the fall of 2005 in Eastbourne, a nice city at the seashore of the English Channel. The next such event is scheduled for September 25-28, 2007 in Grasse.

The first ITRF realization based on technique-dependent weekly time series (ITRF2005) produced by the IGN showed significant discrepancies between the average heights of the reference stations (“scale” of the reference frame) of the VLBI and SLR contributions. As of now the reason is unclear, but investigations are underway. This example clearly shows the need to have multiple geodetic techniques available to identify (and hopefully eliminate) technique-dependent systematic errors or possibly other subtleties in the measurements and the analyses.

I would like to thank all of our colleagues in the tracking network, at the Central Bureau, in the analysis and data centers, and those who undertook additional duties as working group chairs or members, for their continuous contribution to our Service. Special thanks of course to the agencies, institutions and foundations for their ongoing financial support of our activities.

Werner Gurtner
Chairman, ILRS Governing Board
Astronomical Institute
Bern, Switzerland

SECTION 1
ABOUT ILRS



SECTION 1

ILRS ORGANIZATION

The Mission of the ILRS

Michael Pearlman/CfA

The International Laser Ranging Service (ILRS) organizes and coordinates Satellite Laser Ranging (SLR) and Lunar Laser Ranging (LLR) to support programs in geodetic, geophysical, and lunar research activities and provides the International Earth Rotation Service (IERS) with products important to the maintenance of an accurate International Terrestrial Reference Frame (ITRF). This reference frame provides the stability through which systematic measurements of the Earth can be made over thousands of kilometers, decades of time, and evolution of measurement technology. The Service provides precision ephemerides to support active Earth sensing missions and is now preparing to support extraterrestrial missions with optical transponders. The ILRS is one of the technique services of the International Association of Geodesy (IAG) and is now a participant in the Global Geodetic Observing System, GGOS.

The Role of the ILRS

The International Laser Ranging Service (ILRS):

- coordinates activities for the international network of SLR stations;
- develops the standards and specifications necessary for product consistency;
- develops the priorities and tracking strategies required to maximize network efficiency;
- collects, merges, analyzes, archives and distributes satellite and lunar laser ranging data to satisfy user needs;
- provides quality control and engineering diagnostics to the global network;
- works with new satellite missions in the design and building of retroreflector targets to maximize data quality and quantity;
- works with science programs to optimize scientific data yield; and
- encourages the application of new technologies to enhance the quality, quantity, and cost effectiveness of its data products;

ILRS Data Products

Official Submission to the IERS

- Weekly solutions for station coordinates and Earth Orientation Parameters (EOPs) for the derivation of scale (Gm) and time-varying Earth Center of Mass for the ITRF

Other User Products

- Static and time-varying coefficients of the Earth's gravity field
- Accurate satellite ephemerides for POD and validation of altimetry, relativity, and satellite dynamics
- Backup POD for other missions
- Lunar ephemeris for relativity studies and lunar libration for lunar interior studies

The Structure of the ILRS

The ILRS is composed of the following components, shown in Figures 1-1 and 1-2:

- Forty Satellite Ranging Stations that provide ranging data on an hourly basis and two Lunar Ranging Stations;
- Three Operations Centers that collect and verify the satellite data and provide the Stations with sustaining engineering, communications links, and other support;
- Two Global Data Centers that receive and archive data and supporting information from the Operations Centers and provide these data to the Analysis Centers; and receive and archive ILRS scientific data products from the Analysis Centers and provide them to the users;
- Two Combination Centers that prepare the ILRS weekly data product for the IERS; six SLR Analysis Centers that provide the input solutions to the Combination Centers for the data product process, eighteen Associate Analysis Centers that provide specialized SLR products to the users community and provide a second level of data quality assurance in the network; and four Lunar Analysis Centers that provide lunar data products;
- Five ILRS Working Groups that provide technical expertise and help formulate policy;
- ILRS Central Bureau that is responsible for the daily coordination and management of ILRS activities including communications and information transfer, monitoring and promoting compliance with ILRS network standards, monitoring network operations and quality assurance, maintaining documentation and databases, and organizing meetings and workshops;
- Governing Board that is responsible for general direction, defining official ILRS policy and products, determining satellite-tracking priorities, developing standards and procedures, and interacting with other services and organizations.

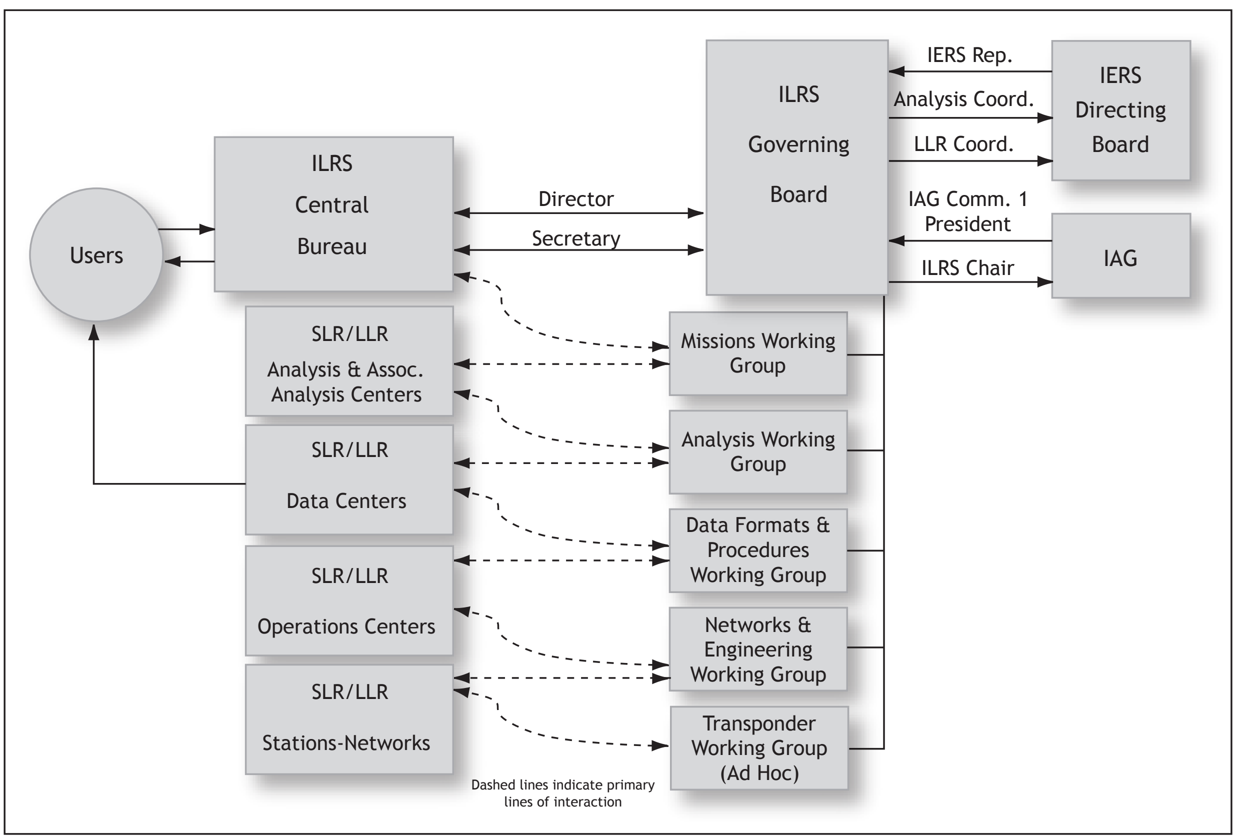


Figure 1-1. ILRS Organization

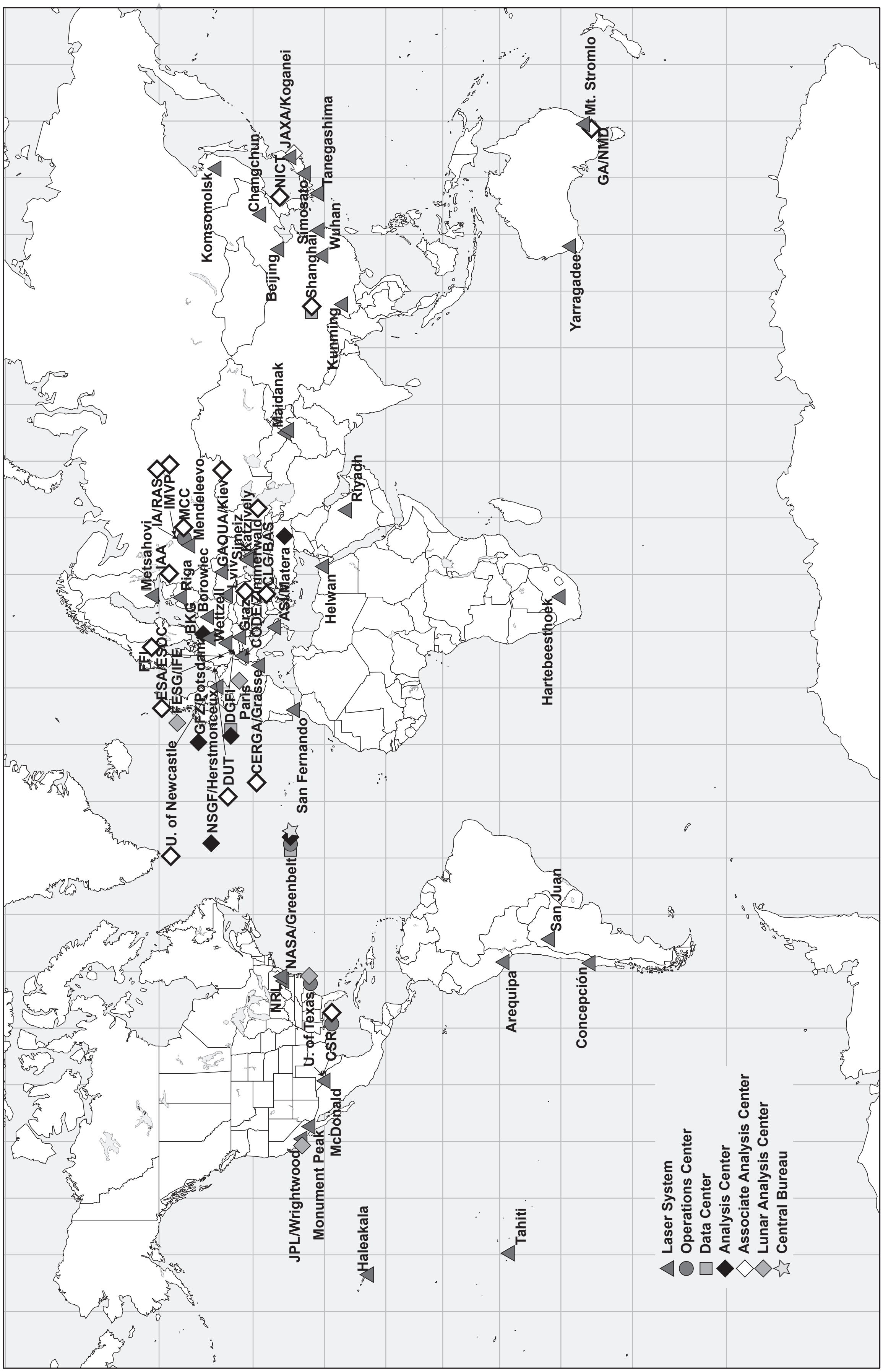


Figure 1-2. Components of the ILRS in 2005-2006.

ILRS Information and Outreach

The ILRS Central Bureau (staff shown in Figure 1-3) maintains a comprehensive Web site as the primary vehicle for the distribution of information within the ILRS community and as a means of outtreach. The site, which can be accessed at: *http://ilrs.gsfc.nasa.gov* is also available at a mirrored site at the European Data Center (EDC) in Munich. The ILRS also provides service-wide bulletins on SLRmail and ILRS exploders and specialized bulletins through Working Group and Urgent Mail exploders.

Figure 1-3. ILRS Central Bureau staff (left to right): Frank Lemoine, Julie Horvath, Peter Dunn, Erricos Pavlis, David Carter, Mark Torrence, Mike Pearlman (director), Carey Noll (secretary).

ILRS Governing Board

Name: Graham Appleby

Position: At-Large Representative

Affiliation: Natural Environmental Research Center (NERC) Space Geodesy Facility (NSGF), UK

Name: Yang Fumin

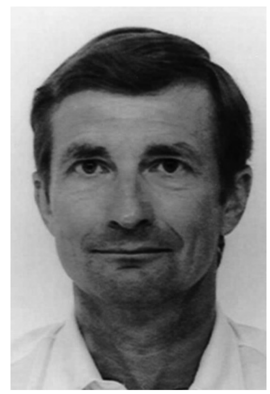
Position: WPLTN Network Representative

Affiliation: Shanghai Astronomical Observatory (SAO), China

Name: Giuseppe Bianco

Position: EUROLAS Network Representative

Affiliation: Agenzia Spaciale Italiana (ASI), Italy



Name: Werner Gurtner

Position: Chairman and EUROLAS Network Representative

Affiliation: Astronomical Institute, University of Bern (AIUB), Switzerland

Name: David Carter

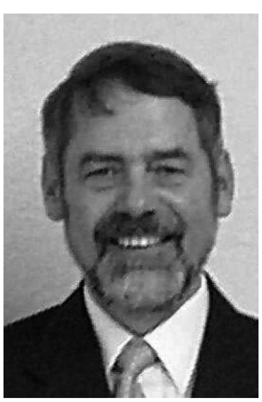
Position: NASA Network Representative

Affiliation: NASA Goddard Space Flight Center, USA

Name: Georg Kirchner

Position: At Large Representative

Affiliation: Austrian Academy of Sciences, Austria



Name: Herman Drewes

Position: Ex-Officio, President of IAG Commission 1

Affiliation: Deutsches Geodätisches Forschungsinstitut (DGFI), Germany

Name: Hiroo Kunimori

Position: WPLTN Network Representative

Affiliation: National Institute of Information and Communications Technology (NICT), Japan

ILRS Governing Board (continued)

Name: Vincencia Luceri

Position: Analysis Center Representative

Affiliation: Telespazio S.p.A./Centro di Geodesia Spaziale, Italy

Name: Erricos Pavlis

Position: Analysis Center Representative

Affiliation: Joint Center for Earth Systems Technology (JCET) and Goddard Space Flight Center (GSFC), USA

Name: Jan McGarry

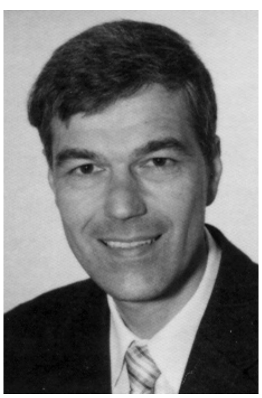
Position: NASA Network Representative

Affiliation: NASA Goddard Space Flight Center, USA

Name: Michael Pearlman

Position: Ex-Officio, Director, ILRS Central Bureau

Affiliation: Harvard-Smithsonian Center for Astrophysics (CfA), USA



Name: Jürgen Müller

Position: Lunar Representative

Affiliation: U. of Hannover/Institut für Erdmessung (IFE), Germany

Name: Bob Schutz

Position: IERS Representative to ILRS

Affiliation: Center for Space Research (CSR), University of Texas, USA

Name: Carey Noll

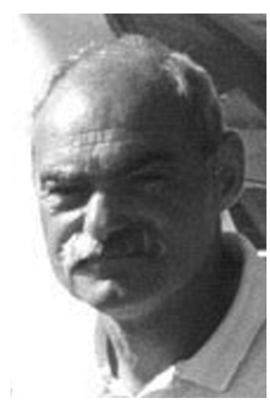
Position: Ex-Officio, Secretary, ILRS Central Bureau

Affiliation: NASA Goddard Space Flight Center, USA

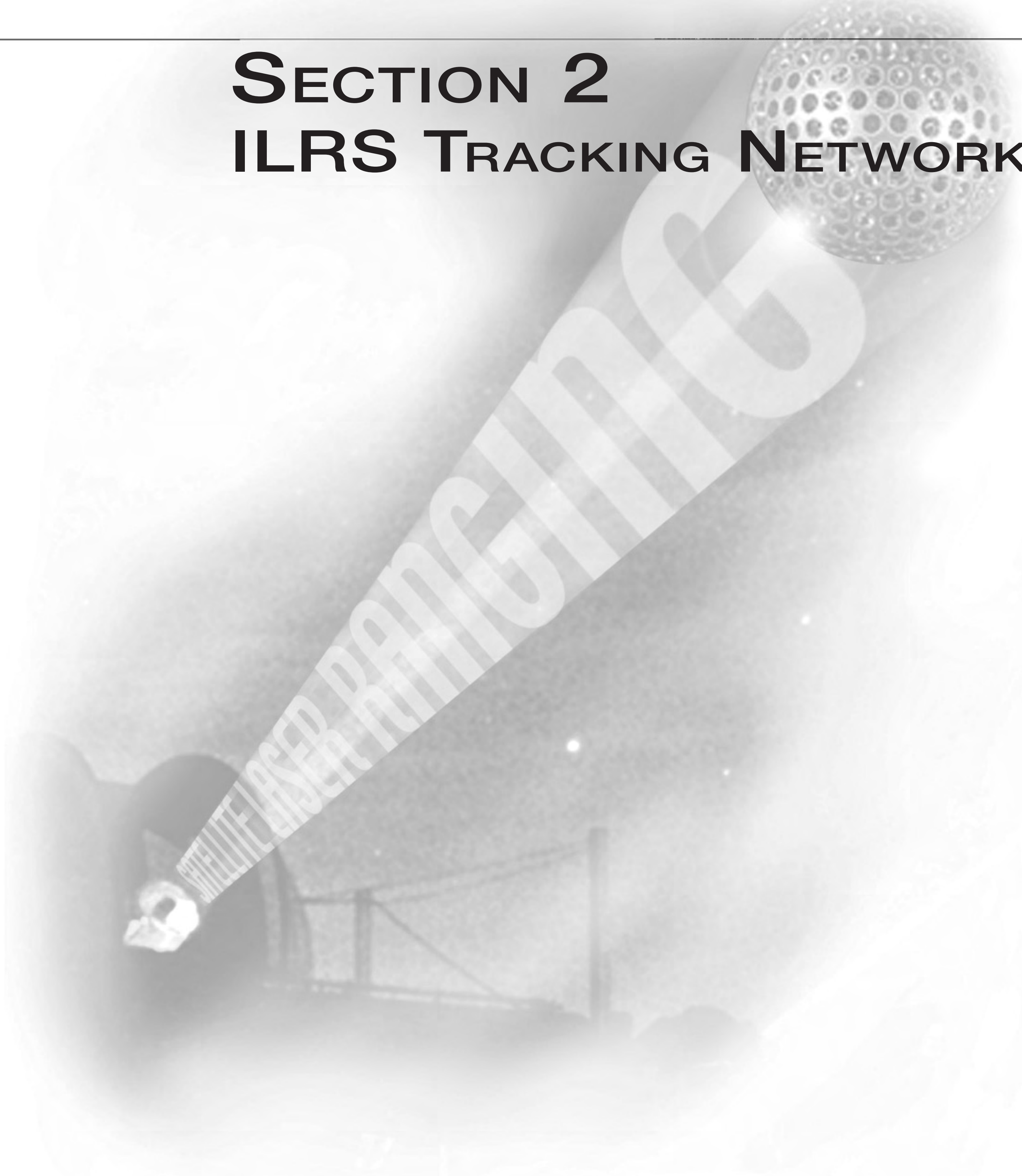
Name: Wolfgang Seemueller

Position: Data Center Representative

Affiliation: Deutsches Geodätisches Forschungsinstitut (DGFI), Germany



SECTION 2
ILRS TRACKING NETWORK



SECTION 2

ILRS TRACKING NETWORK

Satellite Laser Ranging (SLR) Network

Michael Pearlman/CfA

The SLR technique is now over forty years old, having originated in 1964 with ranging to Beacon-B from GSFC. Systems have evolved from a manually operated mount with meter-level ranging systems to automated and semi-autonomous systems with sub-centimeter ranging accuracies.

The present ILRS network, as shown in Figure 2-1, includes forty stations in 23 countries. Stations designated as operational have the minimum ILRS qualification for data quantity and quality. Several stations that were not operating during most of this reporting period for either fiscal or technical reasons are now back in operation and are rapidly qualifying as operational stations.

The last two years have witnessed considerable activity within the ILRS. After some discouraging cutbacks in 2003-5, the ILRS network has had some resurrection. NASA and the University of San Agustin reopened the TLRS-3 system at Arequipa in late 2006. A rededication ceremony will be held in early 2007. Fortunately the GPS receiver has been in operation since SLR closure in 2003, so some continuity has been provided during the intervening period. Several upgrades including the "restricted tracking capability" have been added to the system to enhance operations. The Mt. Haleakala station has also been reopened with the TLRS-4 at a new site about 100 meters from the old site. The system began producing data also in late 2006. A rededication of this site is scheduled for late January. Both stations have produced sufficient LAGEOS data to verify their performance. Staffing reductions persist at the MLRS (McDonald) and MOBLAS-7 (GSFC) and to a lesser extent at MOBLAS-4 (Monument Peak). The partner stations at Yarragadee, Hartebeesthoeck, and Tahiti were unaffected.

The Mt. Stromlo station has been fully operational since its reconstruction after a devastating forest fire. The station is now the second largest data producer in the ILRS network after Yarragadee. The two Australian stations together produced about 14,000 passes in 2006. Congratulations again to the EOS/Geoscience Australia team in their very impressive performance.

The Chinese SLR network continues its very strong support for the ILRS network. The Changchun station maintained its very strong performance with activities underway now to help strengthen daylight ranging. The new Shanghai station is now in operation after relocation; data yield is steadily improving. We are very impressed with the performance of the new Chinese SLR station in San Juan, Argentina; since beginning operations in March 2006, this station has risen to one of the six largest producers of data in the network. This has really helped in the Southern Hemisphere coverage. Congratulations to the operators and the supporting agencies.

We also note again the very strong participation of the Riyadh station. This is the only SLR station on the Arabian Peninsula, so its importance cannot be understated. The station team has done an admirable job.

The TIGO system in Concepción, Chile has undergone substantial repairs and is now back in operation. Data yield has steadily increased over the 2005-6 period, but the station is fighting difficult weather conditions. The location of this station in South America should help greatly in our Southern Hemisphere coverage.

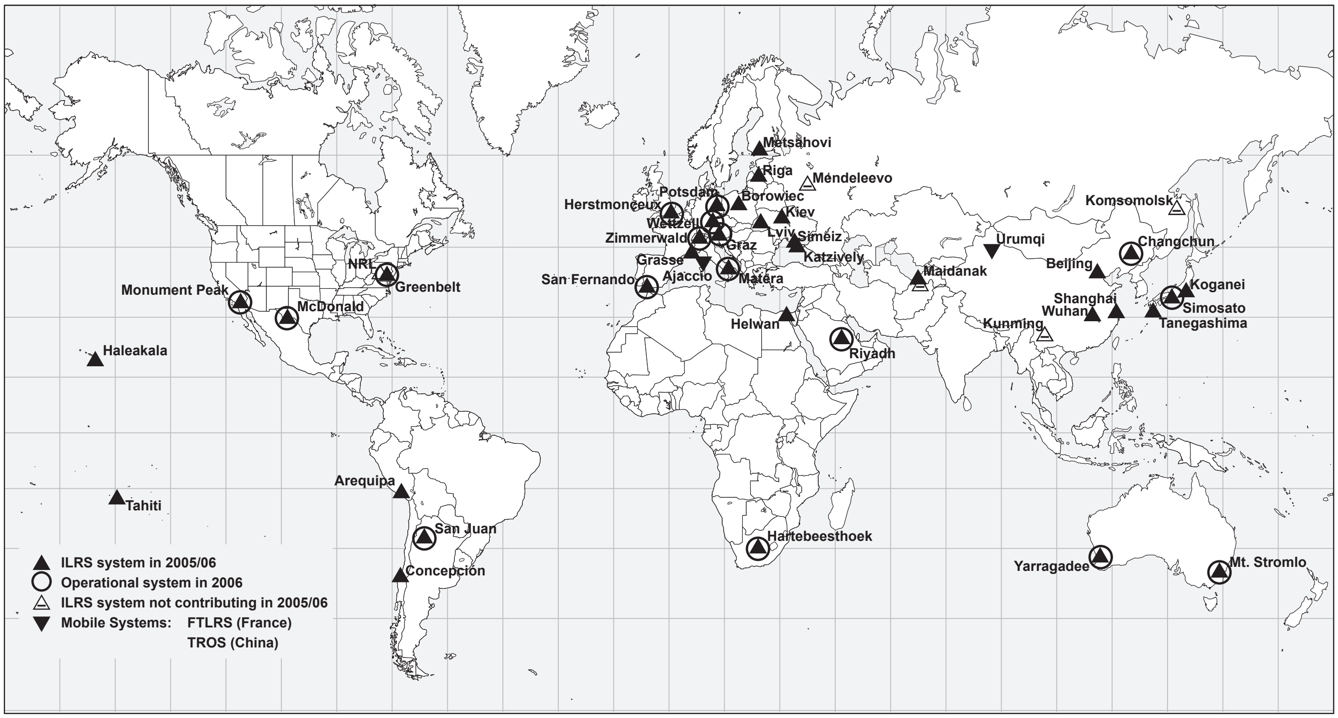


Figure 2-1. ILRS tracking network in 2005-2006.

The Graz system continues its impressive performance with 2kHz operation, a technology that will most likely become more prevalent in the network as time goes on. A 2kHz laser has also been purchased for implementation into the Herstmonceux station; several other stations are seriously considering this upgrade.

The TIGO system in Concepción, Argentina and the upgraded Zimmerwald station continue with two-wavelength ranging using a titanium-sapphire laser operating at 423nm and 846nm to test this as a means for improving the atmospheric refraction correction.

The station at Grasse, France has been temporarily closed for major upgrading. The French Transportable Laser System (FTLRS) is now being readied for relocation to Burnie, Tasmania to support altimeter calibration and validation.

The storm damage at the GUTS facility in Tanegashima, Japan has been repaired and operations resumed but data yield is still sparse.

Lunar Laser Ranging (LLR) Network

Jürgen Müller/IfE and Peter Shelus/CSR

During the Apollo missions the astronauts deployed laser retro-reflectors near their landing sites, which are in continued use up to the present day. Today, the results from Lunar Laser Ranging (LLR) are considered among the most important science return of the Apollo era. The lunar laser ranging experiment has continuously provided range data for more than 37 years. The main benefit of this geodetic technique is the determination of a host of parameters describing lunar ephemeris, lunar physics, the Moon's interior, various reference frames (the terrestrial and selenocentric frame, but also the dynamic realization of the celestial reference system), the Earth-Moon dynamics as well as the verification of metric theories of gravity and gravitational physics, such as the equivalence principle or any time variation of the gravitational constant.

Even with current technology, lunar ranging is an extremely challenging measurement task. Owing to the large lunar distance, energy loss by atmospheric extinction of the outgoing and returning laser pulse, the small reflector sizes on the Moon, and the limited telescope apertures, the laser link budget is extremely poor. Because of the tight link budget, only a handful terrestrial laser ranging stations are capable to routinely carry out the distance measurements (at cm level of precision). Among the more than 30 observatories associated with the ILRS only a few observatories worldwide are technically equipped to carry out laser ranging to the Moon.

The site operated by the Observatoire de la Côte d'Azur (OCA), France has collected the majority of the LLR data. The transmitter/receiver used by OCA is a 1.5 m alt-az Ritchey-Chrètien reflecting telescope. The mount and control electronics insure blind tracking on a lunar feature at the 1 arcsec level for 10 minutes. The OCA station uses a neodymium-YAG laser, emitting a train of pulses, each with a width of several tens of picoseconds. Unfortunately, OCA interrupted its lunar observations in 2006; a continuation is not assured.

The LLR station at the McDonald Observatory in Texas, USA is another major provider of the LLR data. The McDonald Laser Ranging Station (MLRS) is built around a computer-controlled 76cm x-y mounted Cassegrain/Coudé-reflecting telescope and a short pulse, frequency doubled, 532-nm, neodymium-YAG laser with appropriate computer, electronic, meteorological, and timing interfaces. But no recent upgrades of the system are made in the past years.

Until 1990, the Haleakala laser ranging station on the island of Maui (Hawaii, USA) contributed to LLR activities with its 40cm telescope. Single lunar returns are available from Orroral laser ranging station in Australia (closed November 1, 1998) and the Wettzell Laser Ranging System (75cm) in Germany, only a few normal points from the nineties. Other modern stations have demonstrated lunar capability, e.g., the Matera Laser Ranging Station (50cm), Italy in 2005 and Hartebeesthoek Observatory (76cm) in South Africa. A new site with lunar capability has been built at the Apache Point Observatory (New Mexico, USA) around a 3.5m telescope. This station, called APOLLO, is designed for mm accuracy ranging. First normal points have been made available in 2006. The data look very promising.

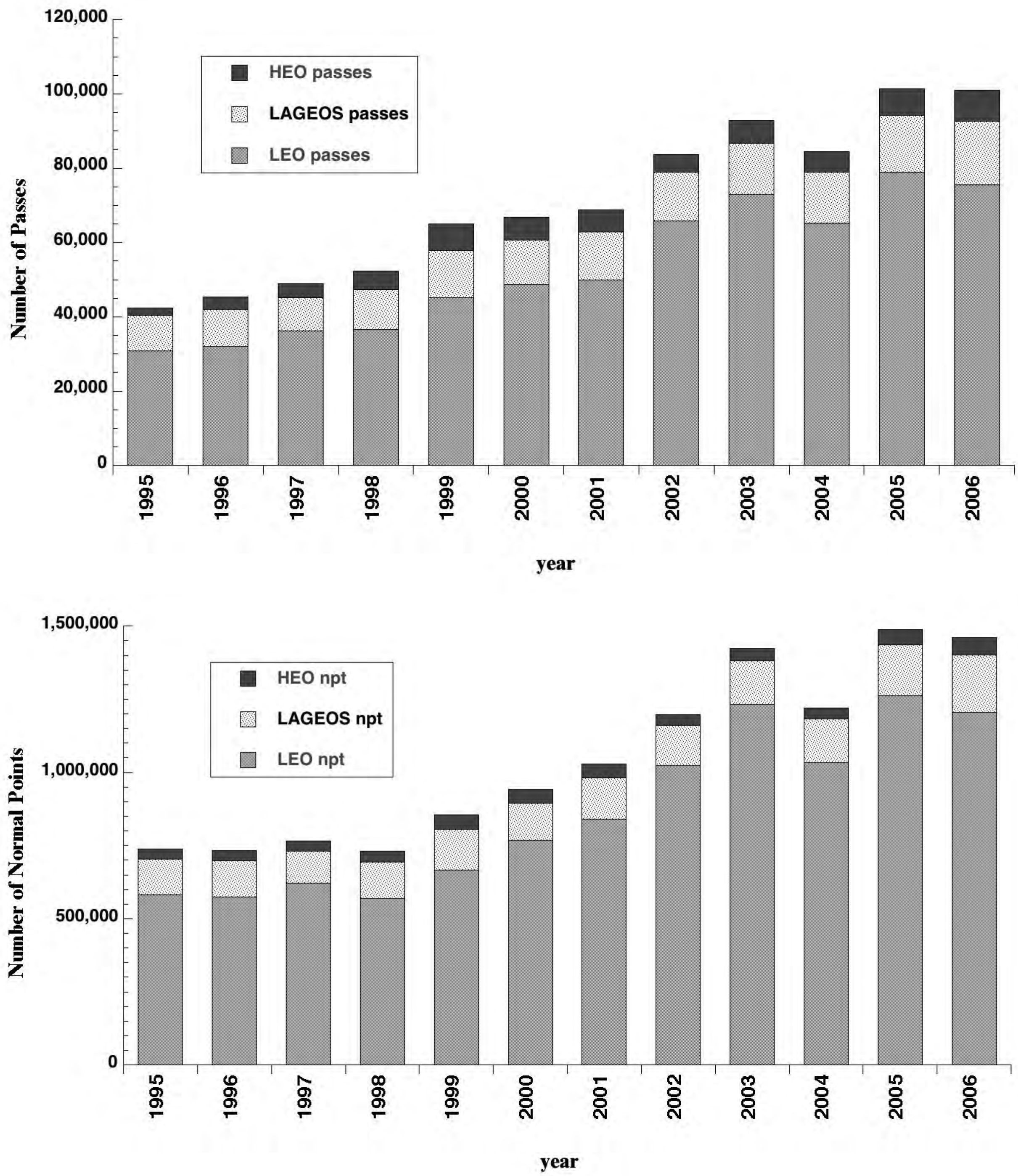
Today MLRS (and OCA) are the only currently operational LLR sites achieving a typical range precision of 18-25mm, hopefully further sites may provide lunar data on a routine basis soon. Current LLR data is collected, archived and distributed under the auspices of the International Laser Ranging Service (ILRS). All former and current LLR data is electronically accessible through the European Data Center (EDC) in Munich, Germany and the Crustal Dynamics Data Information System (CDDIS) in Greenbelt, Maryland.

Network Performance

Network Performance Report Cards are issued quarterly by the ILRS Central Bureau. These reports tabulate the previous 12 months of data quality, quantity, and operational compliance by station and can be found along with established guidelines for station performance on the ILRS Web site at: *http://ilrs.gsfc.nasa.gov/stations/site_info/global_reportcards/index.html*. The ILRS Central Bureau uses these report cards to maintain lists of the best performing stations (operational) which are tabulated at: *http://ilrs.gsfc.nasa.gov/stations/station_classification.html*.

As shown in Figures 2-2-a and -b, network data yield dropped in 2004 due mainly to reductions in NASA network support and the Mt Stromlo outage, but data yield is recovering as these stations have come back into operation and as the rest of the network has become more proficient.

The network is still experiencing a wide dichotomy in performance. As can be seen in Figures 2-3-a and -b, station data yield performance falls into three categories. About a quarter of the stations are very prolific, far exceeding the ILRS criteria for an operational stations. Another quarter of the stations are performing satisfactorily with some caveats on LAGEOS tracking. These two categories of stations are having a major impact on the development of reference frame and POD. Some of the stations on the lower half are recovering from engineering activities and will hopefully experience improved operations in 2007. All of the stations are meeting the 2 cm normal point RMS threshold, with about 75% operating below the cm level (see Figure 2-4).



Figures 2-2-a and -b. After the reductions in 2004, network data yield increased with the reopening of stations, improved network proficiency, and additional satellites.

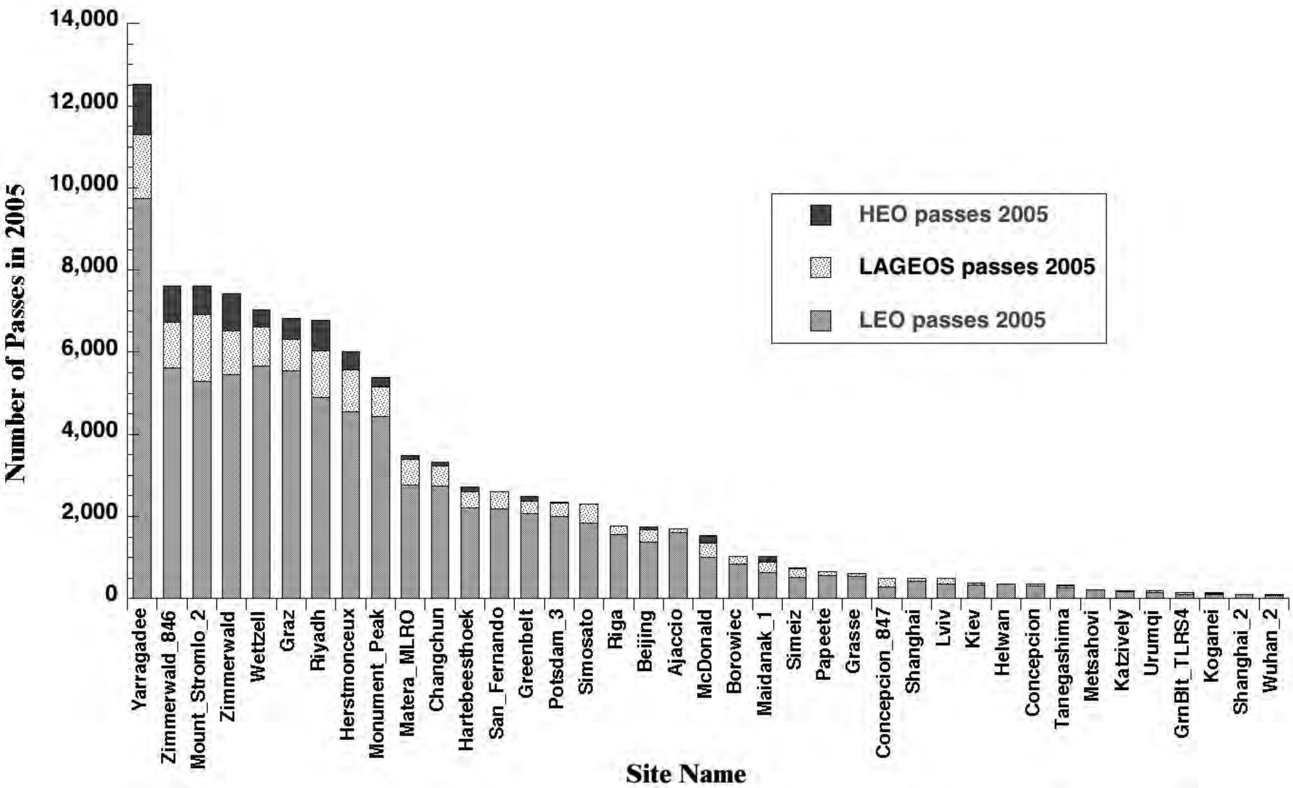


Figure 2-3-a. Number of passes tracked from January 2005 through December 2005.

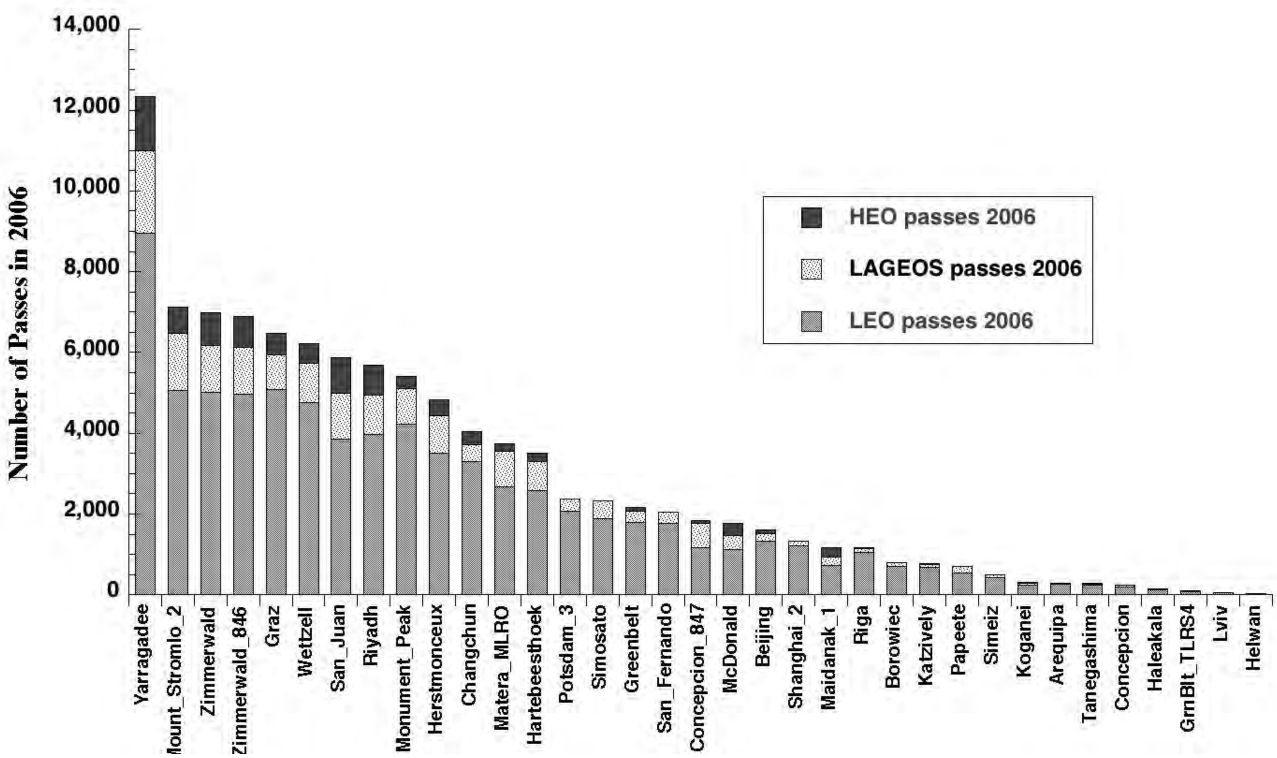


Figure 2-3-b. Number of passes tracked from January 2006 through December 2006.

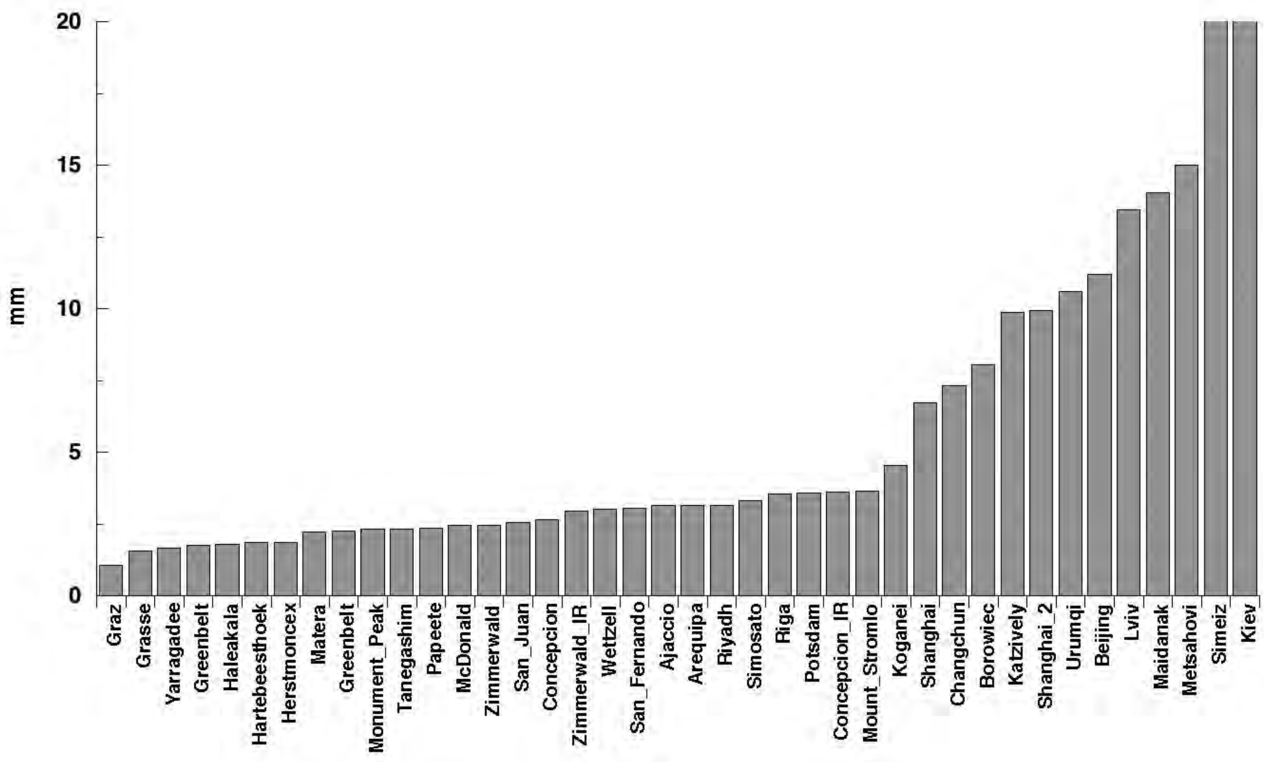


Figure 2-4. Average normal point precision in mm for data from January 2005 through December 2006 as calculated by the National Institute of Information and Communications Technology (NICT), Japan.

Site Surveys and Co-Location Sites

Zuheir Altamimi/IGN and Michael Pearlman/CfA

The Terrestrial Reference Frame (TRF) is the means by which we connect measurements over space, time and evolving technologies. Space may be ten thousand kilometers. Time will be decades and probably generations. Evolving technologies are the changes in the ground systems and the satellites that will happen as measurement capabilities improve. If we are going to see change in the Earth and its environment, we need the long-term stability of the reference frame.

Satellite Laser Ranging (SLR) is one of the fundamental geodetic techniques (along with GNSS, VLBI, and DORIS) that define and maintain the Terrestrial Reference System. Each technique is fundamentally different; each has its own unique strengths and its own systematic errors. We can exploit the strengths and mitigate the systematic errors through the co-location of space techniques (SLR, GNSS, VLBI, and DORIS) at common sites. This is an essential part in our achievement of the high–accuracy TRF required to meet projected oceanographic study needs.

Site surveys between co-located instruments are a basic, but often unappreciated aspect in the development of the reference frame. The value of sub-centimeter measurements across intercontinental distances can be lost through missing or inaccurate local ties, inconsistencies in ground survey techniques, poor survey control network geometry and monumentation, improper analysis of survey data, and lack of proper documentation.

The very existence of the ITRF relies on the availability and quality of local ties in co-location sites as well as the number and distribution of these sites over the globe. A co-location site is defined by the fact that two or more space geodesy instruments are occupying simultaneously or subsequently very close locations, which are very precisely, surveyed in three dimensions, using classical surveys or/and the GNSS technique. Classical surveys are usually direction angles, distances, and spirit leveling measurements between instrument reference points or geodetic markers. Adjustments of local surveys are performed by national geodetic agencies operating space geodesy instruments to provide differential coordinates (local ties) connecting the co-located instruments.

Current Status of the Co-location Sites

The VLBI and SLR networks each include less than fifty sites. The DORIS network is more homogeneous and includes 56 sites. The IGS GNSS network contains more than 350 permanent sites. In the worldwide currently operating Space Geodesy Network, 58 sites host two observing techniques (SLR, GNSS, VLBI, and/or DORIS); only sixteen sites have three, and only two sites have four, as illustrated by Figure 2-5. The figure shows also seven sites where local ties are missing: (four VLBI-GNSS, one SLR-VLBI, one SLR-GNSS and one DORIS-GNSS).

The status of site co-locations with SLR is show in Table 2-1 and Figure 2-5. There are currently only three SLR sites operating with SLR, GNSS, VLBI, and DORIS, and ten SLR sites operating with GNSS and VLBI. Seven are co-located with DORIS. All of the SLR sites in the ILRS operational network are co-located with GNSS; six of the other participating SLR stations do not have GNSS. The distribution of these co-located sites is not well placed and in some cases operations of one or more of the techniques is marginal. Local surveys are also an issue at nine of the SLR co-located sites.

Co-location of techniques and measurement and monitoring of local inter-technique vectors to the mm level must continue to be a high priority with the SLR network.

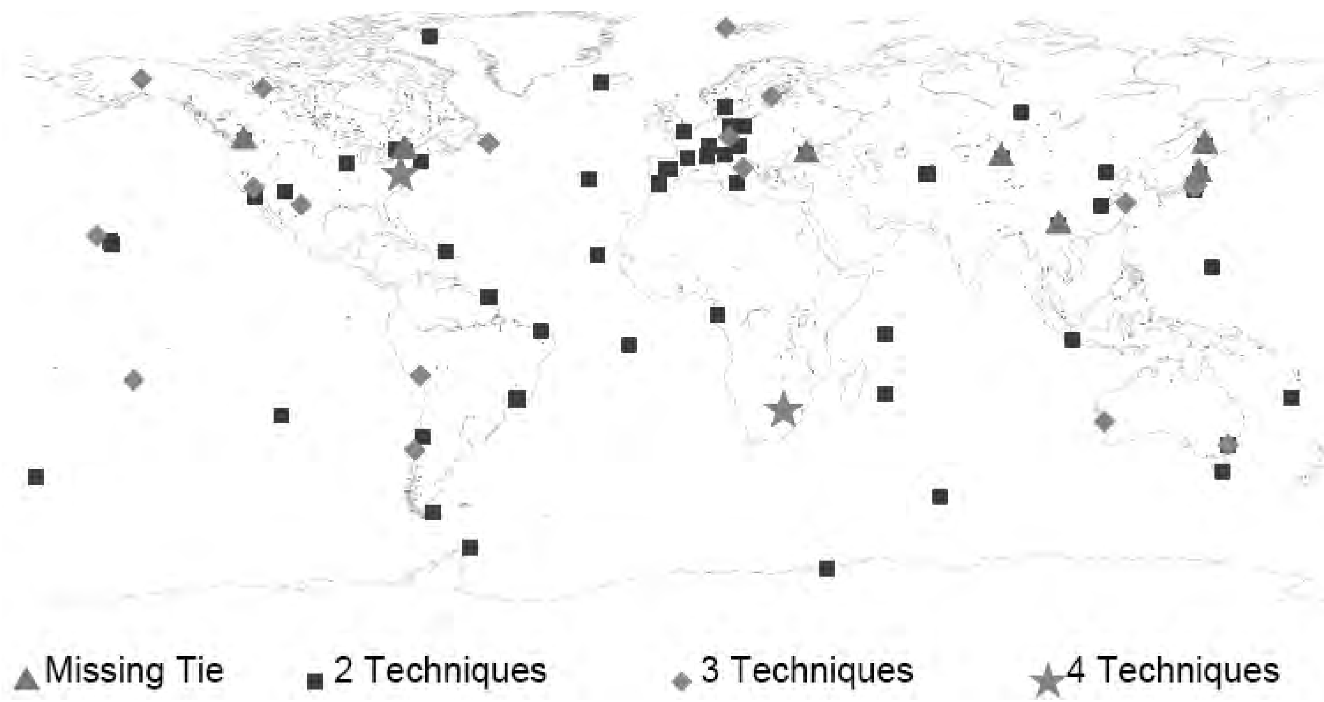


Figure 2-5. Average normal point precision in mm for data from January 2005 through December 2006 as calculated by the National Institute of Information and Communications Technology (NICT), Japan.

New Surveys

During this period, The Institut Géographique National (IGN), France and NASA GSFC participated in complete surveys of the following co-location sites:

- Hartebeesthoek, South Africa, comprising the four techniques: VLBI, SLR, GNSS and DORIS
- Shanghai, China, comprising three techniques: VLBI, SLR and GNSS
- Wuhan, China, comprising three techniques: VLBI, SLR and GNSS

The adjustment of these three surveys is accomplished, including final report and SINEX files, which are available at the ITRF web site *http://itrf.ensg.ign.fr/*.

Table 2.1. Space Techniques Co-Located with SLR (2005-2006)

Site Name	Country	GNSS	VLBI	DORIS	Gravimeter
Arequipa	Peru	X		X	
Beijing	China	X			X
Borowiec	Poland	X			X
Changchun[2]	China	X			
Concepción	Chile	X	X		X
Grasse	France	X			X
Graz	Austria	X			X
Greenbelt, MD	USA	X	X	X	
Haleakala, HI	USA	X			
Hartebeesthoek	South Africa	X	X	X	
Helwan	Egypt				
Herstmonceux	UK	X			X
Katzively	Ukraine				
Kiev	Ukraine	X			
Koganei[2]	Japan	X	X		
Komsomolsk	Russia				
Kunming[2]	China	X			X
Lviv[2]	Ukraine	X			
Maidanak	Russia				
Matera	Italy	X	X		X
McDonald, TX	USA	X	X		
Mendeleevo	Russia	X			
Metsahovi	Finland	X	X	X	X
Monument Peak, CA	USA	X		X	
Mount Stromlo	Australia	X		X	X
Potsdam	Germany	X			X
Riga	Latvia	X			X
Riyadh[2]	Saudi Arabia	X			
San Fernando	Spain	X			
Shanghai	China	X	X		
Simeiz[2]	Ukraine	X	X		
Simosato	Japan	X[3]			
Tahiti	F. Polynesia	X		X	
Tanegashima[2]	Japan	X			
Urumqi1	China	X	X		
Wettzell	Germany	X	X		X
Wuhan	China	X		X	X
Yarragadee	Australia	X		X	
Zimmerwald	Switzerland	X			X
Totals:	39	35	11	9	15

Notes: [1]indicates mobile occupation in 2005-2006
[2]indicates missing tie
[3]indicates pending IGS approval as IGS site and release of older data

SECTION 3
MISSIONS AND CAMPAIGNS

SECTION 3

MISSIONS AND CAMPAIGNS

Current Missions

Michael Pearlman/CfA

During 2005-2006, the ILRS supported 28 artificial satellite missions including passive geodetic (geodynamics) satellites, Earth remote sensing satellites, navigation satellites, and engineering missions. The stations with lunar capability also tracked the lunar reflectors. Missions were added to the ILRS tracking roster as new satellites were launched and as new requirements were adopted (see Figure 3-1). New missions (see Table 3-1) included ANDE-RR, an atmospheric modeling satellite, and GIOVE-A the first engineering test satellite for the Galileo series. GLONASS-95 replaced GLONASS-84 which had failed. The network also supported a short calibration campaign on the ALOS satellite with optical sensors for terrestrial mapping. The ETS-8 synchronous satellite was also launched to a location over the western pacific, but tracking was delayed until early 2007 while the satellite underwent engineering readiness tests. Missions for completed programs were deleted. The TOPEX/Poseidon project ended in 2006 after a remarkable 13 years of service, with SLR providing the sole source of POD during its last year of operations. SLR was the sole means of POD for the SAGE experiment on Meteor-3M which ended in 2006. The GP-B 18-months campaign also ended in 2006.

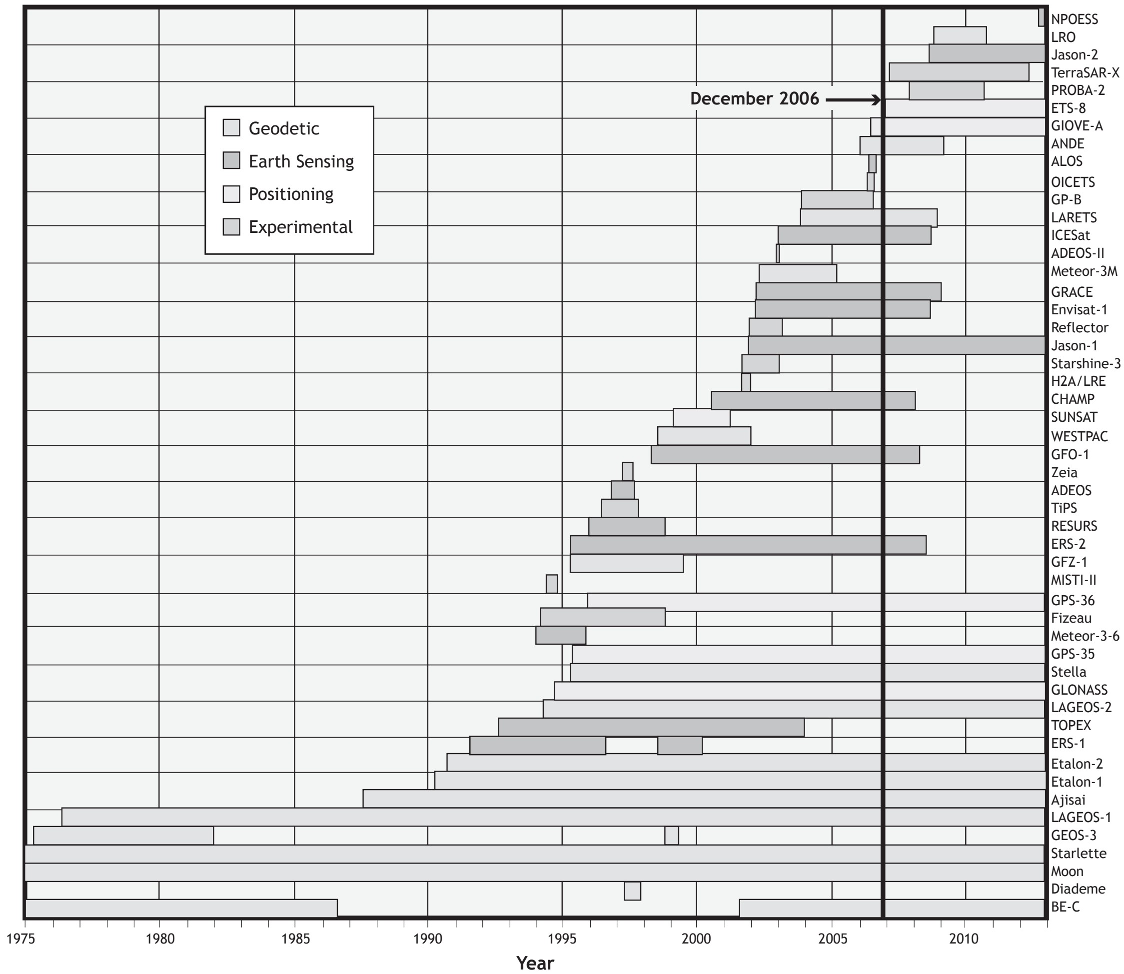


Figure 3-1. SLR tracking mission timeline.

Table 3-1. New Missions in 2005-2006

Mission	Launch date	Sponsor	Application	ILRS Mission Support Status
ALOS	24-Jan-2006	JAXA	Microwave and optical sensing of the environment	POD
ANDE-RR	21-Dec-2006	NRL	Monitor thermospheric neutral density	Augment SSN observations to improve precision orbit determination process
ETS-8	16-Dec-2006	JAXA	Support development, experimentation and confirmation of various new technologies	POD
GIOVE-A	26-Dec-2005	EU/ESA	Galileo test bed satellite	Satellite orbit and clock verification, POD
OICETS	23-Aug-2005	JAXA	Demonstration of optical communications with ESA geostationary satellite	POD

ALOS

The Advanced Land Observing Satellite (ALOS) was launched to perform high-resolution observations of the earth's surface to assist in the process of compiling very detailed maps of the Pacific Rim region. ALOS is also being used for environmental monitoring and for maintaining and developing Earth observation technology. The ALOS satellite was launched January 24, 2006 and is shown in Figure 3-2.

Figure 3-2. ALOS satellite (from JAXA Web site).

The data from three remote-sensing instruments on ALOS, (1) PRISM, (2) AVNIR-2 and (3) PALSAR, are combined to develop digital elevation models to make topographic maps for studies of crustal motion, regional deformation, earthquake and disaster monitoring, and resource survey and exploration. PRISM is a panchromatic radiometer with 2.5-meter spatial resolution. To obtain elevation data, PRISM has three optical systems for forward, nadir, and backward viewing. AVNIR-2 is a visible and near-infrared radiometer for observing land and coastal zones and provides better spatial resolution than the previous ADEOS AVNIR. It is being used to provide land coverage maps and land-use classification maps for monitoring regional environment. The instrument also has a cross track pointing capability for disaster monitoring. PALSAR is an active microwave sensor for cloud-free, day-and night land observation and provides higher performance than the JERS-1 SAR. It has a beam steer able elevation and the

ScanSAR mode, which can provide a wider swath than the conventional SAR. The development of PALSAR is a joint project between NASDA and the Japan Resources Observation System Organization (JAROS).

GPS and SLR are used for POD. The retroreflector array design is similar to the ERS-1 and Envisat arrays. It is optimized for the green wavelength (532 nanometers). The corner cubes are symmetrically mounted on a hemispherical surface with one nadir-looking corner cube in the center, surrounded by an angled ring of eight corner cubes. This allows laser ranging in the field of view of 360 degrees in azimuth and 60 degrees in elevation around the axis of the array.

With the vulnerability of both the PRISM and AVNIR-2 radiometers to the SLR radiation special precautions were taken to protect the onboard systems. A set of pre-selected stations using the ILRS "Restricted Tracking Procedures" provided tracking (see Section 5). A special tracking campaign on ALOS was conducted in August 2006 using these approved stations.

Information on the array (shown in Figure 3-3) can be found on the JAXA ALOS RRA page at: *http://god.tksc.nasda.go.jp/al/lrra/main.html*. More information about the ALOS mission can be found on the Web site *http://www.jaxa.jp/missions/projects/sat/eos/alos/index_e.html.*

Figure 3-3. ALOS retroreflector array (from JAXA Web site).

Atmospheric Neutral Density Experiment (ANDE) Risk Reduction Mission

The Atmospheric Neutral Density Experiment (ANDE) Risk Reduction Mission consists of two spherical spacecraft fitted with SLR retroreflectors. the satellites were launched from the Space Shuttle on December 21, 2006. The main mission objective of the ANDE-RR mission is to test the deployment mechanism from the shuttle for a future ANDE mission and to begin preliminary scientific measurements. Scientific objectives of the ANDE missions include monitoring total neutral density of the atmosphere along the orbit for improved orbit determination of space objects, monitoring the spin rate and orientation of the spacecraft to better understand in-orbit dynamics, and to provide a test object for polarimetry studies. The mission will provide objects in low Earth orbit with well-determined ballistic coefficients and radar cross-sections for comprehensive atmospheric modeling. Each mission will include a passive and an active spherical spacecraft (as shown in Figure 3-4) in a lead-trail orbit configuration. The passive sphere will be tracked with the Space Surveillance Network (SSN) and SLR to study atmospheric drag and in-track total density. The active sphere will have on-board instrumentation to measure atmospheric density and composition. The active sphere will monitor its position relative to the passive sphere to study drag models. The active satellites will communicate on-board data through a system of modulated retro-reflectors (MRR).

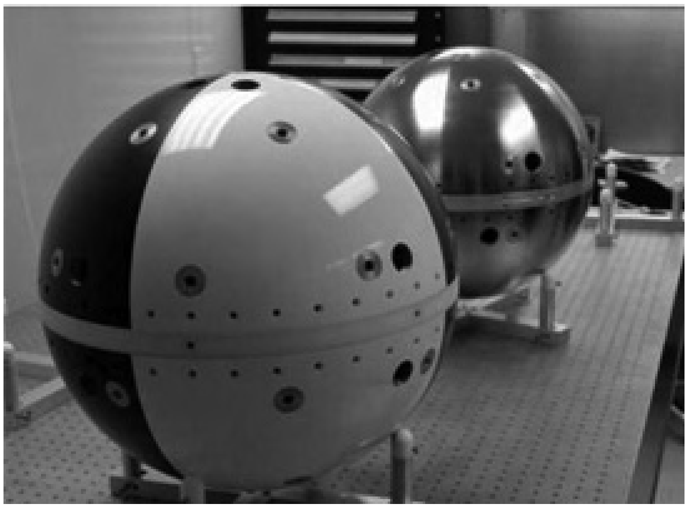


Figure 3-4. Active and passive spheres of the ANDE mission (from NRL).

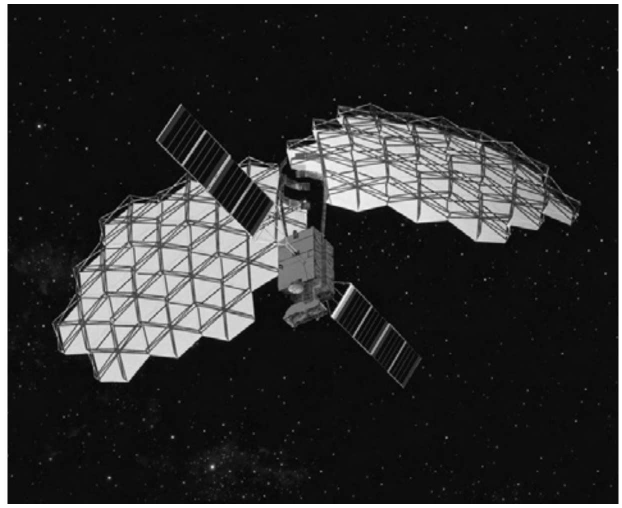


Figure 3-5. ETS-8 satellite (from JAXA Web site).

Engineering Test Satellite 8 (ETS-8)

The Engineering Test Satellite-8 (ETS-8), shown in Figure 3-5, was launched to support development, experimentation and confirmation of large satellite bus technology, large-scale deployable antenna technology, mobile satellite communications system technology, mobile satellite digital multimedia broadcasting system technology and basic positioning technology using high-accuracy time standard devices. ETS-8, the largest geosynchronous satellite ever placed in orbit, was launched from the H-IIA vehicle on December 16, 2006. JAXA plans to conduct a time synchronization experiment for future positioning satellite technology, including time management using an atomic clock onboard the satellite. SLR will provide POD for the mission. Of great interest with ETS-8 is the use of uncoated retroreflectors designed specifically to compensate for the velocity aberration.

GIOVE-A

The Galileo constellation, a satellite radio navigation system initiative by the European Union and the European Space Agency, will consist of 30 satellites and ground stations providing position information to users in many sectors (transportation, social services, justice system, custom services, public works, search and rescue, etc.). Two experimental spacecraft, GIOVE-A and -B (formerly known as GSTB-V2/A and GSTB-V2/B), are being launched as part of the Galileo System Test Bed V2 to (1) secure the Galileo frequency allocations by providing a signal in space, (2) develop procedures for on-board clock characterization, (3) better understand the radiation environment, and (4) conduct related experiments. The first experimental spacecraft, GIOVE-A (shown in Figure 3-6) was launched on December 26, 2005; SLR tracking commenced on May 2006 after the satellite checkout was completed. Data yield is comparable to that of GPS-35 and -36. The second satellite, GIOVE-B is currently scheduled for the second half of 2007. The first satellites in the full constellation are scheduled for launch in 2008.

GIOVE-A and GIOVE-B have different retroreflector arrays; both have flat arrays with solid back-coated cubes. The array for GIOVE-A (GSTB-V2/A) was built by Surrey Satellite Technology Ltd in the UK and has 76 cubes; the array for GIOVE-B (GSTB-V2/B) has been manufactured by Galileo Industries and has 67 cubes. The anticipated signal link for both satellites is comparable to that of the GPS satellites.

For more information on the GIOVE aspects of the Galileo mission, refer to the ESA Web site *http://www.giove.esa.int/.*

Optical Inter-orbit Communications Engineering Test Satellite (OICETS)

The JAXA Optical Inter-orbit Communications Engineering Satellite (OICETS) is a demonstration of the optical communications with the ESA geostationary Advanced Relay and Technology MISsion (ARTEMIS). The experiment is testing important technology for large volume optical communications between satellites, a crucial capability for future space activities, including global-scale data acquisition from Earth observation satellites and stable communications for manned space missions. Optical communications provides wider bandwidth that radio frequencies and lighter on-board equipment. The experiment includes acquisition, tracking, and pointing technologies with ARTEMIS, and a study of the effects of micro-vibrations of the satellites on the communications link. OICETS, shown in Figure 3-7, was launched on August 23, 2005. SLR provides the primary POD for OICETS.

For more information on OICETS, refer to JAXA's Web site *http://god.tksc.jaxa.jp/oi/oicets.html*.

Figure 3-6. GIOVE-A satellite (from ESA Web site).

Figure 3-7. OICETS satellite (from JAXA Web site).

Completed Missions

The ILRS completed support on several missions during 2005-2006; these missions are listed in Table 3-2.

Table 3-2. Missions No Longer Requiring SLR Support

Mission	Sponsor	Start Date	End Date	Application	Reason for Ending Tracking
GLONASS-84	Russia	20-Dec-2000	13-Sep-2005	Radio navigation satellite system	Replace with GLONASS-95
GP-B	Stanford U.	07-Jul-2004	05-Jun-2006	POD with GPS	Mission request
Meteor-3M	NASA, Russia	19-Dec-2001	03-Mar-2006	Meteorology	Spacecraft instability
TOPEX/Poseidon	NASA, CNES	01-Jan-1992	15-Dec-2005	Oceanography, altimetry	Loss of satellite maneuver ability

Future Missions

A number of new missions, shown in Table 3-3, requiring SLR support for POD and instrument calibration and validation, are scheduled for launch over the next two years.

Table 3-3. New Missions Requesting SLR Support

Mission	Sponsor	Scheduled Launch	Altitude (km)	Inclination (degrees)	Application
GIOVE-B	ESA	2007	23,916	56°	Radio navigation satellite system
GOCE	ESA	2007	250	96.5°	Earth's gravity field and geoid modeling
Jason-2	NASA, CNES, Eumetsat, NOAA	June 2008	1,336	66	Oceanography, T2L2
LRO-LR	NASA	October 2008	Lunar	N/A	POD for LRO
NPOESS	NOAA, NASA, DoD	2013	833	98.7°	Sea surface height
PROBA-2	ESA	December 2007	721	98	Technology validation
TerraSAR-X	Infoterra, DLR, GFZ, CSR	April 2007	514	97.44	X-band SAR

Requests for new mission support by the ILRS should be submitted via the online request form on the ILRS Web site at *http://ilrs.gsfc.nasa.gov/satellite_missions/ilrssup.html.*

Requests are reviewed by the ILRS Missions Working Group for suitability and then vetted by the ILRS Governing Board. It is also very important that mission sponsors supply precise details of the on-board characteristics of the proposed retro reflector arrays, and an additional form to input this information is provided via the above link.

GIOVE-B

See the section on GIOVE-A for more information on GIOVE-B or refer to ESA's Web site: *http://www.esa.int/export/esaNA/galileo.html*.

Gravity Field and Steady-State Ocean Circulation Explorer (GOCE)

As a follow-on to GRACE, GOCE is dedicated to measuring the Earth's gravity field and modeling the geoid with extremely high accuracy and spatial resolution. It is the first Earth Explorer Core mission to be developed as part of the ESA Living Planet Program and is scheduled for launch by the end of 2007.

The geoid, which is defined by the Earth's gravity field, is a surface of equal gravitational potential. It follows a hypothetical ocean surface at rest (in the absence of tides and currents). A precise model of the Earth's geoid is crucial for deriving accurate measurements of ocean circulation, sea-level change and terrestrial ice dynamics – all of which are affected by climate change. The geoid is also used as a reference surface from which to map all topographical features on the planet. An improved knowledge of gravity anomalies will contribute to a better understanding of the Earth's interior, such as the physics and dynamics associated with volcanism and earthquakes and also further our knowledge of land uplift due to post-glacial rebound.

The mission objectives are to determine the gravity-field anomalies with an accuracy of 1 mGal (where 1 mGal = 10^{-5} m/s^2), determine the geoid with an accuracy of 1-2 cm, all with a spatial resolution better than 100 km.

The GOCE spacecraft is a rigid octagonal shape of approximately 5 m long and 1 m in diameter with fixed solar wings with no moving parts. The payload will include a gravity gradiometer with three pairs of 3-axis, servo-controlled, capacitive accelerometers (each pair separated by a distance of 0.5 m), a 12-channel GPS receiver with geodetic quality, and laser retroreflector for ground-based ranging.

For more information on GOCE, refer to: *http://www.esa.int/export/esaLP/ESAYEK1VMOC_goce_0.html*.

Figure 3-8. GOCE satellite (from ESA Web site).

Jason-2

Jason-2, also known as the Ocean Surface Topography Mission (OSTM), will continue the oceanography program begun by the TOPEX/Poseidon and Jason-1 missions. Jason-2 will continue to monitor global ocean circulation, investigate the tie between the oceans and atmosphere, improve global climate predictions, and monitor events such as El Nino conditions and ocean eddies. The CNES, Eumetsat, NASA, and NOAA cooperative mission will carry nearly the same payload as Jason-1. The satellite payload will include the next generation Poseidon altimeter (Poseidon-3, with the same general characteristics as Poseidon-2, but with a lower instrumental noise and an algorithm enabling better tracking over land and ice). The measurement accuracy should be about 1 cm on the altimeter as POD.

The Time Transfer by Laser Link (T2L2) payload (see *http://www.obs-azur.fr/gemini/projets/t2l2/home.htm*), initially planned for MIR in 1999, then with the ACES mission on the ISS, has recently been accepted by the French space agency CNES as a passenger on the Jason-2 altimetry satellite. T2L2 on Jason-2 will allow the precise characterization of the USO (ultra-stable oscillator) used by the DORIS positioning system. Relying on this clock, T2L2 may also be able to perform some orbit improvements on Jason-2 using one-way laser ranging. Jason-2, at its high altitude and with its very long integration times, in common view mode, provides an excellent opportunity for time transfer over many intercontinental links.

Precision orbit determination is a fundamental requirement for achieving the goal of Jason-2. Jason-2 also has GPS receivers and DORIS for POD. The SLR data will provide a crucial centering of the orbit relative to the Earth's center of mass. SLR will also provide absolute calibration of the radial orbit error through the analysis of high elevation SLR passes.

More information about the Jason-2 mission is available at the Eumetsat Web site
http://www.eumetsat.int/Home/Main/What_We_Do/Satellites/Jason/index.htm?l=en.

LRO-LR

The Lunar Reconnaissance Orbiter (LRO) is the first mission of the Robotic Lunar Exploration Program (RLEP). The LRO mission objective is to conduct investigations that will be specifically targeted to prepare for and support future human exploration of the Moon. This mission is currently scheduled to launch in October 2008 and is planned to take measurements of the Moon for at least one year.

The LRO Laser Ranging (LR) system will make one-way range measurements using laser pulse time-of-flight from Earth to LRO to determine LRO position at sub-meter level with respect to Earth and the center of the Moon (on the lunar near-side or whenever possible). The LR aspect of the mission will allow for the determination of a more precise orbit than possible with S-band tracking data alone. To improve the orbital position of LRO, and meet the Level 1 requirements for data products some improvement to the lunar gravity field is needed.

The LRO-LR flight system consists of a receiver telescope that captures the up linked laser signal and a fiber optic cable, which routes it to the LOLA instrument. The LOLA instrument captures the arrival time of the laser signal in the spacecraft time system, records that information and provides it to the onboard LRO data system for storage and/or transmittal to the ground through the RF link.

The laser ranging data to the LOLA instrument on board LRO will provide relative range measurements to the spacecraft with better than 10cm precision at 1 Hz. These data will allow scientists to produce a gravity model with sufficient accuracy to calculate the spacecraft position to within 50 m along track, 50 m cross track, and 1 m radial. This calculation requires S-band tracking data, LR range data, and LOLA science data. In synchronous mode, SLR stations will transmit 28 Hz 532 nm laser pulses to LRO; the time stamp departure and arrival times will be used to calculate ranges to the spacecraft. Asynchronous operations may also be possible. More information about LRO can be found at *http://lunar.gsfc.nasa.gov*. More information on the LR aspect of the mission can be found at *http://lrolr.gsfc.nasa.gov/*.

Figure 3-9. Jason-2 satellite (from Eumetsat Web site).

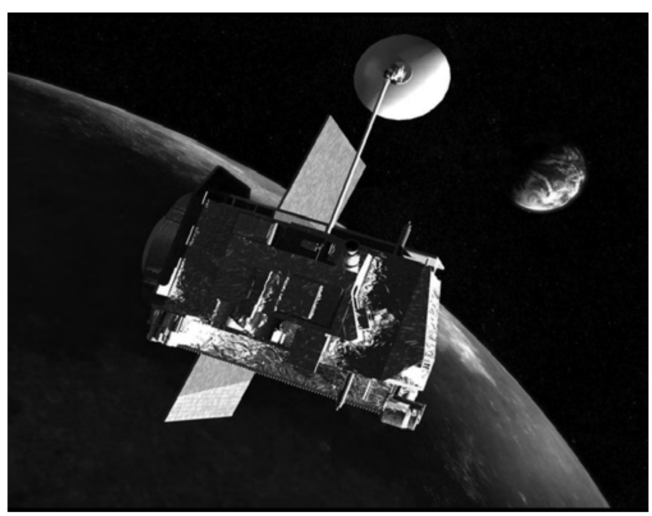


Figure 3-10. LRO satellite (from NASA GSFC Web site).

PROBA-2

The Project for On-Board Autonomy (PROBA) is a series of technology demonstration missions of the European Space Agency. The first satellite in the series, PROBA-1, was successfully launched on 22 October 2001, initially for a two-year mission and now operational for five years. PROBA-2 is currently under development, with a planned launch in December 2007. PROBA-2 will continue ESA's validation of new spacecraft technologies while also carrying a scientific payload. The objectives of PROBA are in-orbit demonstration and evaluation of new hardware and software spacecraft technologies, in-orbit demonstration and evaluation of onboard operational autonomy, and in-orbit trial and demonstration of Earth observation and space environment instruments. SLR will augment GPS observations to improve precision orbit determination. More information about PROBA-2 is available at the ESA Web site *http://www.esa.int/esaMI/Proba_web_site/index.html.*

TerraSAR-X

TerraSAR-X is an X-band SAR mission for scientific research and applications; the satellite is scheduled for launch in early 2007. It is the first satellite to be built in a public/private partnership in Germany with Infoterra, DLR, GFZ and CSR in the U.S. The satellite carries the experimental Tracking, Occultation and Ranging (TOR) package provided by GFZ and CSR. TOR consists of a two-frequency CHAMP type GPS receiver and a CHAMP Laser Retro-Reflector (LRR). The mission's objectives are scientific research and applications using X-band SAR as well as to establish a commercial EO-market to develop a sustainable EO-service business based on TerraSAR-X derived information products. Satellite laser ranging data will be used for precise orbit determination and validation and is complementary to the onboard TOR GPS. More information is available from the GFZ Web site: *http://terrasar-x.gfz-potsdam.de/.*

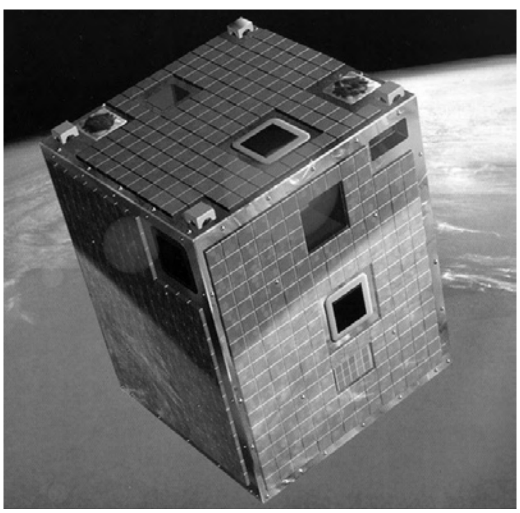


Figure 3-11. PROBA-1 satellite (from ESA Web site).a

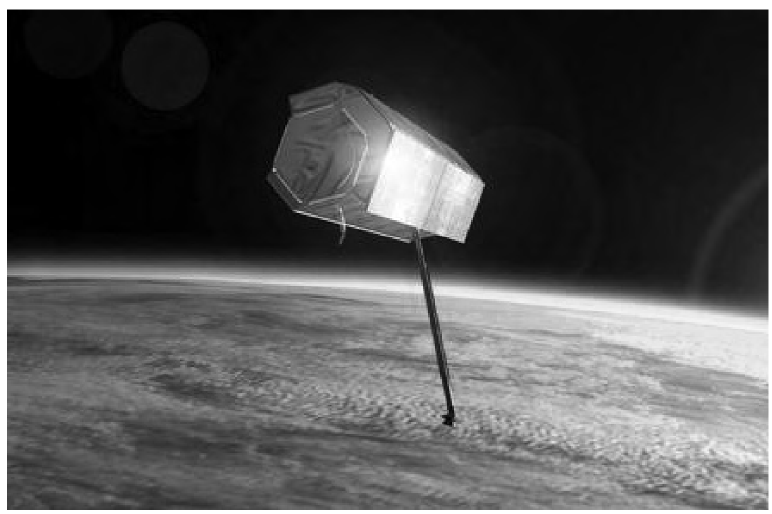


Figure 3-12. TerraSAR-X satellite (from GFZ Web site).

Section 4
Infrastructure

Section 4

Infrastructure

Web Site Developments

Carey Noll/GSFC

Enhancements to the ILRS Web site continued in 2005 and 2006. A completely re-designed satellite section was implemented in 2006. A list of satellites, categorized as current, past, and future provides quick access to information by mission name. Navigation tabs are shown on each satellite "home" page that sub-divides available information into general, retroreflector, mission support, and center of mass information. The satellite pages are available at: *http://ilrs.gsfc.nasa.gov/satellite_missions/list_of_satellites/*.

The ILRS station information pages were also expanded in 2006. The ILRS Central Bureau staff developed various reports and plots to monitor network performance. This information is updated on a frequent basis dependent upon the type of report. Station operators, analysts, and other ILRS groups can view these reports and plots to quickly ascertain how individual stations are performing as well as how the overall network is supporting the various missions. All plots and reports can be accessed through the station pages on the ILRS Web site at URL: *http://ilrs.gsfc.nasa.gov/stations.*

A plot of the satellite ground tracks of the last seven days of geodetic satellite data is updated daily and available through the ILRS Web site at: *http://ilrs.gsfc.nasa.gov/stations/recent_groundtrack.html*.

The plot, shown in Figure 4-1 for a week in November 2006, graphs the actual network ground tracks of Etalon, LAGEOS, Ajisai, Starlette, and Stella over the previous seven days based upon the archived normal point data.

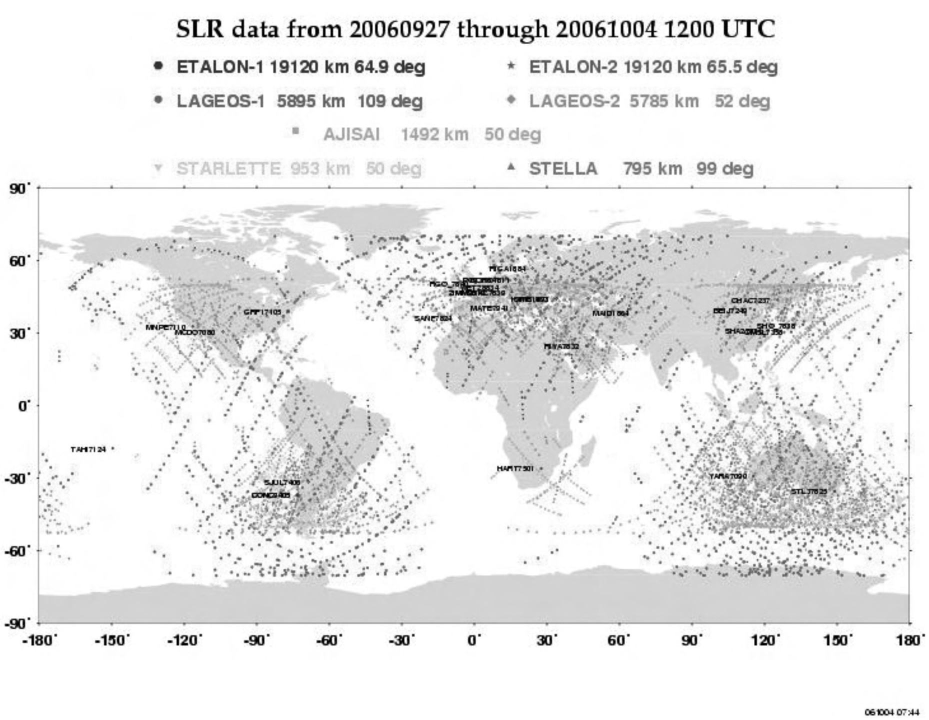


Figure 4-1. Plot of the satellite ground tracks of the last seven days of geodetic satellite data.

Plots of station performance and meteorological data are regularly generated. The plots are sorted by station and come in two forms: for data from the past year and for data since the year 2000. The information presented in these plots for each station in the ILRS network are: total number of normal points, total number of full-rate points, average number of data points per LAGEOS normal point, LAGEOS normal point rms, calibration rms, and system delay, and station temperature, pressure, and humidity (as recorded in the normal point data). Examples of these plots for the Yarragadee station are shown in Figure 4-2-a, -b, and -c. The plots are available through the individual station pages on the ILRS Web site (*http://ilrs.gsfc.nasa.gov/stations*).

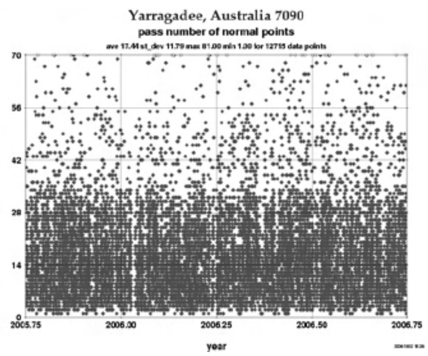


Figure 4-2a. Total number of normal points from Yarragadee for the past year.

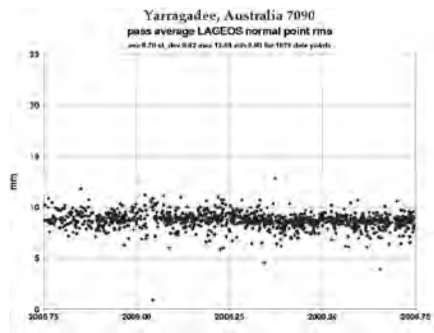


Figure 4-2b. Pass average LAGEOS normal point RMS from Yarragadee for the past year.

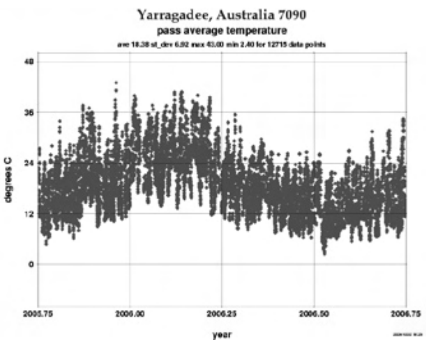


Figure 4-2c. Average temperature Yarragadee for the past year.

Several Web sites (distinct from the ILRS Web site) have been developed to link to proceedings from the International Workshops on Laser Ranging. PDFs of papers (and in some cases, presentations and posters) are available for the proceedings listed in Table 4-1. The ILRS CB staff is currently scanning proceedings documentation from the remaining workshops and will make the PDF files available through the ILRS Web site in the near future.

Table 4-1. Proceeding Web Sites for International Workshops on Laser Ranging

Workshop	Year	Location	URL
8	1992	Annapolis MD, USA	http://ilrs.gsfc.nasa.gov/reports/workshop/lw08.html
11	1998	Deggendorf, Germany	http://cddis.gsfc.nasa.gov/lw11
12	2000	Matera Italy	http://cddis.gsfc.nasa.gov/lw12
13	2002	Washington DC, USA	http://cddis.gsfc.nasa.gov/lw13
14	2004	San Fernando, Spain	http://cddis.gsfc.nasa.gov/lw14
15	2006	Canberra, Australia	http://cddis.gsfc.nasa.gov/lw15

ILRS Reporting

The Central Bureau continued to provide station performance "report cards" in 2005 and 2006. These quarterly reports show data volume, data quality, and ILRS operational compliance information. These results include independent assessments of station performance from several of the ILRS analysis/associate analysis centers. The statistics are presented in tabular form by station and sorted by total passes in descending order. Plots of data volume (passes, normal points, minutes of data) and RMS (LAGEOS, Starlette, calibration) are created from this information and available on the report card Web site *http://ilrs.gsfc.nasa.gov/stations/site_info/global_report_cards/index.html*;

Example plots from the latest report card (March 2007) are shown in Figure 4-3-a, -b, and -c.

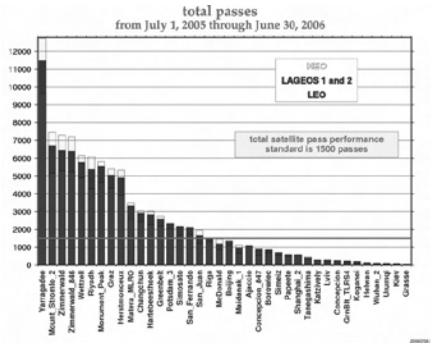


Figure 4-3a. Total passes for 2006q3 report card.

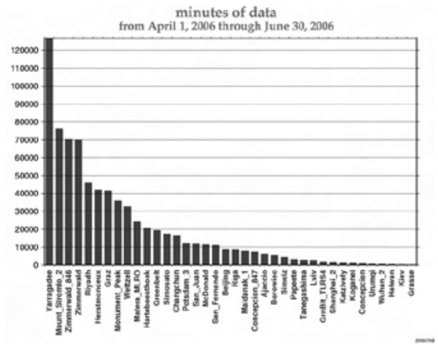


Figure 4-3b. Minutes of data for 2006q3 report card.

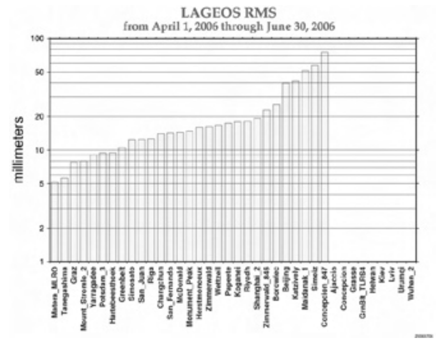


Figure 4-3c. LAGEOS RMS for 2006q3 report card.

Sites were reminded to review and update their Site and System Information Forms. These forms, commonly referred to as site logs, contain detailed site information (e.g., coordinates, contact information, collocation information, site identifiers, local survey ties, and system eccentricities), ranging machine sub-system configuration specifications (e.g., laser, telescope/mount, receiver, timing, meteorological devices, and data processing systems) along with system ranging capabilities. Stations were also asked to complete a survey of prediction usage. This information is utilized by the Central Bureau to determine which data sets are used by the network and whether the predictions are sufficiently accurate for ranging operations.

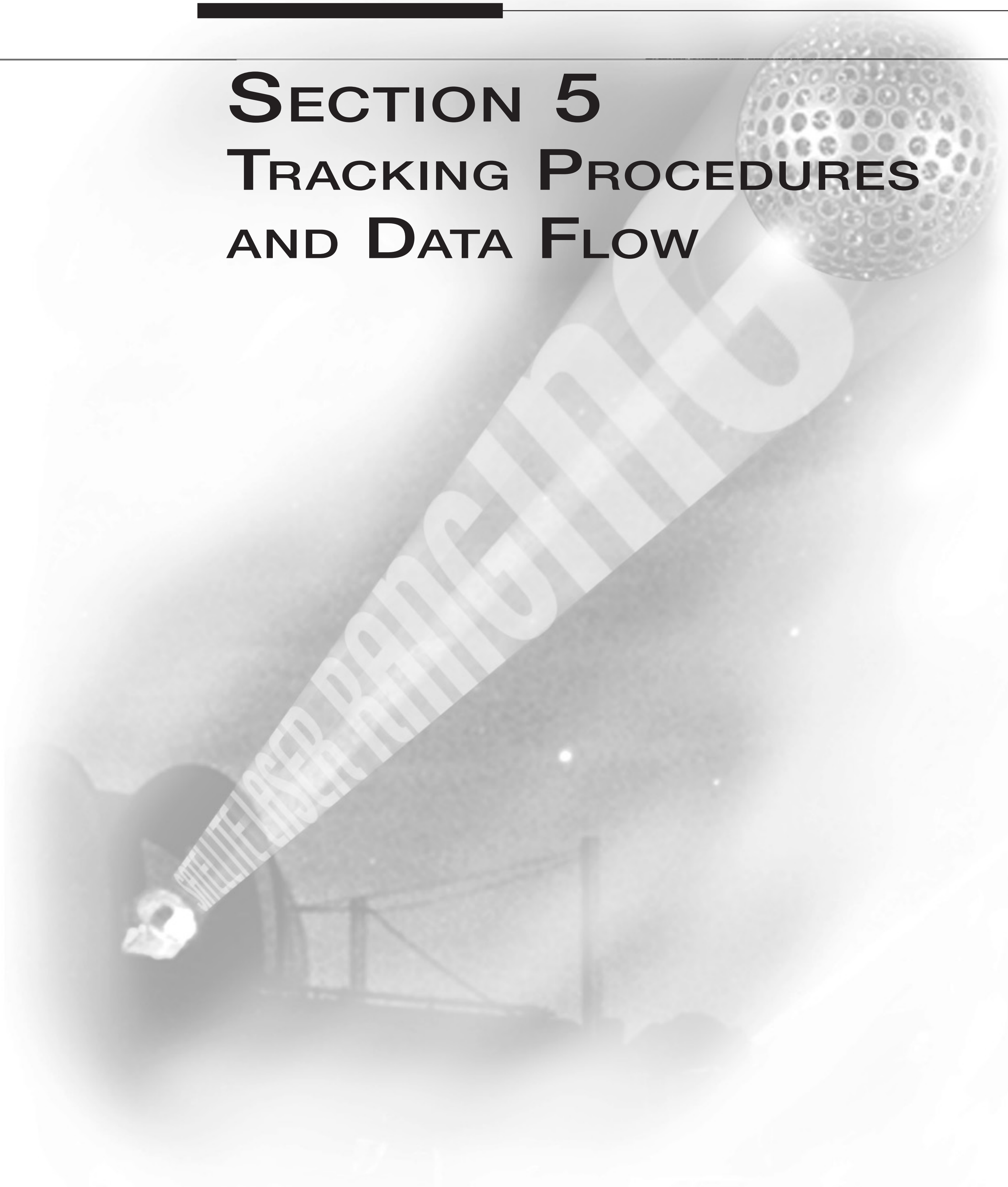
The 2003-2004 ILRS Report was issued and can be viewed on the ILRS Web site. ILRS analysis center reports and inputs are used by the Central Bureau for weekly review of station performance and to provide feedback to the stations when necessary. These reports as well as special weekly reports on on-going campaigns are issued by e-mail. A catalogue of diagnostic methods, for use along the entire data chain starting with data collection at the stations, has emerged from this process and will be made available on the ILRS Web site. The evaluation process has been helpful in comparing results from different analysis and associate analysis centers, a role soon to be assumed by the Analysis Working Group.

Data Center Developments

Data integrity checks

Both HTSI and the EDC, as part of their operational data center responsibilities, provide data integrity checks on all incoming SLR normal point data. The software tests for valid values for seconds, surface pressure, temperature, and humidity, checks for modifications to the release flag, and validates the number of digits in the data record and the checksum as specified on the ILRS Web site at:
http://ilrs.gsfc.nasa.gov/products_formats_procedures/normal_point/format_and_data_integrity.html.

Section 5
Tracking Procedures and Data Flow



SECTION 5

TRACKING PROCEDURES AND DATA FLOW

Tracking Priorities

Carey Noll/NASA GSFC

The ILRS tries to order its tracking priorities (shown in Table 5-1) to maximize the utility to the users of ILRS data. Nominally tracking priorities decrease with increasing orbital altitude and increasing orbital inclination (at a given altitude). Priorities for some satellites are then increased to intensify support for active missions (such as altimetry), special campaigns (such as IGLOS), and post-launch intensive tracking campaigns. Some slight reordering may then be given missions with increased importance to the analysis community. Some tandem missions (e.g., GRACE-A and -B) may be tracked on alternate passes at the request of the sponsor. Stations may also adjust priorities to accommodate local conditions such as system capabilities, weather, and special program interests.

Table 5-1. Satellite and Lunar Tracking Priorities

Satellite Priorities

Priority	Satellite	Sponsor	Altitude (km)	Inclination (degrees)	Comments
1	GRACE-A/B	GFZ, JPL	485-500	89	Tandem mission
2	CHAMP	GFZ	429-474	87.3	
3	GFO-1	U.S. Navy	790	108.0	No other tracking technique
4	Envisat	ESA	796	98.6	Tandem mission with ERS-2
5	ERS-2	ESA	800	98.6	Tandem mission with Envisat
6	Jason	NASA, CNES	1,350	66.0	Tandem mission with TOPEX
7	ANDE-RR Active	NRL	400	51.6	
8	ANDE-RR Passive	NRL	400	51.6	
	Larets	IPIE	691	98.2	
10	Starlette	CNES	815-1,100	49.8	
11	Stella	CNES	815	98.6	
12	Ajisai	JAXA	1,485	50	
13	LAGEOS-2	ASI, NASA	5,625	52.6	
14	LAGEOS-1	NASA	5,850	109.8	
15	BE-C	NASA	950-1,300	41	
16	Etalon-1	Russian Federation	19,100	65.3	
17	Etalon-2	Russian Federation	19,100	65.2	
18	GLONASS-89	Russian Federation	19,400	65	Replaced GLONASS-86 (20-Mar-2003)
19	GLONASS-99	Russian Federation	19,400	65	Replaced GLONASS-87 (12-Jan-2007)
20	GLONASS-95	Russian Federation	19,400	65	Replaced GLONASS-84 (26-Aug-2005)
21	GPS-35	U.S. DoD	20,100	54.2	
22	GPS-36	U.S. DoD	20,100	55.0	
23	GIOVE-A	ESA	29,601	56	

Table 5-1. Satellite and Lunar Tracking Priorities (continued)

Lunar Priorities

Priority	Retroreflector Array	Sponsor	Altitude (km)
1	Apollo 15	NASA	356,400
2	Apollo 11	NASA	356,400
3	Apollo 14	NASA	356,400
4	Luna 21	Russian Federation	356,400
5	Luna 17	Russian Federation	356,400

Tracking priorities are formally reviewed semi-annually by the ILRS Governing Board. Updates are made as necessary. The Central Bureau communicates these updates to the ILRS stations.

Predictions

Current Status

There are now ten centers that provide SLR predictions on a regular basis (see Table 5-2).

Table 5-2. Satellite Prediction Providers

Center	Type	Interval	Satellites
CODE	CPF	Daily	GIOVE-A, GLONASS, GPS
CSR	CPF, TIRV	Daily	ICESat, Moon
ESOC	CPF, TIRV	Daily	Envisat, ERS-2, GIOVE-A
GFZ	CPF, TIRV	Sub-daily	GRACE, CHAMP
GSFC	CPF, TIRV	Daily/Sub-weekly	GFO-1
HTSI	CPF, TIRV	Daily	All
JAXA	CPF, TIRV	Weekly	Ajisai, ALOS LAGEOS, OICETS, ETS-8
MCC	CPF, TIRV	Sub-weekly	LARETS
NSGF	CPF	Daily	Ajisai, BE-C, Envisat, ERS-2, Etalon, GFO-1, GIOVE-A, Jason, LAGEOS, LARETS, Starlette, Stella
NRL	CPF	Sub-daily	ANDE-RR

The consolidated laser ranging prediction format (see below) is now operational within the ILRS. This format can be used for ranging to retroreflectors on satellites in low Earth orbit and out to the Moon, and for transponder ranging to planets and interplanetary spacecraft. Also included are options for standardizing prediction interpolators used at the stations. In 2006, the tracking of very low Earth orbit satellites increased significantly with sub-daily distribution of the new, higher quality CPF predictions.

The ILRS is encouraging stations to use the mission provided or sanctioned predictions for restoreflector satellites where they are available. Some of the recent missions have periodic maneuvers or drag compensation capability, and some also have GPS data to enhance the SLR predictions. Since the missions have the most up-to-date information of this type, they are in the best position to keep predictions current.

Consolidated Prediction Format (CPF)

Randy Ricklefs/University of Texas at Austin, CSR

The ILRS Governing Board approved the new Consolidated Prediction Format (CPF) in October 2005, so the emphasis during 2006 was on insuring that the stations and prediction centers successfully implemented the format. By the end of 2006, 23 of the 37 ILRS ranging stations had implemented the format while 5 others were to be finished soon. The remaining stations were down for upgrades or repairs. The one currently operational LLR station is also using the new prediction format. There is also an ongoing effort to implement the CPF for the first transponder mission to the moon, the Lunar Reconnaissance Orbiter (LRO). All but one of the predictions centers is now producing predictions in the new format. The ILRS will cease producing TRV predictions at the end of 2007.

Restricted Tracking on Vulnerable Satellites

Michael Pearlman/CfA, Julie Horvath/HTSI

During the last two years, network procedures have been implemented to protect satellites that are vulnerable to laser radiation. Satellites such as ICESat and ALOS have optical sensors aboard that could be damaged. Restricted satellite missions may opt to request one, two, or all of the possible restrictions for their mission, but the numbers 1 and 5 below are required procedures. The procedures include:

1. predictions are sent to only participating (qualified) stations;
2. stations are restricted to a **maximum ranging elevation** to protect fixed nadir pointing sensor(s);
3. missions provide **files of allowable pass segments** to carefully define tracking and non-tracking periods;
4. stations are constrained by a mission provided, Web accessible **GO/NO-GO flag** which allows immediate (within 5 minutes) cessation of all network tracking of target; and
5. participation is limited to trusted stations that have demonstrated ability to handle the pass segment file and GO/NO-GO flag.

ILRS stations that have implemented these procedures include: Mt. Stromlo, Riga, Koganei, Monument Peak, Hartebeesthoek, Yarragadee, Tanegashima, Zimmerwald, Herstmonceux, Greenbelt, and TLRS-4 (Maui). Two ALOS tracking campaigns in 2006 using restricted tracking procedures were highly successful. ICESat is presently operating under restricted tracking conditions.

Data Transmission

The ILRS continues to improve data throughput. Data from the field stations are now submitted hourly and made available immediately through the data centers for rapid access by the user community and prediction providers. With this faster submission of data, better quality predictions are available more frequently and prediction quality assessment is available in near real-time.

Consolidated Laser Ranging Data Format (CRD)

Randy Ricklefs/University of Texas at Austin, CSR

Due to the upcoming Lunar Reconnaissance Orbiter (LRO) mission, and the growing number of stations with lasers firing at a kilohertz rate, the Data Formats and Procedures Working Group is undertaking a project to rewrite the formats for the ILRS full-rate, normal point, and sampled engineering data types. The current formats do not allow for many of the fields or field sizes required for ranging to transponders. In addition, the current full-rate format is too cumbersome for the amount of data produced by kilohertz laser ranging. The new format encompasses all three data types for SLR, LLR, and transponder targets. The CRD uses the same building block approach as the CPF, which allows modularity, flexibility, and expandability.

SECTION 6
EMERGING TECHNOLOGIES

SECTION 6

EMERGING TECHNOLOGIES

John Degnan/Sigma Space Corporation

Introduction

This report is largely, but not exclusively, based on the technical papers presented at the 15th International Workshop on Laser Ranging, held in Canberra, Australia in October 2006. The report also draws on material from the published literature and the interim 2005 ILRS Workshop held in Eastbourne, UK. It is not intended as a review of all that was presented, since the online abstracts and papers do that adequately. Instead, it is a subjective attempt to summarize and comment on the key technology trends and highlights (hardware only) and to tie key engineering activities into an overall perspective.

Kilohertz Photon-Counting Systems

Following a long dormant period, work on NASA's eyesafe SLR2000 system was resumed, and several new subsystems were developed [McGarry et al., 2006] including a higher efficiency (33%) GaAsP quadrant microchannel plate Photomultiplier built by Hamamatsu, a liquid crystal optical shutter to protect the sensitive detector from backscatter [Degnan and Caplan, 2006], and a software-controlled transmitter beam expander for adjusting beam divergence while maintaining a fixed eye-safe spot size at the telescope exit aperture [Degnan, Jodor, and Bourget, 2006]. As of this writing, SLR2000 has successfully tracked satellites up to and including LAGEOS using the new detector with an eyesafe pulse energy of 65 microjoules emerging from the 40cm telescope exit aperture. Other design features, such as the Laser Pulse Repetition Frequency control (to prevent "collisions" between incoming and outgoing pulses) and the dual Risley Prism unit for transmitter point ahead, also appear to be working properly although, at present, the transmitter is being pointed at the satellite and the receiver FOV is widened to about 25 arcseconds in order to accept the return pulse. Near term plans include pointing the receiver at the satellite and implementing both the transmitter point-ahead and quadrant tracking systems.

The highly successful (but non-eyesafe) 2kHz Graz station continued to demonstrate high signal count rates on all satellites, which enabled researchers to investigate the spin parameters of LAGEOS-1 [Kucharski et al., 2006] as well as GP-B and Ajisai [Kirchner et al., 2006a]. By monitoring the distribution of backscattered laser light on an ISIT and computing the angular variation in the position of the intensity peak, the Graz group also estimated the pointing jitter produced by atmospheric turbulence at their site to be as high as 10 arcseconds (comparable to their raw beam divergence) at rates up to 40Hz [Kirchner et al., 2006b]. The observed jitter was worse at low ambient temperatures (with heat emanating from their dome), at low elevation angles (as would be expected for atmospheric turbulence effects), and at higher tracking speeds (which they attributed to a rapidly changing atmospheric propagation path but might also include an additional mechanical component introduced by the tracking mount).

Herstmonceux joined the "Kilohertz Club" during this period [Gibbs et al., 2006]. Herstmonceux, using the same High-Q laser and C-SPAD detector as Graz, successfully tracked satellites up to LAGEOS altitudes but was unable to track the faster low altitude satellites, GRACE and CHAMP, due to temporary "software issues".

In Canberra, Russia unveiled a planned 15 station network of very compact SLR stations with a 25cm telescope aperture to be completed by 2010. They have also designed a mobile sister station having a larger 60cm aperture. The new Russian stations, equipped with a higher energy (2.5mJ) but lower rep rate (300Hz) transmitter, bridge the gap between the older 5-10Hz systems and the new kHz systems [Burmistrov et al., 2006].

Components

Detectors

With the growing emphasis on photon-counting and high repetition rate systems, the quantum efficiency (QE) and deadtime of the detector following detection of a "photon event" become increasingly important. The range return rate varies linearly with QE, and a long dead time necessitates narrower range gates, spectral filters, and/or spatial FOV for daylight operation against a solar background. At 532nm, conventional bi-alkali or multi-alkali cathodes typically have QE's in the 10 to 18% range. Actual counting efficiencies are often reduced to 60% or 70% of these numbers due to internal tube losses (e.g., the "dead space" between microchannels).

Burle Industries in the U.S. offers gated GaAs photomultipliers with 30% QE. Hamamatsu Corporation is offering micro-channel plate photomultipliers with 40% QE GaAsP photocathodes and overall counting efficiencies of 26% at 532nm, but they are significantly more expensive than the older bialkali tubes. The Hamamatsu tubes are also available in multi-anode configurations for quadrant or 3D lidar imaging applications. A quadrant GaAsP tube was recently installed in SLR2000 and helped obtain the first LAGEOS returns in that low energy, eyesafe system.

In Canberra, the Czech Technical University reported the latest results on their space-qualified photon counting module for the Chinese Laser Time Transfer Project [Prochazka et al., 2006]. The silicon K14 SPAD has the following properties at 532nm:

- Active area: 25 micron diameter
- Quantum Efficiency: 10%
- Timing Resolution: 75psec
- Dark Count Rate: < 8kHz @ 20°C
- Operating Temperature Range: -30°C to 80°C (no cooling)
- Power Consumption: <400mW
- Mass: 4g

In addition, it is highly resistant to solar and ionizing radiation (100krad) damage and has an expected lifetime of greater than 10 years in space.

Precision Timing

By far, Event Timers (ET's) dominated the technology contributions at the recent Canberra workshop. The Riga group [Bespal'ko et al., 2006; Artyukh et al., 2006a] presented the characteristics of their latest timer, the A032-ET, which is an improved version of their previous instrument, the A031-ET. The latest model is designed to support kilohertz laser ranging (up to 10kHz) with a burst rate up to 16MHz but can also support low repetition rate systems. The single shot resolution is less than 10psec, and the deadtime has been reduced to less than 60nsec, comparable to actively quenched APD's. It can be controlled remotely by a Client-server and has built-in online stop-pulse gating with a multiple stop capability. The Riga SLR group also described an approach for integrating the A032-ET into a full kilohertz rate SLR receiver [Artyukh et al., 2006b]. The Chanchung SLR group also reported their recent results using the A032-ET [Dong et al., 2006].

The French delegation [Samain et al., 2006] described the spaceborne and ground-based timers for the Laser Link Time Transfer (L2T2) experiment. For the spaceborne timer, they claim a precision of less than 2psec, a linearity of less than 1psec, a time stability of 30fsec over 1000sec, and a thermal stability of 1psec/°C with no sensitivity to magnetic fields. On the negative side, however, the spaceborne timer has a relatively long 3 μsec dead time. The ground-based timer has similar precision and linearity specifications and a somewhat shorter (1 μsec) deadtime.

HTSI [D. McClure et al., 2006] reported on a high performance ET controller designed to operate in tandem with the HTSI ET, which is currently installed in various systems (MLRO, SLR2000, GUTS). It allows UTC-tagged event epochs with <2psec jitter and 0.5psec resolution from up to 12 input channels at acquisition rates up to 50kHz. Multiple channels permit the integration of multiple detectors or data arrays and the generation of a single real-time stream of UTC-epoched event data with associated channel ID flags. The authors pointed out that, in the recent past, the MLRO and GUTS systems have reported the lowest RMS to LAGEOS of all the ILRS stations.

The Czech Technical University [Hamal et al., 2006] reported on their Portable Pico Event Timer. They currently claim a timing resolution of 1.2psec, a precision of 3psec, a timing stability of 1psec/hr, and a thermal stability of 1psec/°K. The timer, which operates at rates up to 2kHz, is in use at Graz, Wetzell, and TIGO (Chile).

The Shanghai Observatory [Zhang et al., 2006] reported on a Time-to-Digital Converter (TDC) integrated onto a single Field Programmable Gate Array (FPGA) chip. The authors predict that the current 50-60psec timing resolution will improve to 30psec in the near future. While not as precise as the timers discussed previously, the FPGA-based systems are very light and compact, making them ideal for portable or satellite-based systems. Furthermore, they have low deadtimes relative to other timers. In the altimetry session, Sigma Space Corporation [Degnan et al., 2006] reported on a 100 beam 3D imaging lidar which incorporates a 100 channel FPGA-based timing system with a ±93psec timing resolution, a multistop capability limited only by onboard memory storage, and a deadtime of less than 2 nsec. The latter feature is important for mapping volumetric scatterers such as tree canopies. The Sigma timer is extremely compact with 50 channels on a single printed circuit board.

Picosecond, Kilohertz Lasers

With the advent of photon-counting kilohertz SLR systems, the search for suitable lasers producing subnanosecond, mJ-level pulses at kHz rates continues. NASA's SLR2000 system using a very compact microchip laser followed by a six-pass amplifier built by Q-Peak Inc. in the USA. The relatively long 300psec helps SLR2000 meet its unique eyesafe requirement at 532nm. The Graz and new Herstmonceux system use a significantly larger and more complex (but apparently reliable) regenerative amplifier system offered by High-Q Corporation in Austria, which produces ultrashort (10–20psec), 400μJ pulses at a 2kHz rate. Australian researchers also used a regenerative amplifier approach to achieve comparable pulse energies and pulsewidths at kHz rates [Gao, 2006].

Russian researchers [Andreev et al., 2006] reported on a very different laser approach based on Stimulated Raman Scattering (SRS) pulse compression which produced 25psec, 1mJ pulses, at a 1kHz rate and with good spatial mode quality ($M^2 = 1.1$). Using a Nd:YAG Master Oscillator (MO) and three single pass Nd:YAG amplifiers in conjunction with a Ca_8Fl_{16} SRS cell, they generated 100mJ, 350psec pulses at 1319nm. They used this radiation to pump a $Ba(NO_3)_2$ SRS-MO and two SRS amplifier cells to obtain 50mJ, 30psec pulses at an eyesafe wavelength of 1530nm and a 100Hz rate. It was observed that the Raman conversion efficiency decreased noticeably at kHz rates for the higher peak pump powers.

In important related work not represented in Canberra, researchers at Aculite Corporation in the USA [Brooks and DiTeodoro, 2005] have reported on a high average power (mJ @ 10kHz = 10W) laser, which uses a one nsec microchip oscillator as the seed source and two Yt:YAG photonic fiber amplifiers. The 40 micron fibers were terminated with 2mm flared ends to prevent coating damage at the facet face. The fiber amplifier approach could ultimately yield highly compact, efficient, and rugged picosecond pulse SLR transmitters provided the fibers can withstand the higher peak intensities at short pulsewidths.

Multi-Wavelength Ranging

The need and accuracy requirements for multiwavelength ranging are driven by the quality of the atmospheric models used to correct for the atmospheric delay in single wavelength systems. Many of the multiwavelength papers submitted to the 2006 Canberra workshop were devoted to atmospheric modeling and, in contrast with past workshops, only a few dealt with multiwavelength ranging hardware. In previous workshops, it has been demonstrated that the multicube responses of current SLR targets often produce different reflected waveforms at different wavelengths, which makes a computation of atmospheric delay difficult, if not impossible, to measure even with bias-free timing equipment. In Canberra, Werner Gurtner presented additional sobering material that further highlighted the difficulty in beating down dual wavelength instrument bias errors to the level required for millimeter accuracy ranging [Gurtner, 2006]. Zimmerwald operates at the fundamental and second harmonic wavelengths of Ti:Sapphire (423 and 846nm), for which the amplification factor is about 14. In order to measure the atmospheric correction to 1 mm accuracy, the calibrated range difference (423–846) must be bias-free and good to 1/14 mm (i.e., 0.07–0.08mm). Thus, in addition to a differential time-of-flight (TOF) measurement accurate to about 0.5 psec, the calibration values (or their differences) must be bias-free to much better than the 0.08 mm, a requirement that he deemed impossible to meet.

The French delegation reported that, after 30 years of excellent service, the Grasse LLR station is being replaced by the more advanced MEO system. MEO is scheduled to be completed by early 2008 and is intended to have a two color capability.

Remote or Autonomous Operation

The drive toward remote and totally autonomous operation has not only spurred the development of increasingly sophisticated operational software at a number of stations but also a variety of new sensors and actuators to replace crucial human interactions. Most of the automation efforts reported in Canberra were in the software area and outside the scope of this report.

Interplanetary Laser Transponders

Almost a decade after it was first proposed at the Shanghai workshop [Degnan, 1996] and after three prior attempts to laser altimeters on the MGS and NEAR spacecraft which failed due to weather or spacecraft problems [Zuber, 2006], NASA announced the first successful two way asynchronous transponder [Degnan, 2002] experiment in late May 2005 [Sun et al., 2005; Smith et al., 2006a]. The 24.3 million km two-way link was established between the GSFC 1.2 meter telescope and the Mercury Laser Altimeter (MLA) onboard the MESSENGER spacecraft. In September 2005, the GSFC team demonstrated a one-way link to the Mars Orbiter Laser Altimeter (MOLA) instrument on Mars Global Surveyor at a distance of 80 million km in which approximately 500 laser pulses were observed by the MOLA receiver. The latest analysis results were presented at the Canberra workshop [Neumann et al., 2006]. A second transponder experiment has been proposed for June 2007 when MESSENGER is in the vicinity of Venus.

At the Eastbourne Workshop in 2005, John Degnan and Ulrich Schreiber, co-chairs of the Transponder Working Group, were discussing low cost ways to further the transponder cause through the use of the existing SLR satellite constellation, via either single station experiments or two closely spaced stations ranging to a common satellite. Subsequently, it was demonstrated that the existing constellation can be used to simulate laser transponder and communications links ranging from the Moon to Saturn at PCA [Degnan, 2006]. The Apollo 15 reflector on the Moon would simulate links on the order of 100 AU, over twice the distance to Pluto and the Kuiper Belt. The Wettzell SLR station is currently planning single station simulation experiments while NASA is presently in the process of setting up dual station, dual wavelength transponder and communications experiments using the 1.2 meter and SLR2000 stations at GSFC [McGarry et al., 2006].

With the launch of the Lunar Reconnaissance Orbiter (LRO) spacecraft by NASA in 2008, the international SLR community will have the opportunity to support a “half-transponder” experiment [Smith et al., 2006b]. The experiment is designed to provide accurate differential range measurements to improve knowledge of the lunar gravitational field and support topographic measurements by the Lunar Orbiter Laser Altimeter (LOLA). Green 532nm pulses from Earth, properly synchronized with LOLA’s 28Hz fire rate, will be detected and timed by the LOLA receiver and used to generate the differential range.

On a final note related to extra-terrestrial ranging, the new multiphoton APOLLO lunar laser ranging facility received its first lunar returns on July 24, 2005 [Murphy, 2006]. Return rates during some experiment sessions were as high as 25%, and the precision of the normal point centroid was estimated to be in the 1 to 2mm range.

Laser Time Transfer

Laser time transfer experiments are being pursued vigorously by the SLR Community. After several aborted attempts since 1994, the French Time Transfer by Laser Link (T2L2) Experiment has been accepted as a payload on the Jason-2 oceanographic mission and is scheduled for launch in June 2008 [Samain et al., 2006a]. The T2L2 goal is time transfer at the 100 psec level or better (i.e., two orders of magnitude better than the microwave link) with possible application to fundamental physics experiments (e.g., the anisotropy of the speed of light on the downlink vs. uplink) or one-way interplanetary ranging. A second ground-to-satellite time transfer experiment between a rubidium oscillator on the ground and a second rubidium on a much higher satellite at 20,000km is also underway [Fumin et al., 2006].

At the 1992 Workshop, it was suggested that the mirrored panels on the Ajisai satellite might be used to transfer laser pulses from one SLR station to another [Kunimori et al., 1992]. Unfortunately, the proper geometry for transfer occurs only three times per Ajisai spin period (~ 2 sec) and for only 5 to 10msec per opportunity. Thus, with the 5 to 10Hz laser fire rates (100 to 200msec interpulse periods) of the current network, the likelihood of a pulse transfer between stations is greatly reduced. However, it has been suggested [Otsubo et al., 2006] that the new 2kHz systems could potentially transfer up to 30 pulses per second between stations via Ajisai.

Laser Altimetry

As NASA’s Mercury Laser Altimeter (MLA) on the MESSENGER spacecraft makes its way to Mercury, work continues on the BELA altimeter to be flown as part of ESA’s Bepi-Colombo mission [Michaelis et al., 2006]. BELA is designed to operate at altitudes up to 1000km (70% probability of detection) with a goal of providing a global topographic map of the planet. The beam diameter on the surface will be less than 100m with an along-track spacing of 300m. The system utilizes a 20cm telescope and a 50mJ, 3nsec laser operated at 10Hz. The detector is a space-qualified APD built by Perkin Elmer. The 250psec resolution timing system is provided by the Czech Technical University and is based largely on their P-PET hardware with TDC chips replacing the larger Dassault units [Jirousek et al., 2006]. The overall instrument is expected to weigh 12kg and draw 33W of spacecraft prime power. They propose to perform a transponder demonstration in collaboration with Dr. Ulrich Schreiber of the Wetzell SLR station.

Sigma Space Corporation [Degnan et al., 2006] described a second-generation photon counting 3D imaging and polarimetric lidar designed for high resolution mapping (15cm horizontal, 3cm vertical) from a low altitude (~1km) mini-UAV. The total system, including the integrated GPS/IMU system, weighs approximately 35kg, occupies about 0.06 cubic meters of volume, and consumes about 400W of 28VDC power. The passively Q-switched microchip Nd:YAG laser transmitter produces 381mW of power in a 22kHz train of 700psec pulses. A frequency doubler produces 141W of power at 532nm. The green beam is broken up by a Diffractive Optical Element (DOE) into a 10x10 grid of beamlets in the far-field, and the individual beamlets are imaged onto a microchannel plate photomultiplier with 100 anodes. The anode outputs are input to individual channels of a multistop, FPGA-based timer having a resolution of 93psec (1.4cm range) and a dead time of nsec. Thus, each laser pulse produces a 10x10 pixel volumetric 3D image, which, through the action of a dual wedge scanner and the aircraft motion, produces a contiguous 3D image over a 2km swath. With 100 beams at the maximum 22kHz rate, the system generates 2.2 million 3D pixels per second. The residual 240mW of 1064 nm radiation is used to generate a coregistered 1.5m x 1.5m polarimetric image of the ground scene.

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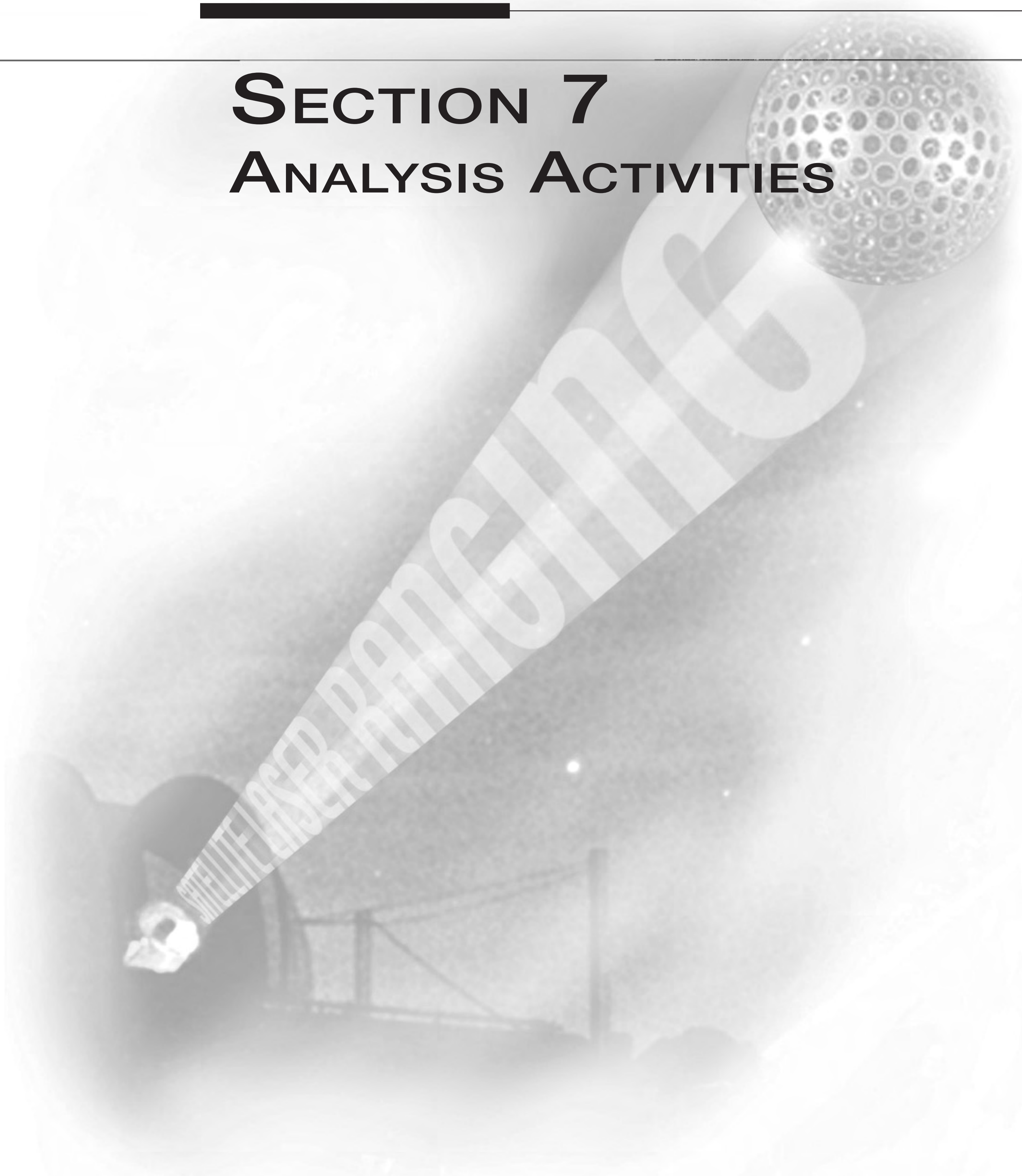
SECTION 7
ANALYSIS ACTIVITIES



SECTION 7

ANALYSIS ACTIVITIES

Ron Noomen/DUT, Graham Appleby/NERC, Erricos C. Pavlis/JCET, Cinzia Luceri/Telespazio S.p.A.

Introduction

The most important aspect of the SLR/LLR observations is their absolute accuracy, which approaches the level of a few mm for modern stations. This makes laser ranging an ideal technique to monitor and study specific elements of system Earth. In the case of LLR, applications include the study of fundamental lunar theory (both orbital and internal composition), as well as gravitational theory and relativity. For SLR, applications include determination of the geocenter and its temporal variations, absolute scale, global plate tectonic motions and local vertical deformations. The SLR community also produces other geophysical products including Earth Orientation Parameters (EOPs), time-variations of the long-wavelength components of Earth's gravitational field, satellite orbit dynamics, precise ephemerides, and others. The ILRS is an official Technique Service in the International Earth Rotation and Reference Frame Service (IERS). To fully exploit the unique aspects of the SLR observations, the ILRS Analysis Working Group (AWG) addresses various issues of SLR products, such as quality control, the estimated parameter group, the satellite data to be used, and format definition/use, optimization, and (the development of) an official combination product on the basis of the individual analysis center (AC) contributions. To this aim, a number of so-called pilot projects have been initiated during the past few years, with several of them successfully completed and several of them still ongoing. This contribution to the ILRS Report presents an update on the status and the results of these efforts. General information on AWG activities, membership and more detailed information on the pilot projects can be found on the relevant Internet pages (*http://ilrs.gsfc.nasa.gov/working_groups/awg/index.html*).

Activities in 2005 and 2006

An important instrument for contacts and discussions among SLR/LLR analysts proves to be the AWG workshops. During the period covered by this ILRS Report, such workshops were organized during April 2005 (Vienna, Austria), October 2005 (Eastbourne, UK), April 2006 (Vienna) and October 2006 (Canberra, Australia). All meetings took place on dates close to major geophysical meetings (EGU) or other (ILRS) venues, in order both to maximize AWG members' attendance and also encourage contact with other scientists.

A main element of the AWG activities is the development of a unique, best-possible (in terms of quality) analysis product (e.g., station positions and EOP) that can be used by the widest possible science community. In particular, an official solution for station coordinates and daily EOPs are generated by the ACs on a weekly basis, and submitted to the IERS as an official ILRS contribution. These weekly results depend on high-quality laser range observations to LAGEOS, LAGEOS-2 and to the Etalon satellites, and the ILRS network is encouraged to support this valuable work, ideally by tracking these satellites seven days a week. Two different products are distributed each week: 1) a loose constrained estimation of coordinates and EOP and 2) an EOP solution, derived from the previous product, fully constrained to an ITRF, (currently ITRF2000). The development of these products goes back to the very first days of the ILRS AWG. The currently operational products and the adopted analysis scheme were agreed upon by the AWG and have been run continuously in an operational mode since 2003.

At this moment, six different ACs support this activity and routinely provide this product: ASI, BKG, DGFI, GFZ, JCET and NSGF. ILRS has also adopted two official combination centers (CCs), the primary hosted by ASI and the back-up CC at DGFI. These two CCs are responsible for combining the six input solutions, and the delivery of the quality-checked and combined ILRS product to IERS. In preparing the weekly combination of the individual solutions, these combination centers follow a strict timeline and have to make sure that the products are of the highest possible quality. Official weekly ILRS products from the two combination centers are available in SINEX format each Wednesday at CDDIS and EDC. All ACs are encouraged to improve the quality of their contributions. It is noteworthy that a number of other institutes (Geosciences Australia, CNES, and NCL) are also in the process of being certified as official ACs in order to eventually contribute to the combination solutions. During the period covered by this ILRS Report, the procedures and analysis models have been scrutinized and documented thoroughly in order to avoid artificial differences and inconsistencies between results.

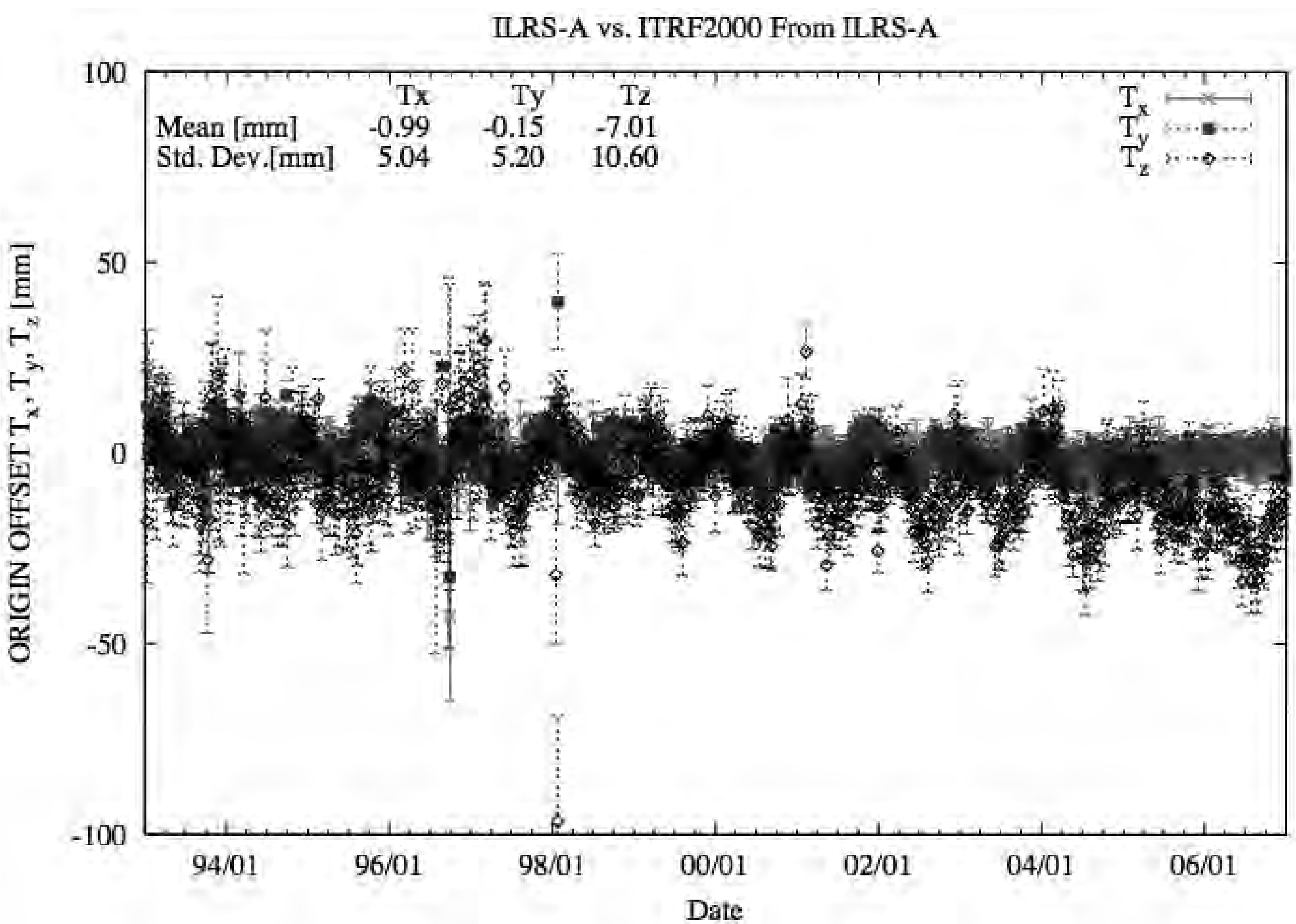


Figure 7-1. Time series of the origin offsets after a similarity transformation of the weekly ILRSA product with respect to ITRF2000 for 1993-2006.

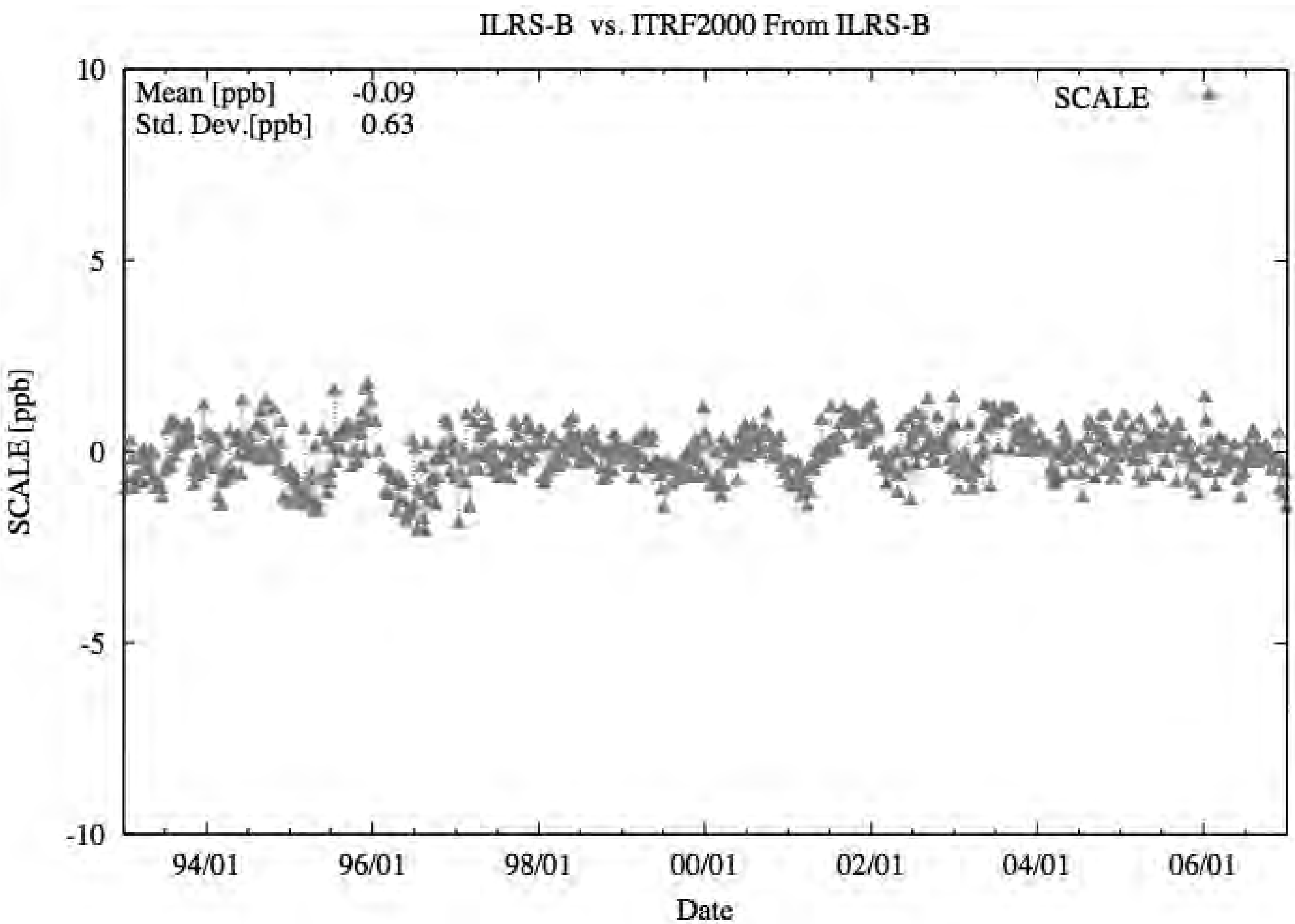


Figure 7-2. Time series of the scale differences after a similarity transformation of the weekly ILRSB product with respect to ITRF2000 for 1993-2006.

The results of the combination process are used as input for a number of products computed by others, e.g., the International Terrestrial Reference Frame (ITRF) 2005 solution, developed under the coordination of the IERS, and the IERS Combination Pilot Project (CPP) towards a unified EOP product. As a result of the weekly combination process, the ILRS also maintains a time series of the similarity transformation parameters of the weekly product with respect to the current ITRF – ITRF2000 during this reporting period. For SLR, the weekly geometric offsets of the origin from the conventionally defined ITRF origin (Figure 7-1) provide a measure of the motion of the geocenter due to mass redistribution in the Earth system. Similarly, the time series of the scale differences with respect to the current ITRF provide a measure of the stability of the SLR-defined TRF (Figure 7-2). To improve the usefulness of the time series of combination solutions and the ancillary products, thus improve its prospects for future utilization (reliability of resulting velocities, results on historical SLR stations, etc.), the ILRS AWG decided to extend the period covered by these solutions. In a first step, this was done by a full re-analysis of the LAGEOS-1 and -2 and Etalon data (where available) for the interval 1993-2006, with the same procedures and conventions as those applied in the operational product. Currently, the contributing ACs are working on a re-analysis of these data over the historical period 1983-1993; since the observations from this time frame are of an inferior quality and prior to the launch of LAGEOS-2, these analyses require a modified parameterization approach (e.g., biweekly arcs, consideration of bias adjustment, etc.). Results are expected by the middle of 2007.

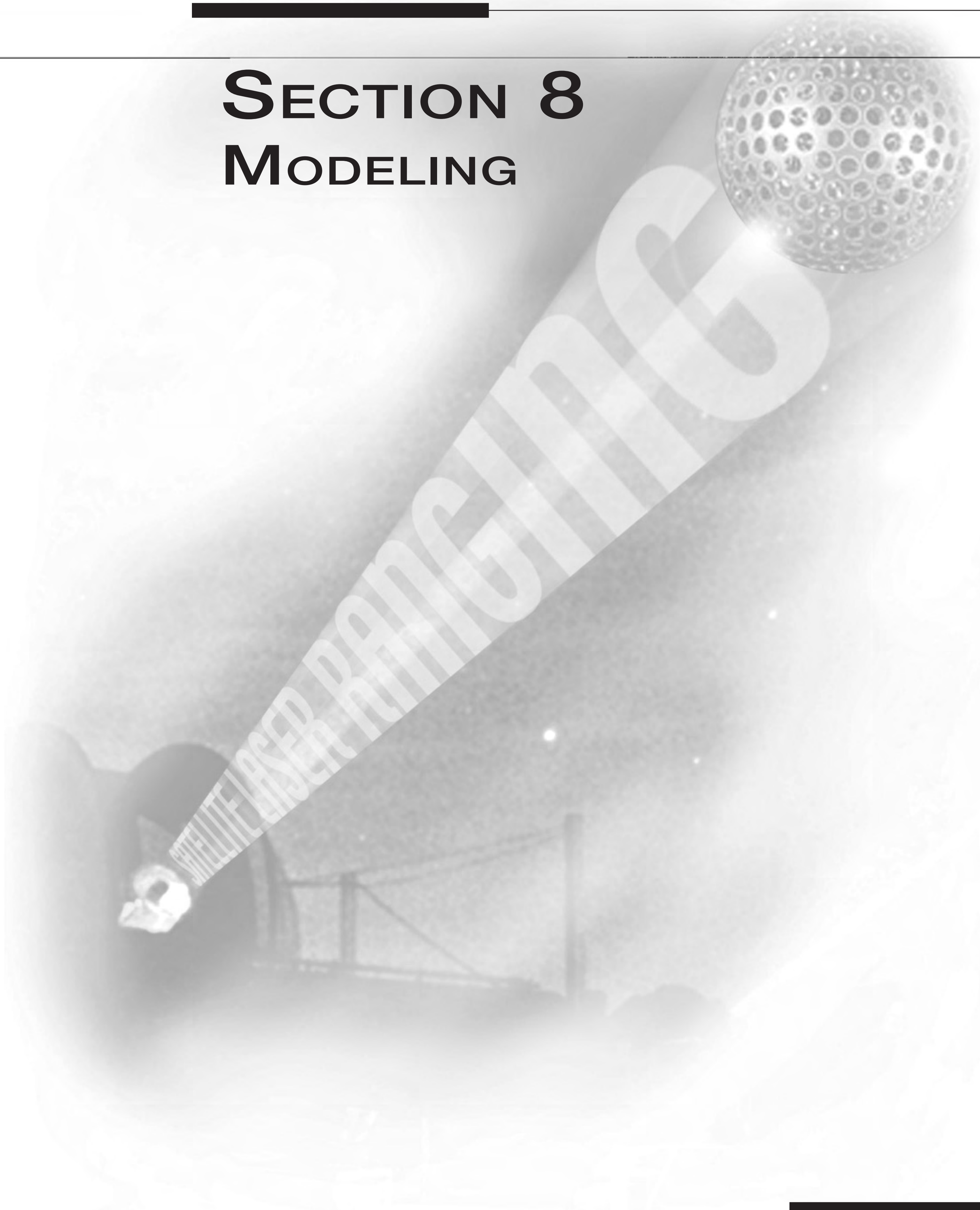
IERS has selected the SLR solutions to exclusively determine the origin of the new ITRF2005 solution. Unlike the previous ITRF2000 solution, the scale for the 2005 realization was determined exclusively by the VLBI solutions, due to an unresolved disagreement in the scale between the SLR- and VLBI-only "technique" solutions. Resolution of this unexpected, apparent inconsistency between the two oldest and most accurate techniques is the focal point of studies underway at various agencies, institutions and the IERS and ILRS Analysis Centers. The exclusion of SLR from the scale definition for ITRF2005 was discussed extensively during the last AWG meeting in Canberra and the concern of the SLR community was formally expressed to the IERS Directing Board with a formal letter from the ILRS GB Chairman and AWG Coordinator.

The AWG is currently expanding its list of weekly products to fill a void in the area of routinely available precise orbits for the primary SLR targets, i.e., the two LAGEOS and two Etalons. At present this is only a pilot project, however, it is expected that by the end of 2007 these products will be delivered routinely on a weekly basis. Another ongoing activity of the AWG is the improvement of the quality control (QC) process in various semi real-time analysis results. Traditionally, such QC results are distributed in a rather uncoordinated way, i.e., each analysis center producing its own unique analysis report, which is then made available to customers (stations, satellite managers, ILRS) typically without comparison or checking with results that are obtained by others. With this effort it is attempted to reduce possible inconsistencies among the various reports. A major improvement in the consistency of these results was the adoption of a single set of high quality station coordinates. Based on the findings of this pilot project, all analysis groups doing such real-time QC assessments have by now switched to ITRF2000. The results of the QC process are combined in a single report, which is available weekly at: *http://aiuas3.unibe.ch/ftp/slr/summary_report.txt*.

Organizational

Finally, from the organizational point of view, the last round of ILRS elections in October of 2006 brought new leadership at the helm of the AWG. The coordination of the analysis activities switched hands in late 2006 with Erricos C. Pavlis and Cinzia Luceri replacing Ron Noomen and Graham Appleby as Analysis Coordinator and Co-coordinator, respectively. We wish to thank Ron and Graham for their hard work and leadership during their tenure as chair and co-chair of the ILRS AWG.

Section 8
Modeling



Section 8

Modeling

Refraction Modeling

Erricos C. Pavlis and Glynn Hulley/JCET and Virgílio B. Mendes/University of Lisbon

Improvements in refraction modeling

The accuracy of satellite and lunar laser ranging (SLR and LLR) is greatly affected by the residual errors in modeling the effect of signal propagation through the troposphere and stratosphere. The ILRS recognizes this and it has established a Refraction Study Group (RSG) to look into ways to improve the current state of art. The chairmanship of the RSG, initially held by Stefan Riepl, was passed on to Erricos Pavlis during the 2005 Technical Workshop at Eastbourne, UK.

Although several models for atmospheric correction have been developed, the traditional approach in LR data analysis used until recently was a model developed in the 1970s [Marini and Murray, 1973]. A recent study [Mendes et al., 2002] had pointed out some limitations in that model, namely in regard to the modeling of the elevation dependence of the zenith atmospheric delay the mapping function (MF) component of the model. The MFs developed by Mendes et al. [2002] represent a significant improvement over the built-in MF in the Marini-Murray (M-M) model and other known MFs. Of particular interest is the ability of the new MFs to be used in combination with any zenith delay (ZD) model, used to predict the atmospheric delay in the zenith direction. Subsequently, Mendes and Pavlis [2004] developed a more accurate ZD model, applicable to the range of wavelengths used in modern LR instrumentation. The combined set of the new Mendes-Pavlis (M-P) mapping function and new ZD prediction model were validated with extensive tests, with the results reported in [Hulley et al., 2006]. Subsequent tests with several years of LAGEOS and LAGEOS 2 data analyzed at different ILRS ACs, and with the results compared to previous analyses using the traditional M-M model, also indicated the improved performance of the new M-P model. These findings were reported and discussed recently during the October 2006 Analysis Working Group (AWG) and the RSG meetings in Canberra, Australia. As a result, the RSG made a recommendation to the AWG to adopt the new model as the standard, and to proceed with the regeneration of the entire set of weekly ILRS Position and EOP products on the basis of the new model. The recommendation was accepted and the M-P model was adopted as the new standard for future analyses of LR data, starting January 1, 2007. The new standard was also documented and communicated to IERS, and it has been included in IERS' on-line "living document" version of its Conventions 2003 publication.

Future Developments

Since the accuracy of the new model is still significantly lower than what is required for near future applications of LR (≤1 mm) [Pearlman et al., 2005], the LR community has been looking into ways to achieve that accuracy. The correction of the atmospheric delay using two-color ranging systems is still at an experimental stage with promising results [Hamal et al., 2006], however, it is still years from being a viable alternative to the meteorological data based models. One significant component that is missing from these models though is the effect of horizontal gradients in the atmosphere, an error source that becomes more significant as the observation elevation angle decreases. However, global meteorological fields are now becoming more readily accessible, with higher spatiotemporal resolution, accuracy and of uniform quality. This is primarily due to the availability of satellite observations with global coverage twice daily. We have already developed and tested techniques that will compute the total atmospheric delay (including the gradients' effects) using ray tracing through these 3-dimensional fields [Hulley and Pavlis, 2006a, 2006b]. An example of the anticipated improvement is shown in Figure 8-1, where we see the RMS differences and percent variance improvement in the residuals of core SLR sites tracking LAGEOS-1 and LAGEOS-2 over the two-year period 2004-2005.

At present the new approach is being validated in precise satellite data reductions and an effort is in progress to secure funding to establish a "service" that will compute these corrections for all of the collected LR data in the future, as well as for all of the already existing SLR data in the ILRS archives.

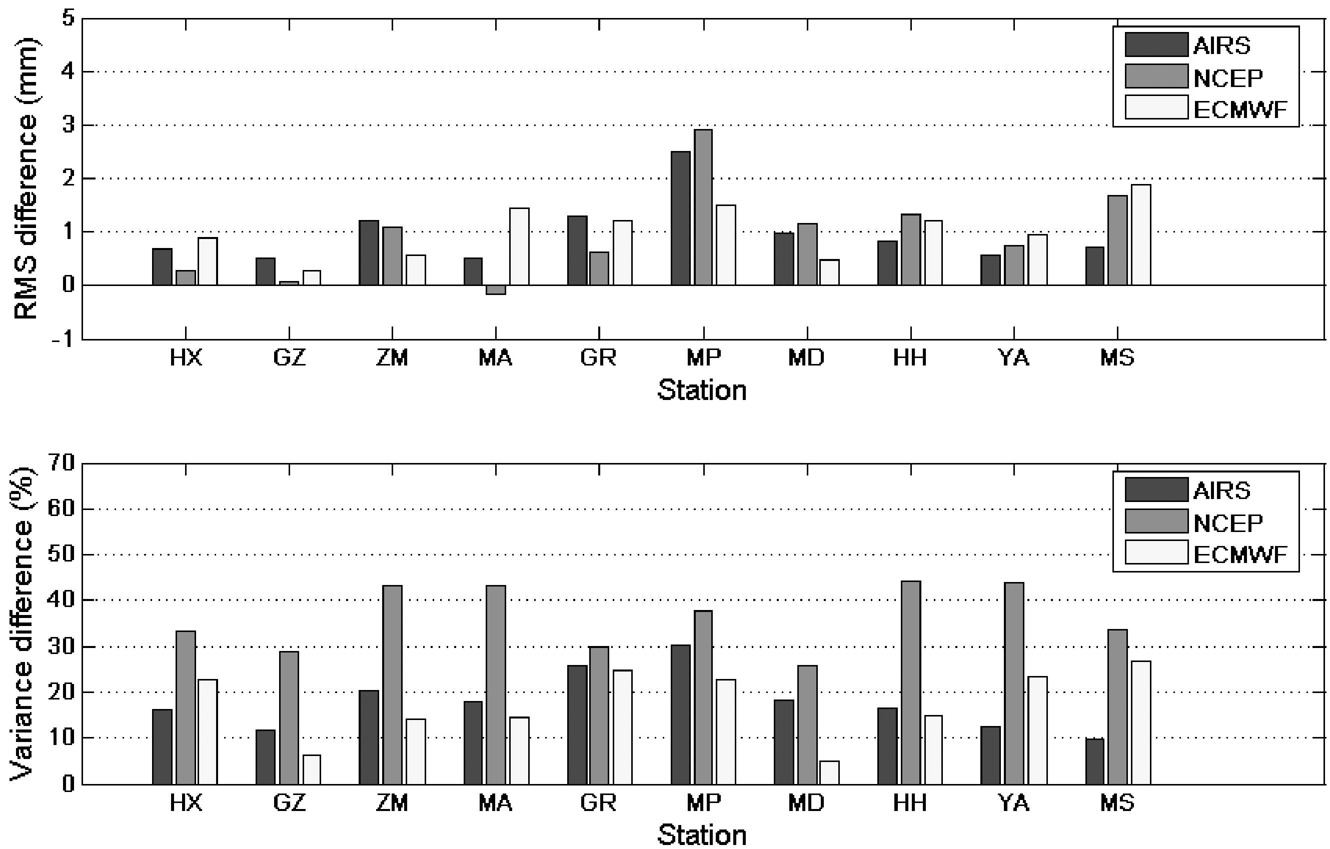


Figure 8-1. Differences between the original range residuals (model) and the fully corrected residuals (ray-tracing + gradients) for ten of the core ILRS stations: HX (Herstmonceux, UK), GZ (Graz, Austria), ZM (Zimmerwald, Switzerland), MA (Matera, Italy), GR (Greenbelt, MD), MP (Monument Peak, CA), MD (McDonald, TX), HH (Hartebeesthoek, South Africa), YA (Yarragadee, Australia), and MS (Mt. Stromlo, Australia). The corrections were obtained using three different sources of meteorological data: AIRS, the satellite-borne Atmospheric InfraRed Sounder on NASA's AQUA platform, NCEP, the National Center for Environmental Prediction, and ECMWF, the European Center for Medium Weather Forecasting.

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Improved LAGEOS Spin Axis and Thermal Force Modeling

José Ignacio Andrés and Ron Noomen/DUT and Stefano Vecellio-None/Politecnico di Milano

The use of space geodetic tools and techniques for geophysical investigations requires extremely precise orbital models of the LAGEOS spacecraft in order to meet the currently imposed stringent science requirements [Pearlman et al., 2005]. An element of the dynamic model for these spacecraft that has gained significance during the last few years is the regime of thermal forces during their lifetime in orbit (the pressure force exerted by the photons emitted by the hot components of the satellite surface). During the reporting period, DEOS developed and finalized a number of essential elements for the characterization and understanding of such forces. First of all, LOSSAM (LageOS Spin Axis Model) [Andrés et al., 2004] was finalized, providing solutions and predictions of the instantaneous rotation (direction and magnitude) for the two LAGEOS satellites. The accuracy of LOSSAM has already been demonstrated by an improvement of about 50% in the RMS residual of the Yarkovsky-Schach effect signal as shown by Lucchesi et al. [2004]. Error estimates of the spin axis estimates are typically on the order of about 10° and 1° for attitude, and about 6 s and less than 1 s for the period of rotation, for LAGEOS-1 and LAGEOS-2 respectively. LOSSAM is crucial for the description and determination of the actual thermal forces.

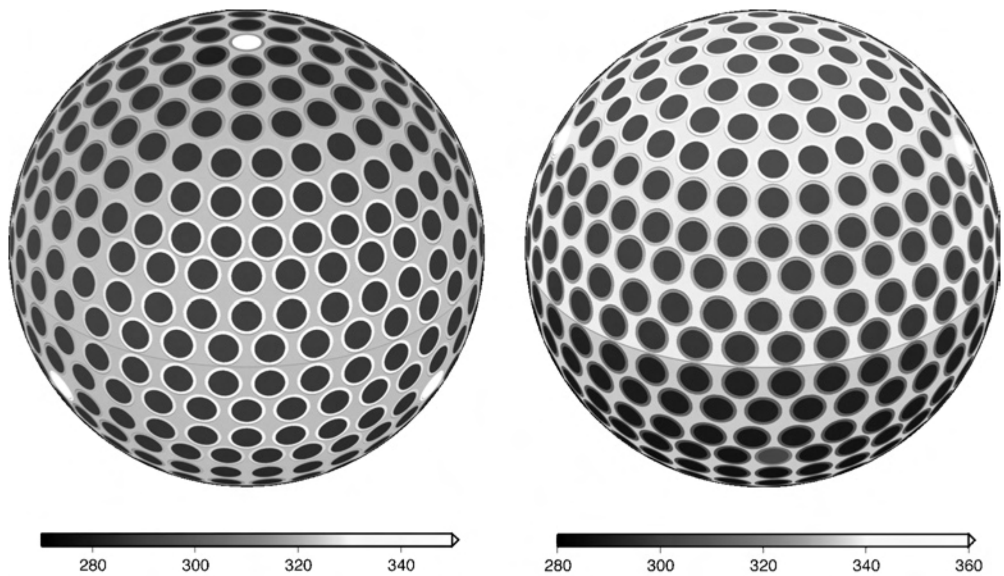

Figure 8-2. Surface temperature distribution [K] on January 1, 2002, for LAGEOS-1 (left) and LAGEOS-2 (right).

To this aim, the finite-element model LOSTHERM (LageOS THERmal Model), was also developed [Andrés et al., 2006]. LOSTHERM includes a representation of 2133 different elements for each satellite, for which the thermal response to various radiation sources has been simulated accounting for non-eclipse conditions as well as umbra/penumbra crossings, with a step-size of 60 s from launch to present. By evaluating and integrating the temperature (Figure 8-2) and resulting forces (photon thrust) exerted by each surface element, the magnitude and direction of the net, thermally induced, acceleration that acts on the spacecraft can be determined for every individual epoch. The LOSTHERM results show a consistent temperature behavior of the various LAGEOS elements, and yield accelerations that are in agreement with the results obtained by previous investigations, with the advantage of being able to account for any rotational regime (i.e., rapid, slow) as well as a full characterization of the different spacecraft materials (e.g., Si and Ge for the retroreflectors). In addition, an accurate model of the accelerations due to the interaction with the magnetic field and collisions with charged particles has also been developed. Such high quality models for satellite dynamics are indispensable for proper force modeling, and ultimately for the highest quality of typical LAGEOS science products (POD, tectonic motions, geocenter and low-degree terms of Earth gravitational field variations, EOP, etc.). These models can be expected to find their way in the precise orbit computations to ensure the highest possible quality for the ILRS products.

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Modeling Target Signature Effects

Graham Appleby/NERC and Toshi Otsubo/Hitotsubashi University

Progress has been made on modeling target signature effects in terms of a better understanding of the magnitude of small tracking-system-dependent corrections that should be applied to 'standard' center of mass (CoM) corrections in order to refer raw range observations accurately to the satellites' mass centers. This work follows on from that published in Otsubo and Appleby in 2003 and at present primarily addresses effects seen in the LAGEOS data. Within the network there are essentially three different station technology modes, each of which has strengths and weaknesses. A major subset of the network works in the multi-photon return regime; this is primarily the micro-channel plate (MCP) technology employed by the NASA systems, where system discrimination selects only multi-photon returns and thus essentially eliminates background noise. The second subset employs first-photon detection technology using photo-multipliers (PMT) and single photon avalanche diodes (SPAD), at multi-photon return levels. The third subset employs PMTs and SPADs, but at a controlled-single or near-single return level.

The work by Otsubo and Appleby [2003] showed, and presented through a series of tabular values, that appropriate CoM values for LAGEOS vary by up to 10mm when applied to these inhomogeneous systems of the ILRS network. The study also concluded that, for all but those stations employing a strict single-photon return regime, the absolute values and range of possible CoM corrections depends upon site-dependent electronic discriminator setup parameters, as well as on actual shot-by-shot return levels. This latter point is demonstrated in the following three range residual plots shown in Figure 8-3.

The plots show laser range residual means from fitted coordinate and orbital solutions for LAGEOS-1 and LAGEOS-2 summed from the period January 2004 to July 2005. The residuals have been binned according to the numbers, shown in the histograms below each residual plot, of individual returns that contributed to each normal point used in the analysis. We make the assumption that the return numbers per normal point are a good proxy for return level. The stations shown, Monument Peak (MCP), Mt Stromlo (SPAD), and Herstmonceux (SPAD) represent the three technology subsets discussed above. There are clear trends in the residuals that are return-level dependent, for the first two stations at a level of about 3 or 4mm. Note, however, that the extrema of all these residuals, at +3 and -3mm for the MCP station for example, are means of relatively few normal points, and the residuals of the vast majority of the data span as little as 3mm. But it is also clear that, as expected, the residuals from the single photon data of Herstmonceux exhibit the smallest spread, of full extent less than 1mm.

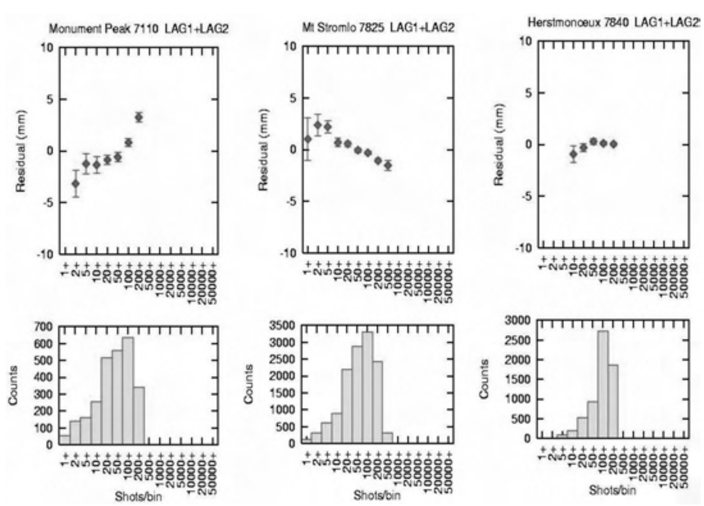

Figure 8-3. Laser range residual means from fitted coordinate and orbital solutions for LAGEOS-1 and LAGEOS-2 summed from the period January 2004 to July 2005 for Monument Peak, Mt. Stromlo, and Herstmonceux.

Taking these effects into consideration, and following from the work of Otsubo and Appleby [2003], we have developed for LAGEOS the CoM values shown in Table 8-1 for most of the ILRS stations.

The information on detector, return level, and processing strategy for each station was taken from the station's log file. This information, in conjunction with the empirical approach adopted in Otsubo and Appleby [2003], led to the span of values quoted in the table for the CoM correction for each station. It is our opinion that the span of values is a pessimistic one, but that little further improvement can be expected given the 'large' size of the LAGEOS satellites. It is also our opinion that the magnitude of the span of values for a given station in the table may be used to constrain a solution for a site-dependent correction to the adopted CoM value during an orbital-TRF adjustment. Investigations continue on how signal strength information may be used to reduce this uncertainty. We also must bear in mind, of course, that there may be other factors for a given station that should be taken into account in any such range bias constraint, such as counter accuracy, calibration target survey accuracy, etc.

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Table 8-1. ILRS stations - System configuration and CoM corrections for LAGEOS

Sta. ID	Name	Pulse length (ps)	Detector	Regime (single, few, multi)	Processing Level	Calib. St. error (mm)	LAGEOS St. error (mm)	LAGEOS CoM (mm)
1873	Simeiz	350	PMT	No Control	2.0 sigma	60	70	248-244
1884	Riga	130	PMT	Controlled s->m	2.0 sigma	10	15	252-248
7080	McDonald	200	MCP	Controlled s->m	3.0 sigma	8.5	13	250-244
7090	Yarragadee	200	MCP	Controlled f->m	3.0 sigma	4.5	10	250-244
7105	Greenbelt	200	MCP	Controlled f->m	3.0 sigma	5	10	250-244
7110	Monument Pk	200	MCP	Controlled f->m	3.0 sigma	5	10	250-244
7124	Tahiti	200	MCP	Controlled f->m	3.0 sigma	6	10	250-244
7237	Changchun	200	CSPAD	Controlled s->m	2.5 sigma	10	15	250-245
7249	Beijing	200	CSPAD	No Control, m	2.5 sigma	8	15	250-248
7355	Urumqi	30	CSPAD	No Control	2.5 sigma	15	30	255-247
7405	Conception	200	CSPAD	Controlled s	2.5 sigma	15	20	246-245
7501	Hartebeesthoek	200	PMT	Controlled f->m	3.0 sigma	5	10	250-244
7806	Metsahovi	50	PMT	?	2.5 sigma	15	17	254-248
7810	Zimmerwald	300	CSPAD	Controlled s->f	2.5 sigma	20	23	250-244
7811	Borowiec	40	PMT	No Control f	2.5 sigma	16	23	256-250
7824	San Fernando	100	CSPAD	No Control s->m	2.5 sigma	30	25	252-246
7825	Stromlo	10	CSPAD	Controlled s->m	2.5 sigma	4	10	257-247
7832	Riyadh	100	CSPAD	Controlled s->m	2.5 sigma	10	15	252-246
7835	Grasse	50	CSPAD	Controlled s->m	2.5 sigma	6	15	255-246
7836	Potsdam	35	PMT	Controlled s->m	2.5 sigma	10	20	256-252
7838	Simosato	100	MCP	Controlled s->m	3.0 sigma	20	40	252-248
7839	Graz	35	CSPAD	No Control m	2.2 sigma	3	9	255-250
7839	Graz kHz	10	CSPAD	No Control s->f	2.2 sigma	3	9	?
7840	Herstmonceux	100	CSPAD	Controlled s	3.0 sigma	8	17	246-244
7841	Potsdam 3	50	PMT	Controlled s->f	2.5 sigma	10	18	254-248
7941	Matera	40	MCP	No Control m	3.0 sigma	1	5	254-248
8834	Wettzell	80	MCP	No Control f->m	2.5 sigma	10	20	252-248

Section 9
Science Report

Section 9

Science Report

Steve Klosko/SGT

The 15th International Laser Ranging Workshop held in Canberra, Australia in October 2006 provided an excellent overview of the status of SLR technologies, campaign activities, and science products. This meeting demonstrated that satellite laser ranging continues to provide an important resource for satellite orbit determination, verification and validation of active remote sensing systems, and for producing science products that are needed to support a wide range of space geodesy and geodynamic investigations. These SLR activities have significantly contributed to the progress that has been made in studying important physical processes related to the state and sustainability of the Earth's environment. SLR has contributed to the understanding of the sources and magnitude of mass flux, in defining a stable mm-level reference frame, and in developing an integrated and interdependent understanding of the Earth's system in four dimensions at increasingly detailed scales. At the same time, the SLR technique has been used to both directly provide precision orbits and calibrate precise orbit positioning provided by other tracking systems. And by being a dynamic as opposed to reduced dynamic technique, SLR investigators have contributed significant insight into the intricate force modeling needed to produce cm-level orbit accuracy.

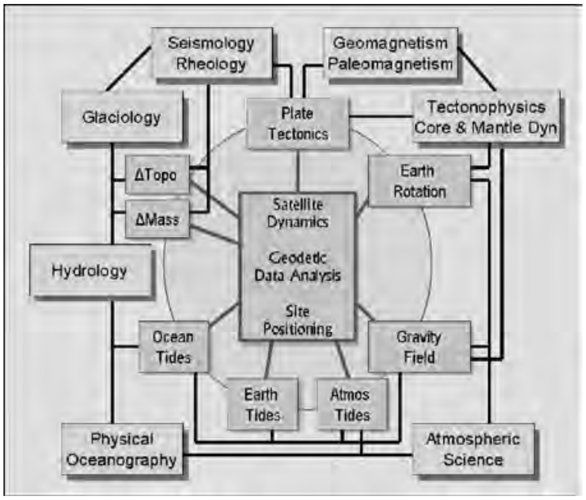

Figure 9-1. SLR data, techniques and products provide a means to measure the manifestation of key geophysical processes.

SLR provides important and in many cases key independent validation capabilities within the CHAMP, GRACE, Envisat, Jason, and ICESat missions. Herein, SLR is complementing the unprecedented set of measurements being acquired by these missions to improve our understanding of the interrelationship within the solid earth, ocean, hydrological, and cryospheric systems. At the same time, dedicated SLR satellite missions like LAGEOS-1 and -2 continue to provide unique long wavelength gravity and decadal time histories of site motions to help establish the geophysical context for many of the phenomena being observed by missions like GRACE. This is especially evident when modeling the Glacial Isostatic Adjustment (GIA) processes dominant over high latitude regions needed to understand contemporary ice sheet mass balance and its contribution to sea level rise. Overall, in each of these missions, and in our attempts to optimally exploit their data, SLR plays an important role.

Current SLR activities are occurring within the "decade of the geopotential" where there is a set of complimentary satellites in orbit, which are and will continue to improved understanding into key geophysical processes, which, in many cases, are manifestations of climate change. SLR is an integral part of several of these mission components, is providing a valuable resource to independently calibrate altimeter systems and orbit accuracies, while also providing the historical context for these more short lived observational records. This was demonstrated by Canberra workshop reports prepared by Urschl et al. [2006], Deleflie et al. [2006], and Govind [2006] in using SLR to understand the dynamics and unreported maneuvers of the GIOVE-A satellite.

The above Figure 9-1 gives an overview of the role SLR is playing within multidisciplinary and interdependent investigations ongoing in the Earth Sciences. In the center green box shows the basic analyses that are undertaken using SLR data. These analyses yield significant products (connected to this center box with red lines), which have multiple uses. These products provide important evidence and constraints used in a wide range of science applications and disciplines through direct observation of the temporal behavior of geodynamical processes. Many of these products are uniquely provided over many decades from SLR whereas other complementary technologies have much shorter time histories. These SLR products and their interpretation are being applied to some of the key questions confronting the Earth Sciences with regard to the sustainability of our environmental system.

Reference Frame

Space geodesy is now required to resolve geodynamical signals at mm to sub-mm levels of accuracy. To accomplish this goal, an International Terrestrial Reference Frame and the motion of the Earth within both the Inertial and Celestial System are required with high temporal resolution and with comparable accuracy. The implementation of the terrestrial reference frame (including its origin and scale) is now being derived by combining results from station coordinate solutions independently being solved using four space geodetic technologies – SLR, VLBI, GPS and DORIS.

The most recent combination of these technologies (see *http://itrf.ensg.ign.fr/ITRF_solutions/2005/ITRF2005.php*) has yielded some controversial results. As shown in the Figure 9-2 obtained from a Workshop presentation by Zuheir Altamimi (IGN, France) [2006], there, a progressively larger scale difference between SLR (ILRS) and VLBI (IVS) is observed for the period of 2002 onward. This is a surprising and yet to be explained result given the ability of both technologies to measure absolute scale. Without the overlap of such a robust set of results from independent systems, we would lack the wherewithal to identify and resolve these subtle yet important discrepancies.

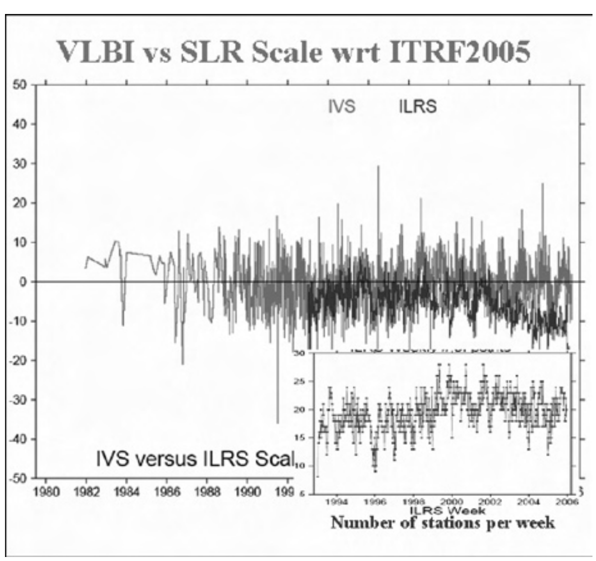

Figure 9-2. Comparison of SLR and VLBI station heights reveal an apparent scale difference and trend since 2001.

Long-Wavelength Gravity Field

One of the most interesting developments in the last 15 years has been our ability to measure the Earth's gravity field to sufficient accuracy and temporal resolution to observe subtle changes in its longest wavelength features. The SLR analyses have observed temporal variations in the gravity field, which was the forerunner of the very successful GRACE mission. SLR remains a key component in validating the changes in the long wavelength gravity field observed from GRACE [Tapley et al., 2005].

From these observations of mass redistribution on and within the Earth significant improvements have been achieved in our understanding of Earth's upper mantle viscosity, the tidal response at different frequencies, and the tidal braking in the Earth/Moon system. The later of which, given its change in lunar mean motion, is exquisitely confirmed directly through the use of Lunar Laser Ranging.

Figure 9-3, from Frank Lemoine's (NASA GSFC) Canberra workshop presentation [Lemoine, 2006], shows the time history of the change in the Earth's C(2,0) term obtained from SLR going back to the middle 1970s. There is an unmistakable long period trend arising from post glacial rebound as the Earth returns to isostatic equilibrium after the last Ice Age. The interannual excursions, which are seen around this long period linear trend, are of great interest and reflect mass motion, predominately occurring within the world's oceans.

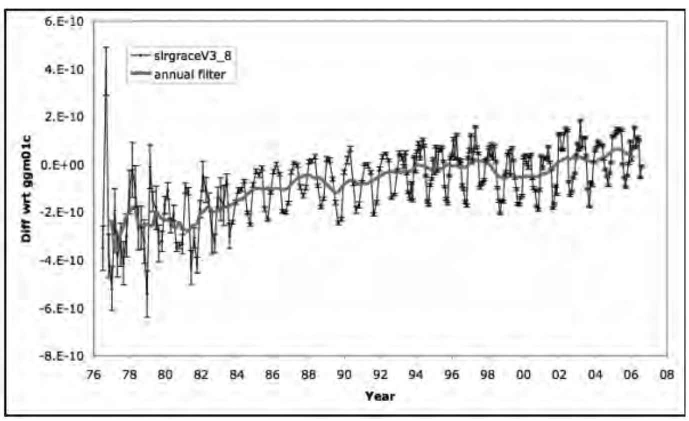

Figure 9-3. Changes in the C(2,0) harmonic over the past three decades obtained from SLR tracking of primarily the LAGEOS satellites.

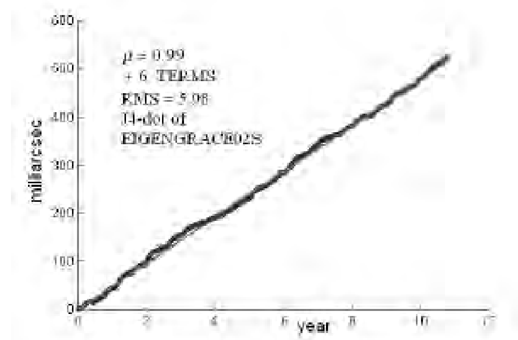

Figure 9-4. Unmodeled LAGEOS node drift compared to expected Lens Thirring effect.

As knowledge of the long wavelength gravity field has improved, especially with advances coming from the GRACE Mission, further improvements have been made in deriving a constraint on the Lense-Thirring effect. Ignazio Ciufolini of the University of Lecce in Italy and Erricos Pavlis of the University of Maryland gave a paper on their improved estimate of the Lense-Thirring term. These authors have measured the value of this term to approximately 1% of its expected value from General Relativity. With improved gravity modeling, errors in the remaining even zonal harmonics have been significantly reduced [Ciufolini and Pavlis, 2004].

The experiment reported by Ciufolini and Pavlis was based on the long term behavior of the argument of the ascending node of the LAGEOS-1 and -2 satellites as shown in Figure 9-4, where the Lense-Thirring predicted effect is compared to the unmodeled node signal for LAGEOS-1. By evaluating more than eleven years of these data, these authors were able to isolate the "frame-dragging" arising from the Earth's rotation apart from errors coming from our models of the Earth's gravity field [Pavlis et al., 2006].

Astrodynamics

While GPS analyses benefit from continuous 3-D tracking, which allows "reduced" dynamic orbital techniques, SLR satellites are only observed and directly tracked for a small percentage of the time. Thereby precision orbit determination for SLR requires a high level of sophisticated conservative and non-conservative force modeling. The LAGEOS-1 and -2 satellites, given their specific design and the stable orbits they were placed in, have provided an excellent laboratory to study very subtle thermal and drag-like effects acting on these orbits. The thermal perturbations evolve over time as the satellite spin rate slows and the satellite experiences larger levels of thermal imbalance.

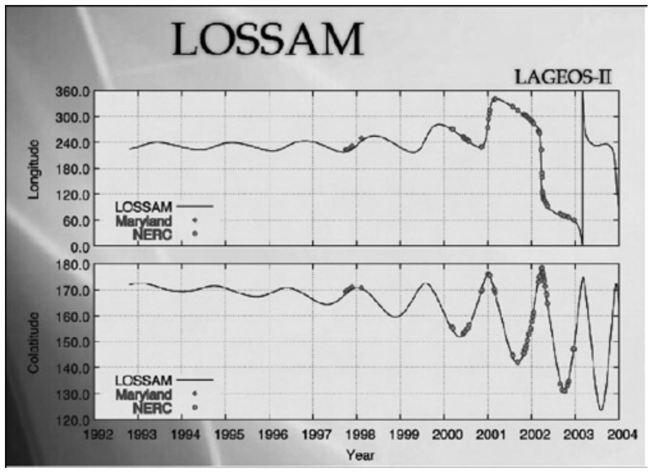

Figure 9-5. LAGEOS-2 spin orientation predicted and observed.

A Canberra workshop presentation by Andres and Noomen showed results they obtained at the Delft Technical University of the detailed modeling they have undertaken for the pair of LAGEOS satellites. Shown in Figure 9-5 is a comparison of the LAGEOS-2 spin orientation they modeled compared to that observed. In the analysis they account for the complete regime of the spin behavior of the LAGEOS satellites as well as a complete description of the satellites' material composition. This has allowed them to greatly improve the orbit accuracy and fit to the SLR data while reducing the need for empirical correction parameters. Shown are results they have obtained replicating, based on the observed orbit motion, the spin axis orientation of LAGEOS-2 compared to that observed by the University of Maryland [Andres et al., 2006].

Satellite Laser Altimetry

Satellite Laser Altimetry is a rapidly advancing form of remote sensing which has yielded extremely interesting results in both Earth and planetary sciences applications. There is a high interest in the SLR community of these developments.

For interplanetary applications, great strides are being made in our understanding of aspects of planetary geophysics with the successful laser altimeter experiments on Mars Global Surveyor and Near Earth Asteroid Rendezvous missions. Figure 9-6 shows a map of Mar's topography produced by using over 670 million altimeter returns obtained by the MOLA instrument [Smith et al., 1999]. Mercury MESSENGER, Dawn, Lunar Reconnaissance Orbiter, and anticipated missions to the icy moons of Jupiter are all expected or are already flying laser altimeter systems.

As a precursor to interplanetary laser communication applications, during the past year GSFC demonstrated a one-way laser transmission from Earth to the Mars Global Surveyor satellite orbiting Mars. This range experiment was over a distance of over 80 million kilometers. This exceeded last year's successful experiment which involved Earth to the MESSENGER satellite transmission and increased the range distance by over a factor of three [Smith et al., 2006].

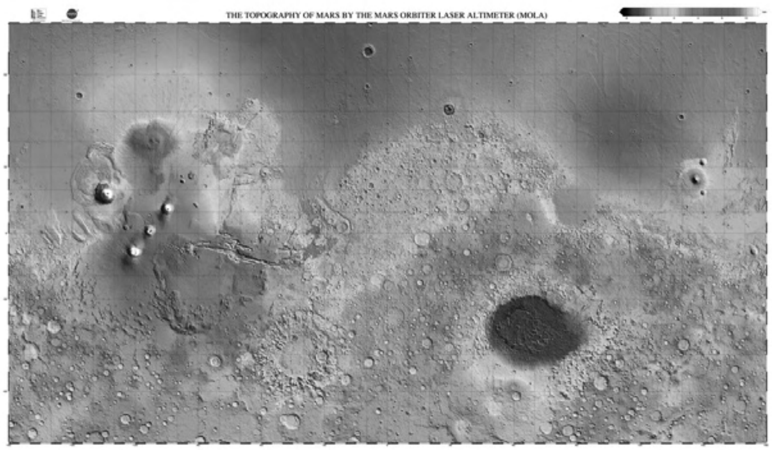

Figure 9-6. The topography of Mars from the analysis of MOLA surface height measurements

Laser altimetry has also matured from near-Earth platforms. For example, ICESat has already delivered over 1.2 billion ranges and has produced the first ever-direct mapping of the thickness of the Arctic ice canopy. These results have been complementary to the tradition measures of ice extent and have made significant contributions to our understanding of the degradation in this canopy seen over the past three years. Figure 9-7 presents the ICESat measured ice thickness measured during each of its campaigns [Kwok et al., 2006].

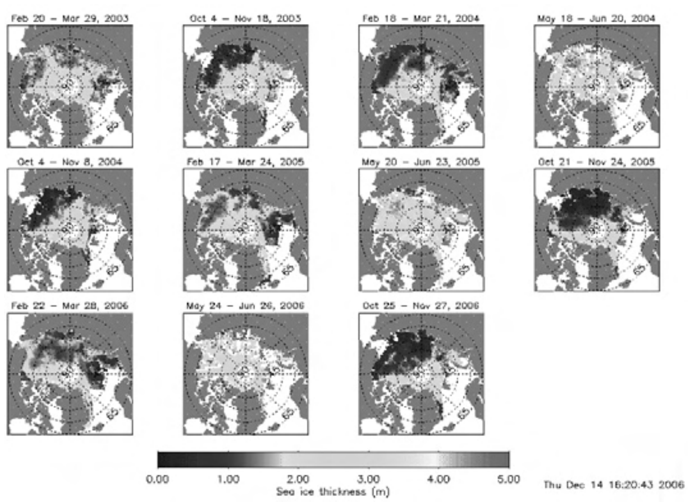

Figure 9-7. ICESat laser altimeter measurements have provided the first ever measure of ice sheet thinning over the Arctic canopy.

Summary

As for the future, the ongoing trend towards higher accuracy, larger data volumes and the need to support more missions is expected to continue. The SLR community needs to continue striving for an absolute single shot accuracy of one millimeter, a more automated and robust international network, and increased collaboration and contribution to many ongoing and future missions. The unprecedented richness of coincident observations, including those from coming from an international SLR network, offers a major challenge to improve our understanding of the integrated Earth and planetary systems awaiting further exploration.

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SECTION 10
MEETINGS

SECTION 10

MEETINGS

Carey Noll/GSFC

In October 2005, the National Environment Research Council (NERC) Space Geodesy Facility, the British National Space Center (BNSC), and the ILRS sponsored the fall 2005 ILRS Workshop, “Observations toward mm Accuracy” in Eastbourne, UK. Information about this workshop can be found at *http://nercslr.nmt.ac.uk/workshop2005/workshop2005.html*. Electro Optic Systems Pty Limited (EOS), Geoscience Australia, the ACT Government, and the ILRS sponsored the 15th International Workshop on Laser Ranging in Canberra, Australia during the week of October 15-20, 2006. The Web site *http://www.ilrscanberraworkshop2006.com.au* provides information about the workshop; proceedings and session summaries can also be found on the Web at *http://cddis.gsfc.nasa.gov/lw15/*.

The ILRS organizes semi-annual meetings of the Governing Board and annual General Assemblies. General Assembly Meetings are open to all ILRS associates and correspondents. The 11th ILRS General Assembly was held in October 2005 in Eastbourne, UK in conjunction with the fall 2005 ILRS Workshop. The 12th ILRS General Assembly was held in October 2006 in Canberra, Australia in conjunction with the 15th International Workshop on Laser Ranging. Detailed reports from past meetings can be found at the ILRS Web site.

ILRS 2005 Workshop “Observations Toward mm Accuracy”, Eastbourne UK

Matthew Wilkinson/NSGF Herstmonceux

Figure 10-1. Attendees of the 2005 ILRS Workshop in Eastbourne, UK.

The NERC Space Geodesy Facility hosted the 2005 ILRS Technical Workshop in October at the T&G Centre in the seaside town of Eastbourne in the UK. An ambitious program covering all aspects of Satellite Laser Ranging was tabled to offer every opportunity for constructive discussion.

Away from the Conference Centre, delegates were treated to an evening tour of the NSGF and a reception in the Science Centre, which is also located in the grounds of Herstmonceux Castle. The Workshop opened with a short welcoming ceremony and included addresses from the Mayor of Eastbourne Cllr Graham Marsden, from Dr. Mike Pearlman, the Director of the ILRS Central Bureau and from Dr. Werner Gurtner, Chair of the ILRS Governing Board.

The workshop Web site contains presentations and session summaries in full at *http://nercslr.nmt.ac.uk/workshop2005/proceedings/proceedings.html*.

The Analysis Working Group met preceding the opening of the Workshop. Early results from the IERS combination work towards ITRF2005 were presented and it was agreed that analysis be done with a consistent strategy. Much discussion was had on range bias and it was decided that the core stations Graz, Greenbelt, Hartebeesthoek, Herstmonceux, McDonald, Monument Peak, Mt Stromlo, Riyadh, Wettzell, Yarragadee and Zimmerwald should have no bias values estimated.

The Analysis session included the network and tracking statistics, as well as a summary of the ongoing, weekly, AWG "pos+eop" project. Discussed was how feedback from the regular analyses that identified, for example, a problem with a station's data, should be communicated to the station and to other interested components in the community. It was clear also that the analysis community in particular should be much more aggressive in voicing its opinion on the current reduction in global tracking caused by closure of important stations and by reduced shift patterns. An analysis of the error budget of SLR observations highlighted that the most important systematic errors continue to be refraction and satellite/station signature. The session concluded with a brief presentation of a CODE analysis of a manoeuvre of GPS-35, which was observed by station Herstmonceux.

A Site Stability session focused on the need for accurate station ground surveys for both accurate ranging (target distances and eccentricities) and inter-technique vectors (reference systems). There are missing or poor standard ties at some of the collocated sites and also sites that have not been resurveyed after significant earthquakes. Examples of the current survey status were presented on Mt Stromlo, Hartebeesthoek, Matera, Wettzell, Riga, Herstmonceux and some of the NASA stations.

The System Operations sessions began with a summary of the ILRS Network and the performance of some of its individual stations. Methods were discussed to advance SLR capabilities and improve data yield from high-orbiting satellites by, for example, detecting backscatter from the laser beam in daylight and improving mount models by daytime star calibration.

The Timer Linearity session demonstrated that some of the interval counters used by SLR stations must in time be replaced with epoch timers if we truly wish to have 1mm systems. Stations presented experiments using movable targets that investigated the uncertainties in calibration values and recent technological developments were discussed.

A QC session found errors in the resubmission of passes, 'spikes' in post-fit residuals, constant trends in station residuals due to range bias or time bias and the use of the wrong information. A summary of the responses to the Quality Control questionnaire was opened to discussion from the floor to include other stations. It was found that there is a variety of different techniques that stations use to monitor and control their transmit and receive energy levels and not all stations reduce their data in the same way.

The Satellite Signature session considered the signatures of future satellite missions such as, LARES, Hollow reflectors and a Russian "zero signature" satellite. For any satellites a CoM correction value is dependent on the return intensity as demonstrated by High -Low tests performed at Yarragadee and Zimmerwald. These tests were recommended to all stations to quantify the energy effect. CoM corrections for most of the current satellites have been made available at the ILRS Web site.

A Restricted Tracking session heard from stations that had successfully upgraded their systems to track satellites that must not be tracked for the full pass. The Control Files session included the Engineering Data File and a summary of the control files routinely shared between stations, the ILRS and its customers to improve overall performance.

The kHz Ranging session reported the experiences of the Graz station and the many improvements in its operation as a result of working at kHz rates. SLR2000 development is progressing and has achieved LEO tracking. Herstmonceux has installed a High-Q Laser and is in the process of installing an event timer towards its kHz ranging goal.

The New Prediction session described implementation of the Consolidated Prediction Format at prediction centres and, as a test, at two of the stations. The benefits of the CPF for improved acquisition were emphasized. The Network Collaboration session stressed the cooperative nature of the ILRS and gave the advent of dynamic priorities, unification of IRVS, time bias functions and the Eurolas realtime-tracking display as examples of this.

The final sessions covered the future applications of SLR, including Transponder missions and Time Transfer by T2L2 on Jason-2, and the additional applications of SLR systems, including photometry and Astrometry.

The Workshop closed with the 2005 ILRS General Assembly, which featured session summaries and reports on progress from the Working Group coordinators.

15th International Workshop on Laser Ranging, Canberra Australia

Michael Pearlman/CfA, Steve Klosko/SGT, Inc., John Luck/EOS Space Systems Pty. Ltd.

Figure 10-2. Attendees of the 15th International Workshop on Laser Ranging, Canberra Australia, October 2006.

Electro Optic Systems Pty. Ltd., Geoscience Australia, the Australian Capital Territory Government, and the ILRS sponsored the 15th International Workshop on Laser Ranging in Canberra, Australia during the week of October 16–20, 2006. The workshop provided an overview of the state of SLR technologies, campaign activities, and science products. Over 110 people from 19 countries participated in the workshop, which included oral and poster presentations on scientific achievements, applications and future requirements, system hardware and software, operations, advanced systems, and analysis.

After the Opening Ceremony, which featured an Aboriginal father-and-son duo welcoming delegates and distinguished guests on didgeridoos, sessions were organized around the following topics:

- Science Achievements, Applications, and Products
- Network Performance and Results
- Lasers and Detectors Session Summary
- Laser Altimetry
- Kilohertz Systems
- Timing Systems
- Multiple Wavelength and Refraction
- Telescopes, Stations, and Upgrades
- Advanced Concepts
- Eyesafe Systems
- Laser Transponders
- Uncooperative Targets
- Software and Automation
- Lunar Laser Ranging
- Targets and Return Signal Strength

Presentations in the Science Products Sessions demonstrated that satellite laser ranging continues to be an important resource for satellite orbit determination, verification and validation of active remote sensing systems, and for producing science products that are needed to support a wide range of space geodesy and geodynamic investigations.

A theme of the meeting was the continued contribution of SLR to the progress being made in studying the Earth's system in four dimensions. SLR techniques are also being used to provide precision orbits and to calibrate precise orbit positioning provided by other tracking systems. By being a dynamic as opposed to reduced dynamic technique, SLR contributes significant insight into the intricate force modeling, including state of the art modeling of thermal imbalance and radiative forces, needed to produce cm-level orbit accuracy on the LAGEOS 1 and 2 satellites.

Dedicated SLR satellite missions continue to provide unique long wavelength gravity and decadal time histories of site motions to help establish the geophysical context for many phenomena, to help provide a robust reference frame to report these changes within, and to place constraints on the geophysical models themselves. SLR on well tracked satellites provides a means to monitor and better understand long wavelength changes in the Earth's gravity field, which gives insight into mass flux within the Earth's system over large spatial scales. The return of the Earth to isostatic equilibrium since the time of the most recent Ice Age is a major source of nearly secular long wavelength gravity field changes. To understand the glacial mass flux apart from the total mass flux dominant over high latitude regions, detailed understanding of the Glacial Isostatic Adjustment (GIA) processes are needed. To understand contemporary ice sheet mass balance and its contribution to sea level rise, both the high latitude gravity changes and their decoupling from GIA processes are needed.

As knowledge of the long wavelength gravity field has improved, especially with advances coming from the GRACE Mission, further improvements have been made in deriving a constraint on the Lens Thirring effect by evaluating time histories of Lageos data. There was also considerable discussion on the fundamental role of SLR in the formulation of the International Terrestrial Reference Frame (ITRF) and activities underway to compare different formulations and procedures.

Some of the other key technique-related items of interest included:

- New event timing systems including the new PICO event timer and control system from TU in Prague;
- Impressive performance (including spin and atmospheric measurements) of the 2KHz laser at Graz;
- The operation of the new San Juan SLR;
- The SLR progress at Arequipa and Maui;
- Transponder developments for interplanetary ranging;
- Laser altimetry technology and its future application in satellites;
- Automated operations at Stromlo and Zimmerwald;
- Web application for data engineering files;
- The new climatic facility at INFN for retroreflector array testing;
- Very impressive lunar ranging results from the Apollo station; and
- Systematic time biases in the SR620 counters

Abstracts, most PowerPoint presentations and other information on the workshop can be found at *http://www.ilrscanberraworkshop2006.com.au/*. Proceedings from the workshop will be available in mid-2007 on CD with selections in hardcopy, and on the web at the above address and at *http://ilrs.gsfc.nasa.gov/*.

Workshop participants also had the opportunity to visit the SLR station at Mt. Stromlo, which has had an extremely impressive recovery after the devastating forest fire in 2003.

The 16th International Workshop on Laser Ranging will be held in Poznan, Poland in the fall of 2008. A specialized SLR workshop similar to those held in Eastbourne and Koetzting will be held in Grasse, France on 24-28 September 2007.

SECTION 11
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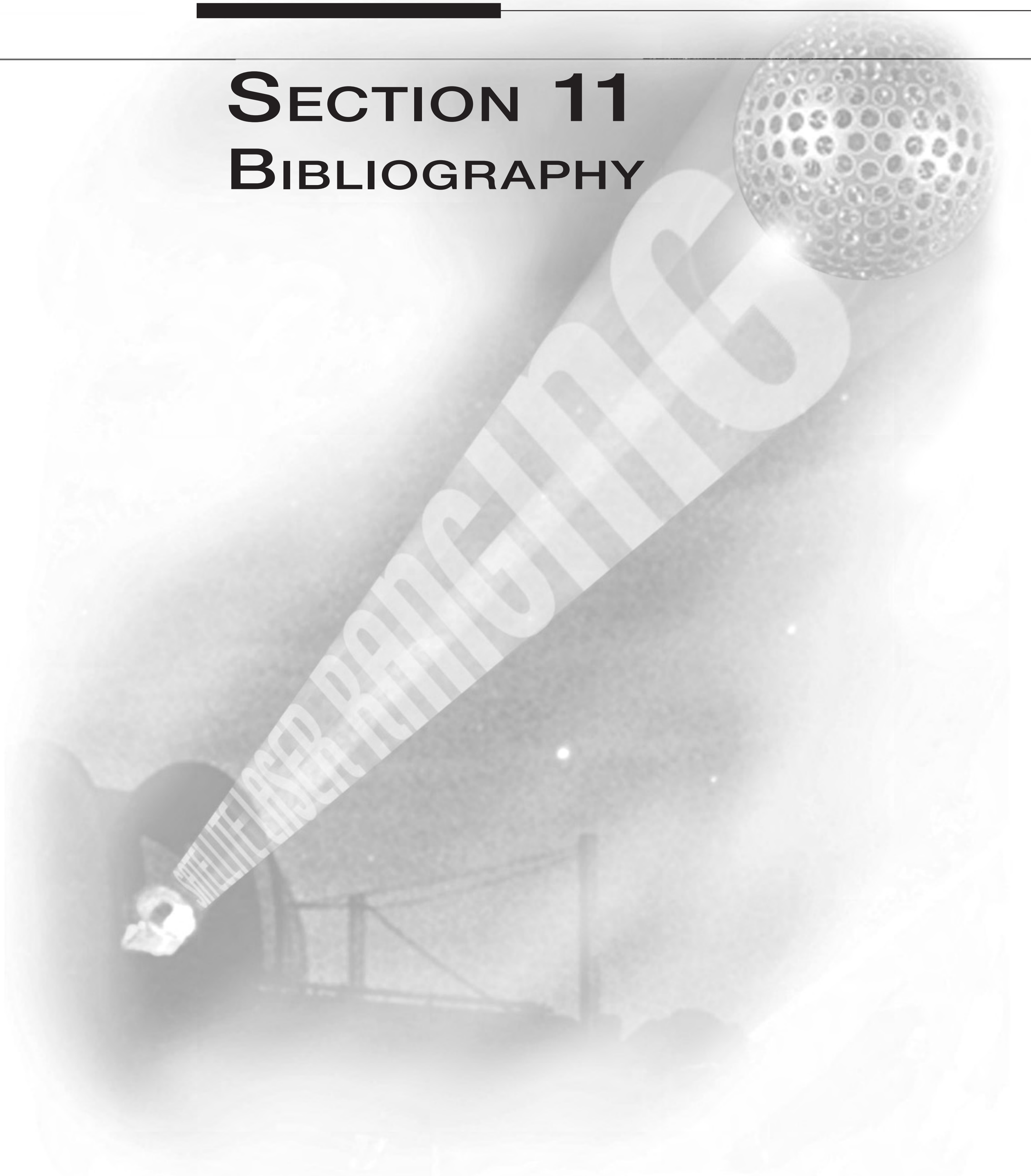

Section 11

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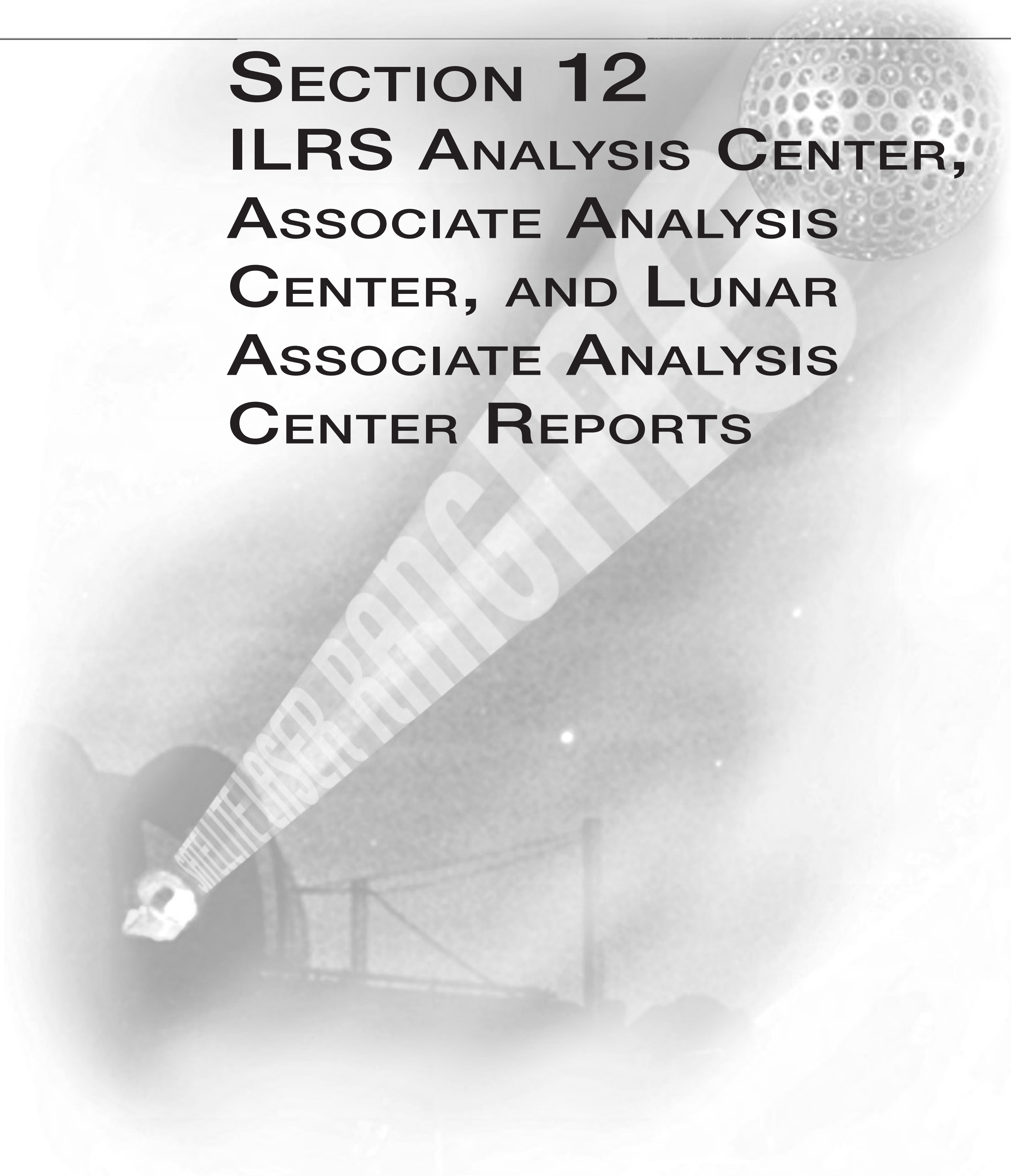
Section 12
ILRS Analysis Center, Associate Analysis Center, and Lunar Associate Analysis Center Reports



Section 12

Analysis Center Reports

Six centers have been qualified as ILRS Analysis Centers. These centers are required to provide weekly submissions of Earth orientation parameters and station coordinates that are included in the production of the official ILRS combination product. The Analysis Centers are appointed based on their demonstrated performance in both the rigor of their analyses and the punctuality with which their weekly solutions have been submitted to the ILRS Combination Centers.

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

Giuseppe Bianco/ASI and Vincenza Luceri, Cecilia Sciarretta/Telespazio S.p.A.

Introduction

The SLR data analysis activities at the ASI Space Geodesy Center "G. Colombo" (CGS) started almost two decades ago and, since then, have been focused primarily on global, extended solutions in support of reference frame maintenance. Due to the multi-technique nature of the CGS mission, geodetic technique combination methods and applications are a top priority objective of the data analysis activities performed at the center: in the years 2005-2006 the usual classic geodetic products (i.e., global SLR network coordinate/velocities, EOP time series, etc.) provided by the CGS, have been complemented with studies and products related to the solution combination, conforming to the ILRS and IERS directions. Information on the CGS and some of the analysis results are available at the CGS Web server GeoDAF (Geodetical Data Archive Facility, *http://geodaf.mt.asi.it*).

Main Activities in 2005 and 2006

In the years 2005 and 2006, the ASI/CGS was heavily involved in the ILRS activities in support of the reference frame maintenance. The ILRS Governing Board recognized the center's continuous and rigorous contribution and appointed ASI/CGS as one of the official ILRS Analysis Centers (ACs).

In June 2004 the center was selected by the ILRS as its primary Official Combination Center (CC) for station coordinates and Earth Orientation Parameters. The provided products are the weekly operational combined ILRS solutions: a loosely constrained SSC/EOP product and a constrained EOP product that is the ILRS EOP operational series for IERS. Moreover, ASI/CGS has produced the official ILRS contribution to ITRF2005, by combining the weekly solutions, from 1993 to 2005, submitted by the contributing ILRS Analysis Centers.

The activities in the main application fields are:

- International Terrestrial Reference System (ITRS) maintenance: the production of IERS oriented products (global SSC/SSV and EOP time series) is regularly performed, both as an annual call response and as a contribution to the operational EOP series (Bulletin B and EOP C 04 update) to assure the CGS contribution to the reference frames establishment.
- ILRS AWG "Pos+EOP Pilot Project": regular submission of coordinate/EOP solutions (following the pilot project requirements) and of combined solutions. In 2004, ASI/CGS was selected by the ILRS as the primary official combination center for two years;

- ILRS AWG "Benchmarking" Pilot Project: participation in the project for comparison of the different analysis software packages;
- IERS CPP Pilot Project: participation in the project through a consortium (ASI, PoliMi, INGV) with the aim to design, implement and maintain the procedures for the rigorous combination of a geodetic solution;
- Geodetic solution combination: realization, implementation, and testing of combination algorithms for the optimal merging of global inter- and intra-technique solutions and of regional (e.g., Mediterranean) solutions to densify tectonic information in crucial areas;
- Gravity field investigations: the long, extended global solutions produced are used to derive low degree geopotential parameter estimations, inferring information about geocenter motion and low degree zonal drift.

Main Data Products Provided

- ASI05L01 global solution, from LAGEOS-1 and -2 data (1985-2005); EOP submitted to the IERS as long term series. Global network SSC/SSV, daily EOP (x, y, LOD), geocenter (C10, S11, C11) are the main parameters estimated in this solution.
- 13-year series (1993-2005) of weekly solutions (SSC, EOP) from LAGEOS and Etalon data, submitted as input to the ILRS product for ITRF2005;
- 13-year series (1993-2005) of weekly combined solutions (SSC, EOP) obtained combining the individual AC solutions, as input to ITRF2005;
- 1-day estimated EOP, from LAGEOS and Etalon data, routinely provided to IERS for the upgrade of monthly Bulletin B and EOP C 04;
- Multi-satellite, long-extended (1986-2006) global solution from LAGEOS-1, -2, Stella, and Starlette data dedicated to the gravity field low degree zonals estimation (J2, J4, J6 and Jodd);
- Regular weekly submission of SSC and EOP solutions, estimated using LAGEOS and Etalon data, for the ILRS AWG Pos+EOP Pilot Project
- Regular weekly submission of SSC and EOP combined solutions, combined from the contributing solutions of the ILRS ACs, for the ILRS AWG Pos+EOP Pilot Project;
- ASI-Med two year solutions, with the estimation of tectonic movements and strain-rates in the Mediterranean area combining SLR, GPS, and VLBI results obtained at CGS

Future Plans

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

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The BKG SLR Analysis Center (AC) contributes regularly to the weekly ILRS solutions. The BKG AC started using the UTOPIA analysis software in January 2005. The a priori station coordinates/velocities are still taken from the ITRF2000, augmented by SLR stations contributing the observations after the release if the ITRF2000 (e.g., station 7405 Conception, Chile). In the weekly UTOPIA analysis, the precision of the weekly solutions is sensitive to the history of the stations. Well performing stations already included in the ITRF2000 (see benchmark set at epoch 1999) and well AC-improved augmented stations lead to sufficient weekly solutions, whereas augmented stations having no core status or/and "weak" a priori coordinates/velocities degraded the precision. These results point out the need for a new SLR-ITRF200# as input for a priori station coordinates/velocities for the weekly ILRS solutions is manifest.

A change of the AC hardware during this period, including the operating system, required repeated adaptations and revisions to the programs and scripts used in the SLR analysis. The UTOPIA software has been updated to match the ILRS directives: tropospheric models and laser observation corrections (center of mass, Stanford counter).

The unique description of a station position requires its epoch of occupation so that the designation of its DOMES number is not sufficient. Therefore, a Perl script was developed that extracts all necessary information describing stations of interest from the ITRF200# SINEX file and compiles this information into one record per station. This table can be extended by additional station information and is used as input for any analysis software. The UTOPIA software used at BKG Frankfurt for the SLR processing has to be upgraded. Investigations in preparation for this work have been completed.

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Deutsches Geodätisches Forschungsinstitute (DGFI)

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Introduction

Since the start of Analysis Working Group (AWG) activities, DGFI has participated in the ILRS pilot projects. In April 2004, DGFI was selected by the AWG as one of the five official ILRS Analysis Centers and since June 2004, DGFI has served as the official backup ILRS Combination Center. In addition to these tasks, DGFI has participated in a number of SLR projects, mainly the processing and evaluation of the SLR part of the ITRF2005 reference frame and the GGOS-D (German part of GGOS) project.

ILRS Analysis Center

As an ILRS analysis center, DGFI processes, on a weekly, operational basis, LAGEOS-1/2 and Etalon-1/2 SLR data and provides loose constrained solutions (SINEX files) with station positions and Earth orientation parameters (x-pole, y-pole and length of day) to the data centers at CDDIS and EDC. This processing is accomplished with the DGFI software package DOGS version 4.07.

During the automatic processing, a number of quality checks are performed, such as the computation of pass-wise range and significant time biases. The weekly solutions and the results of the bias analysis sorted by satellite and week are available from the DGFI Web server, *http://ilrsac.dgfi.badw.de/quality/index.html*. We provide the biases with respect to ITRF2000 coordinates for all stations and passes, but presently for the LAGEOS satellites only.

Furthermore, the two frequency laser systems at Zimmerwald and Concepción were analyzed to see if the use of two frequencies produces better results and to assess the quality of the new Mendes-Pavlis tropospheric refraction model (see Canberra workshop proceedings).

At the ILRS AWG workshop in Canberra, October 2006, DGFI agreed to maintain a list with station discontinuities and data handling, which will be distributed to all analysts through the ILRS data centers at CDDIS and EDC. Additionally, DGFI will develop a procedure for station qualification (ILRS level, AWG use) and a position model for new stations. Another task will be the exchange and comparison of orbits in SP3 format with JCET.

ILRS Combination Center

DGFI, as the official ILRS Backup Combination Center, uses the same procedures and constraints as the ILRS Primary Combination Center, which is the responsibility of ASI, Italy. Both centers are obliged to compute, on a weekly basis, a combined SLR solution as the official product of the ILRS. The products are available through the ILRS data centers. Both combination centers use software enabling automated processing.

The official weekly products are:

- Combined solution for station coordinates and EOP. DGFI delivers a SINEX file with a minimal constraints solution and with an unconstrained normal equation system.
- Combined solution for EOP aligned to ITRF2000. DGFI takes the EOP part of the above combined solution arguing that the minimal constraints solution is indirectly an alignment to ITRF2000, because the a priori coordinate values are taken from ITRF2000.

A detailed description of the activities of both combination centers can be found on the ILRS Analysis working group Web page, *http://ilrs.gsfc.nasa.gov/working_groups/awg/index.html*.

Contribution to ITRF2005

From 1993 to 2005, DGFI has contributed to the ITRF2005 with a series of weekly SLR solutions, polar motion and station coordinates, as part of the combined ILRS series. The backup combination series ILRSB was used for quality control of the primary ILRSA combined series that was delivered to the IERS. In the validation procedure of the ITRF2005 products the analysis center concentrated on the comparison of actual SLR series with the three solutions, including the rescaled SLR-only solution from IGN (see Figure 12-1) and a possible reason for the scale problem in the IGN solution (see Canberra proceedings).

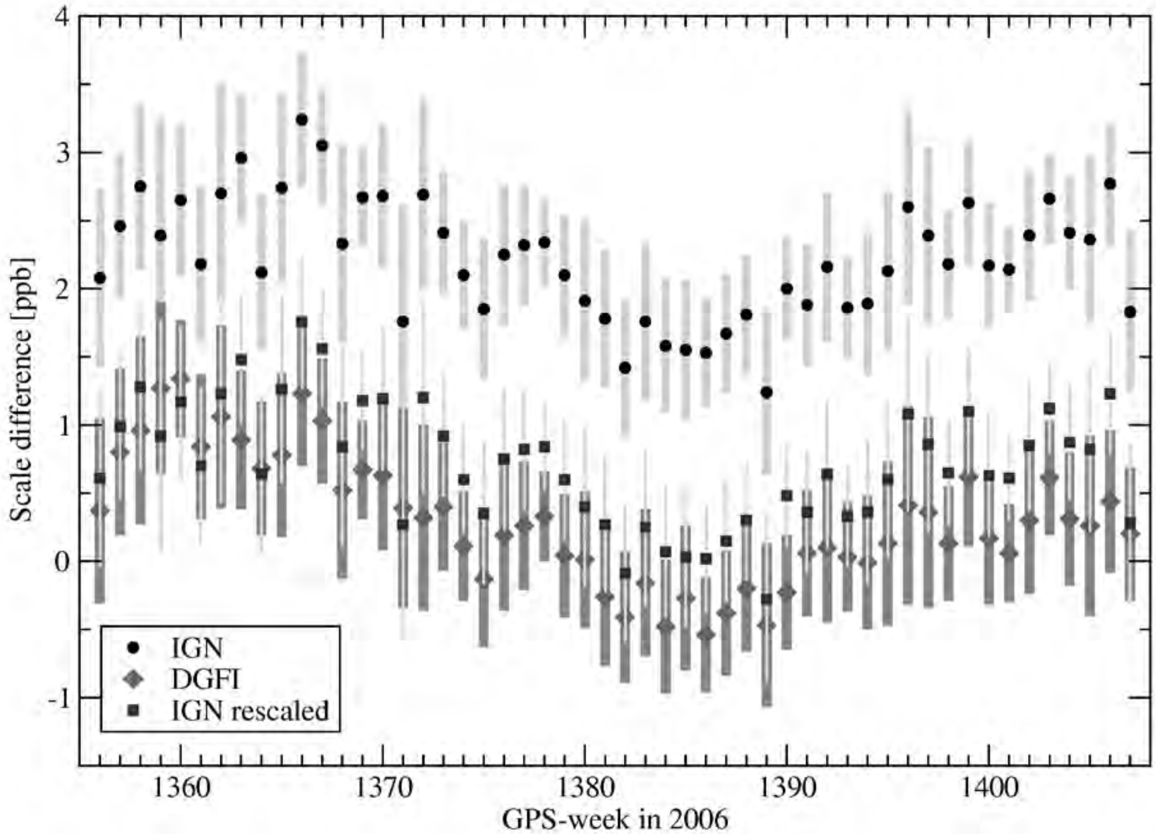

Figure 12-1. Scale differences between the official ILRS weekly solution (ILRSA) and the three ITRF2005 solutions (IGN Paris, and DGFI Munich and the rescaled IGN solution).

Contribution to GGOS-D

The GGOS-D project was initiated by the German institutions BKG, DGFI, GFZ, and GIUB with the overall objective to investigate the technological, methodological and information-technological realization of a global geodetic-geophysical observing system. Fields of research include the generation of consistent and integrated geodetic time series for the description and modelling of the geophysical processes in the Earth system. More information on the project is available from the GGOS-D homepage *http://www.ggos-d.de*. DGFI contributes with SLR and VLBI time series and the combination of weekly products.

Future plans

During 2007-2008 it is expected that DGFI will compute a new ITRF with an SLR series back to 1983 or eventually 1976. DGFI will reprocess all data with the new adopted models and corrections (possibly back to the LAGEOS-1 launch) for this purpose and also for the GGOS-D project. The bias report will be revised by using more satellites and generating reports on a daily basis.

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Activities in Support of ILRS

Production of orbit predictions for ERS-2, CHAMP, GRACE-A and –B

The interval (about two weeks) for ERS-2 prediction generation has been maintained with the exception of maneuver predictions. The orbit predictions were updated daily with time bias functions. The prediction accuracy after one day remained at 6ms RMS in time bias. GFZ stopped producing SLR orbit predictions for ERS-2 at the end of 2005 and asked ESA/ESOC to take over. The orbit prediction service for the PRARE system continued though 2006.

For CHAMP, the orbit predictions were updated three times per day, and for GRACE twice per day. The accuracy of the predictions is continuously monitored in order to enhance the update frequency if necessary. For the year 2006, the prediction quality for CHAMP and GRACE-A/-B is shown in Table 12-1 where percentages of time with biases less than 10ms are given. Thus, the prediction update interval used should have allowed for safe tracking.

Table 12-1. Orbit Prediction Quality for CHAMP and GRACE

Satellite	Rates of Time Biases < 10 ms	
	After 9 h	After 12 h
CHAMP	77 %	57 %
GRACE-A	99 %	96 %
GRACE-B	98 %	96 %

GFZ has used the new CPF orbit prediction format since February 1, 2006; delivery of predictions in IRV format is still maintained at the request of the ILRS CB.

Table 12-2. Generated Orbit Prediction Products (01/10/2004 - 31/12/2006)

Product	ERS-2	CHAMP	GRACE-A	GRACE-B
Tuned IRVs	68	2383	1557	1556
Time Bias Functions	406	-	-	-
Drag Functions	-	2383	1557	1556
Two-Line Elements	68	2381	1557	1556
SAO Elements	68	2381	1557	1556
CPF	-	963	640	641
Total	610	10491	6868	6865
Scheduled Predictions	n.a.	10851	7234	7234
Operations Success [%]	n.a.	96.7	94.9	94.9

Production of position and EOP parameters from LAGEOS-1 and -2 analyses

GFZ continued its ILRS Analysis Working Group (AWG) activities concerning the pos+eop project. Weekly station position estimates and daily Earth orientation parameters from LAGEOS analyses are submitted each week in SINEX files. The weakly constrained coordinate solutions show a 3-D WRMS deviation from ITRF2000 of 10mm for the core stations over the reporting period (see Figure 12-2). The weakly constrained polar motion x- and y-estimates agree with the IERS Bulletin A to 0.3mas and to the excess lengths of day estimates to 0.1ms.

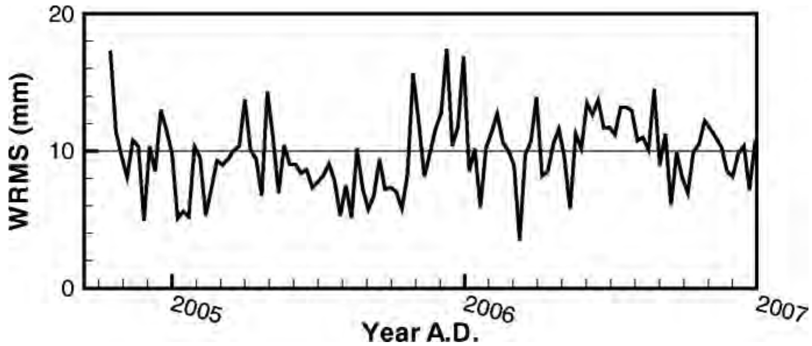

Figure 12-2. Coordinate solutions 3-D disclosures versus ITRF2000

In support of the ITRF2005 development, historical data back to 1993 have been processed and supplied to the ILRS combination centers.

Further Activities Involving SLR Data

- Systematic generation of the ERS-2 preliminary and precise orbits based on SLR and PRARE data under ESA contract
- Reprocessing of altimeter satellite missions
- Monitoring of CHAMP and GRACE operational POD
- Generation of CHAMP, GRACE, and satellite-only gravity field models and combined gravity field models from satellite and surface gravity data
- Combination of GPS, low Earth orbiter (LEO), and SLR observations for reference frame and long wavelength gravity field resolution (integrated approach)

Future Plans

- Process and analyse LAGEOS tracking data back to 1976
- Process LAGEOS long arcs
- Switch to Mendes-Pavlis tropospheric correction in pos+eop and ITRF back series
- Provide LAGEOS orbits in SP3-format and generate SLR Q/L report
- Produce TerraSAR-X orbit predictions and POD

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JCET/GSFC ILRS Analysis Center

Erricos C. Pavlis, Magdalena Kuzmicz-Cieslak, and Glynn Hulley/JCET

Introduction

The JCET/GSFC Analysis Center participated in all AWG-related ILRS activities during the period 2005-06. In addition to continued contributions to the ILRS official product, contributions were also submitted to the IERS ITRF Combination Pilot Project. In connection with the latter, our contribution comprises a fourteen-year series (1993-2006) of weekly SINEX files with positions and EOP. Since April 2001, we routinely analyze data from LAGEOS-1 and -2 and Etalon-1 and -2 for the generation of these products. In 2006 we investigated the incorporation of Starlette and Ajisai as two additional geodetic targets in the development of the official product. A pilot series is now generated routinely in-house, with these two data sets analyzed on a weekly basis in the same mode as the data from LAGEOS-1 and -2 and Etalon-1 and -2. Since the ILRS initiated the routine delivery of its products, it became obvious that an automatic way to check the quality of these products on a weekly basis was necessary. JCET developed a Web-based process to generate a summary, visualizations, and statistical analysis product for the weekly official contributions from the ACs and the CCs combination products, to be used for quality checking and validation of the products. The Web pages can be accessed from:
http://geodesy.jcet.umbc.edu/ILRS_QCQA/. Figure 12-3 shows the initial page.

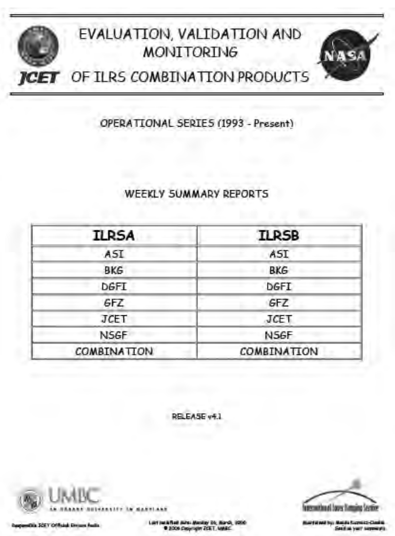

Figure 12-3. Front page of JCET's "Evaluation, Validation and Monitoring of ILRS combination products".

The weekly "Summary Reports" are the latest in several improvements of the site since its initial release. They consist of PDF files with plots and tables pertinent only to the chosen AC or CC. These reports can be browsed on a weekly basis by the AC and CCs, as well as those concerned with the performance of the tracking network and the quality and consistency of the ILRS products.

JCET is also conducting the software benchmarking process for all new candidate ACs for the ILRS. By the end of 2006, Geosciences Australia (GA) was nearing a successful completion, followed by the GEMINI/OCA GRGS group from France, and the Newcastle University that is now entering the process. A great effort to improve the atmospheric delay corrections for SLR is continuing. The new, improved zenith delay model for atmospheric refraction [Mendes and Pavlis, 2004] valid for all optical wavelengths used in SLR at present, was adopted as the new ILRS standard starting Jan. 1, 2007. A detailed description was sent to the IERS Conventions office to be included in the revised version of the appropriate chapter of the current Conventions (2003). In a continued effort to further improve these corrections towards the mm-SLR goal of ILRS, JCET has now developed a 3D ray tracing approach that is even more accurate than the models and includes the effects due to horizontal gradients in the atmosphere [Hulley and Pavlis, 2006]. The collaborative work with the Italian groups at the University of Lecce and Rome ("La Sapienza"), continued, with the publication of an extended description of our data analysis that led to our 2004 result for the Lense-Thirring predicted relativistic effect of frame-dragging. The paper also contains a detailed accuracy assessment of our measurement.

Background

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

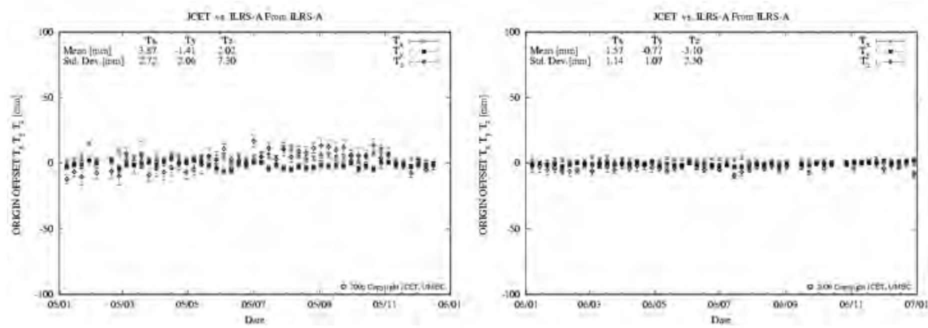

Figure 12-4. Time series of origin shifts of the JCET contribution with respect to the ILRS combination product for 2005 (left) and 2006 (right).

Facilities/Systems

The same facilities and systems support the JCET/GSFC AC as in previous years.

Current Activities

The generation of weekly solutions as a contribution to the IERS/ITRF and the monitoring of episodic and seasonal variations in the definition of the geocenter with respect to the origin of the conventional reference frame continue in a routine manner.

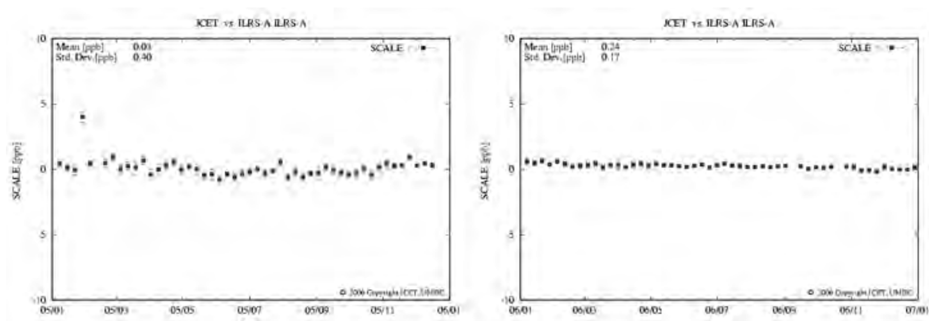

Figure 12-5 Time series of scale of the JCET weekly contribution with respect to the ILRS combination product for 2005 (left) and 2006 (right). Notice the improved stability during 2006, with a std. dev. of 0.17 ppb versus 0.40 ppb in 2005.

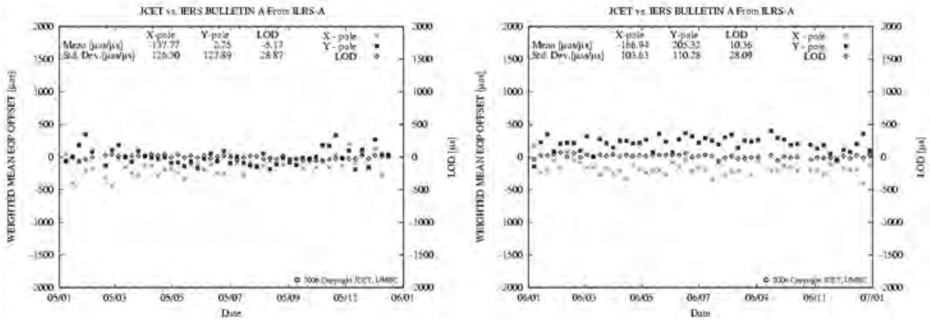

Figure 12-6. Time series of mean weekly offset of JCET weekly EOP mean offsets from IERS' Bulletin A, for 2005 (left) and 2006 (right).

During the October 2006 AWG workshop in Canberra Australia, the AWG adopted changes in the modeling standards that necessitated a new analysis of all prior years' data in order that future products are consistent with the currently analyzed ones. A re-analysis of the 14-year series was decided, using the newly adopted modeling standards, a task currently underway. In parallel, it was also agreed to reevaluate the rules and procedures that the AWG uses to determine when to model or solve and when not, for systematic measurement biases. The need to recover biases at the data analysis stage is increasing, especially as we advance in the background modeling efforts, and errors previously hidden in the noise are now becoming the dominant ones. As the modeling progresses, smaller systematic errors, as the various measurement biases, are now becoming the leading errors. An investigation is underway, with a re-analysis of all of the previous years' data to determine the sites that have significant biases, consistent over extensive periods of time. Elimination of such sources of error in the contributing solutions will lead in a more stable and cleaner combined product with smaller and more random variations in the site coordinates. Figure 12-7 shows the evolution of the weekly local coordinate offsets for four typical sites around the world, for intervals during the two year period covered by the present report.

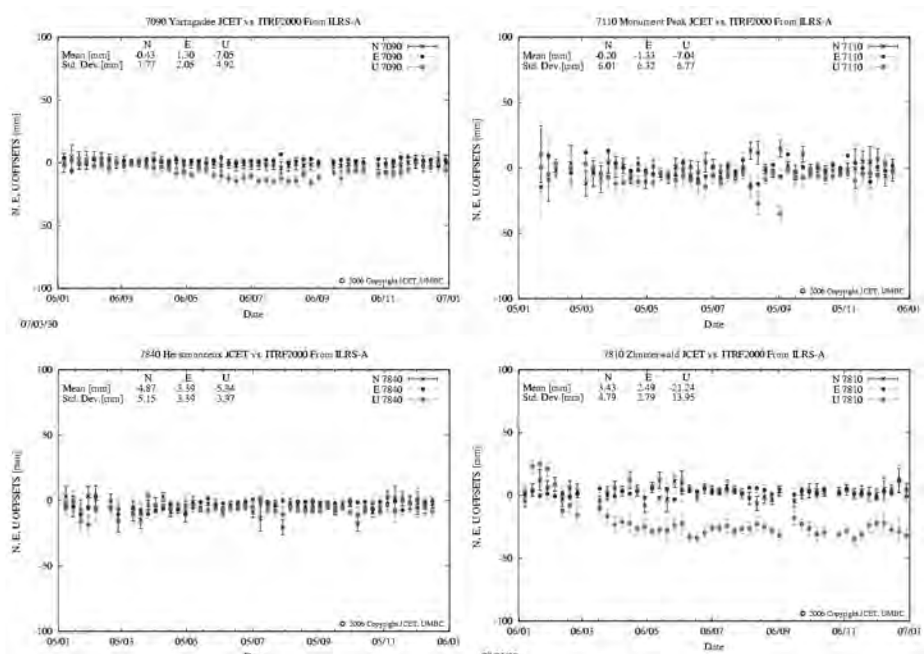

Figure 12-7. Time series of weekly offsets in local coordinates for JCET's weekly products, for 2005 and 2006, for four typical sites in the ILRS network.

Future Plans

ILRS-related activities will continue, with emphasis on the near-real-time generation of weekly products and their dissemination via the Web. We extended our analysis to years prior to 1993, with the generation of 15-day SINEX files beginning with the launch of LAGEOS in May 1976. Emphasis is now placed on the completion of simulation studies that will result in the design of the future geodetic network to support the accuracy goals of the GGOS program of IAG. GGOS is focused on addressing very tough problems, e.g., mean sea level monitoring, imposing stringent accuracy requirements in the definition of the underlying reference frame (less than 1mm accuracy in the origin definition at epoch, and less than 0.1 mm/y stability). Considering the cost associated with the establishment and the operation of SLR tracking sites, the results of these simulation studies will have profound implications for the future of the technique and its support of the ITRF development and monitoring process.

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

Graham Appleby, Philip Gibbs, and Matthew Wilkinson/NERC

Outline

The Analysis Center is an integral part of the Space Geodesy Facility (SGF) at Herstmonceux, UK, which runs and develops the laser ranging, GNSS, absolute gravimetry, and associated environmental monitoring systems. The main work carried out by the AC is analysis of laser range data to the geodetic satellites as well as regular daily predictions and QC for most of the ILRS-tracked satellites. These products are made available to the community via the ILRS data centers and the SGF Web site. The facility was granted Analysis Center status by the ILRS in 2006.

Analysis

The SATAN laser analysis package has been updated to include the improved tropospheric delay model of Mendes and Pavlis and a new implementation of ocean loading as recommended by the IERS. Automated weekly solutions continue to be submitted to the ILRS combination centers, and reprocessing for the periods 1993-2006 and 1983-1992 is underway.

Effort has been spent to characterize a small bias in the laser ranging data from Herstmonceux that has been present since the introduction of Stanford counters into the time-of-flight measurement in 1992. Our previous work in this field had concentrated on a range-dependent error that directly affected satellite measurements at a level of up to 8mm. The recent work, made possible following the in-house build of a ps-level event timer from Thales units, examined the bias imposed on calibration board ranging by short-range effects in the Stanford counters. This result, and its estimated effect on the ITRF 2005 coordinates of Herstmonceux, was presented at the 15th International Laser Ranging Workshop in Canberra in October 2006. The other ILRS ACs agreed to implement this change to the Herstmonceux data in an AWG-driven re-analysis effort, primarily to include for the first time the Mendes-Pavlis refraction model, for LAGEOS and Etalon data during 1992-2006.

Of particular interest to the SGF AC from this analysis effort are the solutions for weekly station height. Shown in Figure 12-8 is the height time series relative to the ITRF2000 value for Herstmonceux for 1994-2007, which exhibits an annual variation of amplitude ±10mm. The error bars are formal 2-_ values, computed from the full covariance of the geocentric rectangular coordinates.

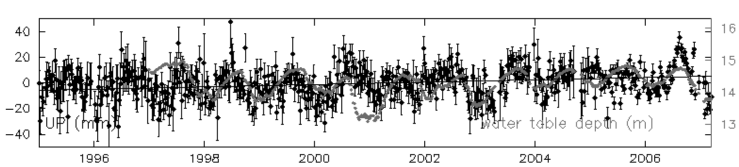

Figure 12-8. Height time series relative to the ITRF2000 value for Herstmonceux for 1994-2007

Superimposed on the plot, in the solid line, is the measured daily depth of the water table beneath the site, scaled (the water table depth varies seasonally by more than 2m) for best fit to the height series. It is likely that water table loading is not solely responsible for the height variations, since true geocenter motion has not yet been removed from the laser solutions. We will add to this time series a further ten years of data on completion of the 1983-1992 analysis, but that series is likely to be noisier since only LAGEOS-1 is available until the launch of the Etalons in 1989. However, it is hoped that a glacial isostatic adjustment (GIA) signal will be estimable from the 24-year time series.

This analysis is being carried out in conjunction with our analysis of the IGS onsite stations HERS and HERT and with now-regular weekly absolute gravity measurements in the SGF basement.

Daily Data Quality Solutions

Automated six-day LAGEOS and Etalon global residual solutions for all ILRS stations continue to be posted daily in graphical form on the SGF Web site. Short arc solutions for most of the satellites are also included in this QC effort.

Daily Predictions in CPF

The SGF AC is a backup prediction provider, and undertakes to provide daily CPFs, at least for all the geodetic spheres, but for other missions too on a best-efforts basis. This is a fully automated process, except that manual intervention is required for post-maneuver solutions.

Publications

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Associate Analysis Center Reports

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

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 (BAS) continues to produce global geodetic SLR solutions — coordinates (SSC) and velocities (SSV) and Earth Orientation Parameters from 1993 to the present. The satellite orbit determination and parameter estimation software package, Satellite Laser Ranging Processor (SLRP), was developed at the laboratory and is used to produce the analysis results. Information about the CLG can be found at *http://clg.cc.bas.bg*.

At the CLG Associate Analysis Center the following data products are available:

1. Global SLR solutions (station coordinates and velocities and EOP) produced yearly for LAGEOS-1 and -2);
2. Geogravitational parameter GM and selected set of geopotential coefficients and ocean loading parameters from LAGEOS-1 and -2 tracking data;
3. Low degree zonal rates from the analysis of LAGEOS-1 and -2;
4. Global tectonic plate motion;
5. Range and time biases for the SLR tracking stations.

Current Activities

1. LAGEOS-1 and -2 SLR tracking data reprocessing with the updated and modified software version SLRP 5.0;
2. IERS and ITRF oriented product generation – SSC, SSV and EOP;
3. Research activities of the low degree zonal drifts of the geopotential, geocenter variations and SLR reference frame;
4. Global tectonic motion with emphasize on the Mediterranean;
5. GPS-35 and -36 SLR data processing.

Future Plans

1. Including tracking data from the Etalon satellites in the analysis;
2. GLONASS orbit determination and parameter estimation from SLR tracking data.

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Center for Orbit Determination in Europe (CODE)

Claudia Urschl/Astronomical Institute, University of Bern, Switzerland

Introduction

CODE, the Center for Orbit Determination in Europe, is located at the Astronomical Institute of the University of Bern (AIUB) in Switzerland. CODE is a joint venture of the AIUB, the Federal Office of Topography (swisstopo), Wabern, Switzerland, and the Federal Agency of Cartography and Geodesy (BKG), Frankfurt, Germany. As an Associate Analysis Center of the ILRS, CODE provides a SLR-GNSS quick-look service, and it submits orbit prediction files for the GNSS (Global Navigation Satellite System) satellites to the CDDIS on a daily basis. In addition, research is carried out in the field of comparing the microwave and the SLR tracking techniques.

CODE Quick-Look Reports

CODE provides daily SLR-GNSS quick-look reports. Currently, GNSS consists of both GPS and GLONASS satellites. The quick-look reports are based on SLR residuals, the differences between the observed SLR ranges and the distances computed from the CODE microwave-based GNSS orbits. Residuals are computed for the two GPS satellites PRN G05 and G06 (GPS-35 and -36), which are equipped with laser retroreflector arrays, and for the subset of three GLONASS satellites that is regularly tracked by the SLR community.

SLR normal points gathered over the last six days are downloaded from the CDDIS daily. The SLR observations of the last four days are then compared with the CODE final orbits, whereas the remaining two days are compared with the CODE rapid orbits. The SLR residuals are summarized in the CODE SLR-GNSS Quick-Look Report, which is distributed via e-mail to the SLReport mail exploder giving rapid feedback on the quality of the SLR observations.

GNSS Satellite Predictions

In July 2006 the Consolidated Prediction Format (CPF) became operational for orbit predictions. CODE provides CPF files for all GNSS satellites that are tracked by the ILRS network. Each day a five-day prediction for each satellite is submitted to the CDDIS. The predictions consist of an extrapolation of the CODE rapid orbits, which are based on microwave observations spanning three days. For the first prediction day, the approximate radial accuracy of the GPS orbit predictions is at the 5-10cm level, whereas for GLONASS orbit predictions the radial accuracy is slightly worse with about 15cm. If predictions are missing, e.g., due to a microwave data outage, the users are informed and asked to use the SLR-based predictions from Honeywell Technology Solutions Inc. (HTSI).

Scientific Research

We analyzed SLR range residuals spanning four years of data for independent validation of the GNSS orbit derived from microwave observations. The range residuals are mainly an indicator for the radial orbit accuracy. The validation results of the CODE final orbit products show a standard deviation of the range residuals of about 2cm for the GPS, and of about 5cm for the GLONASS satellites. The GPS orbits have a better accuracy compared to GLONASS, due to the much denser GPS microwave tracking network. In addition, we found a mean bias of 3-4cm as well as significant seasonal variations of up to 10cm amplitude for the two GPS satellites. The mean bias is already known from previous studies, but its origin is still unexplained. A wrong value for the retroreflector offset, giving the distance from the center of the laser retroreflector array to the satellite’s center of mass, could be one possible explanation.

The observed significant seasonal variations were studied in detail. The largest residuals occur when the satellite is observed within the Earth's shadow during eclipsing seasons. Dependencies on SLR-specific parameters, as the tropospheric zenith path delay, satellite- or station-dependent biases, and SLR site coordinates, were not found. Instead, we could attribute the periodic signature of the range residuals to orbit modeling problems, as the residuals show a strong dependency on the elevation angle of the Sun above the orbital plane and on the satellite's position within the orbital plane. This dependency clearly rules out SLR tracking biases. The pattern is rather caused by the microwave analysis, indicating attitude or orbit modeling problems. Deficiencies in the solar radiation pressure modeling might be one possible explanation. Further studies will follow to improve the orbit modeling.

The first European navigation satellite GIOVE-A (Galileo In Orbit Validation Element) was launched on December 28, 2005. As no microwave tracking data are available until now, the orbit determination based only on SLR tracking data is of big interest. We succeeded in determining SLR-based orbits of GIOVE-A, analyzing about eight weeks of SLR data. Orbital arcs of nine days length were determined with an orbit accuracy of about 10cm, 0.5m, and 1m in radial, along-track and cross-track direction, respectively. In addition, an unannounced satellite maneuver could be detected. The microwave-based orbits for GIOVE-A, as well as for the first Galileo satellites in the IOV (In Orbit Validation) phase, will rely on microwave tracking data of a very limited number of stations. Therefore, SLR would give an important contribution to the orbit determination in a combined analysis of microwave and SLR data. We demonstrated the possible improvement of the orbit accuracy on the basis of an a priori variance-covariance analysis, using SLR range measurements and simulated microwave data.

Related Publications

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Urschl, C., Beutler, G., Gurtner, W., Hugentobler, U., Ploner, M. (2007) Orbit determination for GIOVE-A using SLR tracking data. In: Proceedings of the 15th Laser Ranging Workshop, Canberra, October 15-20, 2006, in press.

Urschl, C., Beutler, G., Gurtner, W., Hugentobler, U., Schaer, S. (2007) Calibrating GNSS orbits with SLR tracking data. In: Proceedings of the 15th Laser Ranging Workshop, Canberra, October 15-20, 2006, in press.

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Delft University of Technology, The Netherlands

Ron Noomen, José Ignacio Andrés, Eelco Doornbos/DUT

Introduction

The Department of Earth Observation and Space Systems (DEOS) at Delft University of Technology (DUT) has been active in the field of SLR analysis since about 1980. The current activities include scientific analyses on LAGEOS orbits and force modeling, which is the topic of another section in this report. In addition DEOS is also involved in operational orbit analysis that will be described here briefly.

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 (QC) 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.

Unfortunately, the computer configuration in Delft was plagued by a series of breakdowns in the first half of 2006, leading to a full stop of the analysis system just before the summer of 2006. So far, manpower limitations have prevented the re-installation of the system on a different computer and the resumption of the analysis flow.

The QLDAC analysis system has been subject to improvements and operational changes (such as its frequency) more or less continuously. The current implementation employs a state-of-the-art computation model, including (amongst others) the ITRF2000 model for station coordinates modeling, corrections for atmospheric pressure loading, estimation of 4-daily empirical accelerations on the satellite in along-track and cross-track directions, provisions for handling SLR observations taken at multiple wavelengths, and the estimation of the geocenter. Since the fall of 2004, the system runs on a daily basis in a fully automatic fashion. Typical rms-of-fit values are in the range from 10 to 14mm. The results are summarized in an analysis report, which provides overall results and statistics (RMS-of-fit, tracking statistics, solutions for EOPs) but also estimates of the possible range and time biases of individual passes of LAGEOS-1 and LAGEOS-2. The latter are combined with the estimates obtained by other analysis centers in an official ILRS Combination Report, and serve to give the stations a realistic feedback on the performance on their equipment. Bias estimates reported at the level of about 20-30mm (in absolute terms) and higher, are considered an indication of real data problems, while all values below that threshold should be ignored.

The most important action item is the re-start of the analysis procedure. As for the (near) future, QLDAC intends to introduce several new elements in the operational analysis: (1) the use of the Internet to disseminate analysis results, (2) the addition of other satellites, probably the Etalons, (3) the implementation of new models to represent the effect of refraction, and (4) the modeling of the station-satellite characteristics. QLDAC staff is confident that the re-start and the new elements will be completed and introduced successfully, and it will continue to serve the SLR community with its timely quality assessments.

ERS-2 and Envisat Precise Orbit Determination

DEOS has continued its analysis of orbits and altimetry of the European remote sensing satellites ERS-2 and Envisat. This is an on-going activity that was initiated originally with the launch of ERS-1 in 1991. In this process, orbits are fitted to measurements covering data arcs of 5.5 days with a one-day overlap both at the beginning and at the end of the arc. ERS-2 orbits are based on SLR-data only, while Envisat SLR data are combined with DORIS tracking. No significant changes have been made to the orbit determination procedure over recent years. Preparations have been made for an investigation on the use of ERS-2 and Envisat tracking data in the validation and calibration of thermospheric density models. Results are made available on the DEOS Web page *http://www.deos.tudelft.nl*.

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European Space Operation Centre (ESOC)

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

Introduction

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

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

Facilities/Systems

All orbit solutions and related products are automatically generated using a common software package (NAPEOS). The orbit solutions for ERS-2 and Envisat consist of 5-day arcs with varying timeliness of availability, depending on the mission. For ERS-2, the solution is generated with a delay of six days to allow collection of all SLR tracking data. For Envisat, the fast-delivery solution is generated after 36 hours, while the final precise orbit solution has a typical delay of around six weeks depending on when the DORIS Doppler data become available.

For each solution, reports are made available on our Web site (*http://nng.esoc.esa.de*) and comparisons of the solutions are made against the routine orbit solution (ERS-2 and Envisat) and the CNES medium and precise orbit ephemerides (MOE and POE) for Envisat.

Current Activities

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

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

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

Future Plans

Besides the ongoing activities for ERS-2, Envisat, and GIOVE-A, the Navigation Support Office plans to process the SLR tracking data from Cryosat-2, where again the data will play an important role in the monitoring of ESOC's operational and predicted solutions. Furthermore, similar support as with GIOVE-A will be provided after the launch of GIOVE-B where the SLR tracking data will play an essential role.

In 2007 the ESOC Navigation Support Office will make a detailed study using the ILRS SLR tracking data of all GNSS targets. This study will focus on analyzing the precise GNSS orbits as provided by the International GNSS Service (IGS). The ILRS data are extremely valuable since they provide a unique and fully independent quality check. The historic ILRS tracking data of the GNSS targets will be of significant value for the planned IGS reprocessing efforts where we will use them to validate our reprocessing results and, if possible, include the data in the actual data processing.

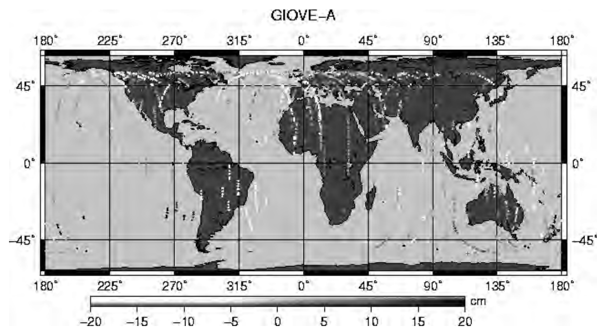

Figure 12-9. The residuals of the SLR observations obtained from the GIOVE-A predictions at the Navigation Support Office since June 2006.

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Forsvarets Forskningsinstitutt (FFI)

Per Helge Andersen/FFI

Introduction

FFI has during the last 24 years developed a software package called GEOSAT for the combined analysis of VLBI, GNSS (GPS, Galileo, GLONASS), SLR, and other types of satellite tracking data (DORIS, PRARE, and altimetry). The observations are combined at the observation level with a consistent model and consistent analysis strategies. With this procedure the time-evolution of the common multi-technique parameters (for example EOP, geocenter, troposphere, or clock parameters) are treated consistently across the techniques. This is not the case when the techniques are combined “rigorously” at the normal equation level. The data processing is automated except for some manual editing of the SLR observations.

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

Recent Activities

The GEOSAT software has undergone extensive changes and improvements during 2005-2006. The most important changes implemented are described here.

The IERS-2003 Conventions, including all extensions/corrections up to 20 Jan 2007, have been implemented and validated.

A new major software component of GEOSAT for 3D raytracing through the atmosphere has been developed and validated during the last three years. A complete 3D atmospheric model provided four times daily by European Centre for Medium-Range Weather Forecasts (ECMWF) is input to the software. Recently, time resolution was increased to eight times per day. Based on the available tracking data (VLBI, GPS, or SLR) for that specific date, a set of tables for each active station is automatically generated with information about the time delay in the different elevation and azimuth directions. If surface meteorological data are available for a given station the measured pressure values are used to re-scale the hydrostatic delay obtained from the raytracing calculations. Since the raytracing starts at the position of the phase center for each instrument/antenna, the effect of different antenna heights will automatically be accounted for to the level of accuracy of the numerical weather model. The Grueger model is the default for the MW refractive index and the Ciddor model is the default for the optical or near optical wavelengths. The Ciddor model has been validated against Ciddor’s own software.

In addition, statistical information concerning the variability of relevant parameters is extracted from the ECMWF data. This information is used in the estimation filter as time-dependent parameter constraints in the estimation of atmospheric signal delay scaling parameters. The raytracing procedure can also be used to detect periods with rapidly changing atmospheric conditions that cannot be modeled accurately. This information can be used to edit such data leading to more stable values for the atmospheric scaling parameters. This strategy is expected to be especially valuable for the combined analysis of GPS and future Galileo tracking data due to the great redundancy of such datasets.

The GNSS part of GEOSAT has undergone extensive changes, for example, with the inclusion of a second and third order ionospheric correction, absolute phase center corrections for all antennas, etc. The ionospheric correction for GNSS applications in GEOSAT is expected to be accurate to around 1 mm.

The pressure loading tables provided by Petrov and Boy are used by GEOSAT. For stations not included in these tables a simple pressure scaling model is used where the load scale parameter is automatically estimated in the analysis. A grid of reference pressure values has been derived by averaging the surface pressure levels provided by National Centers for Environmental Prediction (NCEP) during the last 20 years.

In the global processing of several years of data the stable sources listed by Feissel et al. are automatically estimated as constants while the others are estimated as random walk parameters or session parameters.

The new version of GEOSAT is expected to be ready for routine processing within one year. The new version of GEOSAT will have two additional very useful features:

1. It can simultaneously combine data from virtually any number of VLBI, SLR, and GNSS instruments at a co-located site either observing simultaneously or in different time windows. All information will contribute to the estimation of the migration of an automatically selected master reference point at each station.
2. The solve-for model parameters in the combined processing of the VLBI+SLR+GNSS can either be instrument-dependent, technique-dependent, microwave-dependent, optical-dependent, or site-dependent. The switching between the different types is extremely simple. A simple application would be to, in a first run, treat the zenith wet delay parameters as instrument-dependent parameters which means that, for example, a station with two GPS receivers and one VLBI instrument will have three estimates of this parameter. If the results are consistent, these parameters can be estimated as a single parameter represented by a microwave-dependent parameter in a second run. The same can be tested for clock parameters for co-located clocks etc.

A new software component for the generation of a Geophysical Events file has been included in GEOSAT. This file contains information about earthquakes, the magnitude, and distance to stations included in the ITRF. Based on this information we plan to develop an estimation strategy where noise, dependent on the distance to the epicenter, is added to the station reference point motion for stations affected by earthquakes.

Instrumental events files for VLBI, GPS, and SLR have also been included in GEOSAT. These files give the epochs of changes in software or hardware of the instrument and the type of change. Every time a major instrumental event occurs, noise will be added to the relevant estimated eccentricity vector.

Twelve years of VLBI-only sessions have been analyzed. A clear reduction in a posteriori residuals is observed. Results from analyses of CONT-series data show best-case repeatabilities around 1mm in the horizontal plane and 2mm in the vertical direction.

The validation of GEOSAT with LAGEOS SLR tracking data is also completed with very promising results. The use of detector-dependent center of mass corrections, correction for the non-linearity of the Stanford counter, 3D raytracing, and taking into account a signal strength dependent range bias for some stations, led to a slight change in the value of GM. LAGEOS data from January 1, 1993 to January 31, 2005 have been carefully re-edited. The use of multi-color laser data has been implemented and gives excellent post-fit residuals. This will be further investigated in 2007 when we plan to estimate a new and consistent value for GM. The results so far indicate that for some periods, station biases at the level of 5mm still exist.

Future Plans

Observations from the Galileo navigation system will be applied when available. Only minor changes in GEOSAT are required for this extension.

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

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

Introduction

The SLR Data Analysis Center at the Main Astronomical Observatory of the National Academy of Sciences of Ukraine (MAO NASU) began in 1988 and became an ILRS Associative Analysis Center (GAOUA AAC) in 1998. The primary interests of the GAOUA SLR Data Analysis Center are:

- software development
- data processing of SLR observations
- archiving SLR observations for local needs

The unique Kiev-Geodynamics software is used for SLR data analysis. Since 1989, determinations of EOP and coordinates and velocities of SLR stations are made. A collection of the observation data from all Ukrainian permanent SLR stations is retained in a local archive. Detailed information about the GAOUA AAC is available on the Ukrainian Center of Determination of the Earth Orientation Parameters Web page: *http://www.mao.kiev.ua/EOP/ENGLISH/slr_centre/structure.html*.

Scientific Results

The main scientific results during the period 2005-2006 follow.

The stability of the network of the Ukrainian SLR stations Simeiz, Katzively, Golosiiv-Kiev, Lviv have been investigated utilizing reductions of LAGEOS-1 and -2 observations from January 5, 1989 through November 11, 2004. The stability of the coordinate determination for each station is estimated. The factors influencing the stability of the network are outlined.

GAOUA staff developed methods for the combination of VLBI, SLR, and GPS data in a conditional equations system with a designed parameter estimation algorithm in collaboration with S. Bolotin and O. Khoda.

Current activities of the GAOUA AAC are:

- monitoring the stability of the Ukrainian SLR network
- processing all available LAGEOS-1 and -2 SLR tracking data
- combining VLBI, SLR, and GPS observations

Future plans of the AAC include:

- development of the Kiev-Geodynamics version 6.0 software
- operational analysis of the SLR observations

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Geoscience Australia

Ramesh Govind/Geoscience Australia

Introduction

The Geoscience Australia Analysis Center routinely processes LAGEOS-1, LAGEOS -2, Etalon-1, Etalon-2, Stella, Starlette, GIOVE-A, and GLONASS data for satellite orbit determination, station coordinates, Earth Orientation Parameters (EOPs), station performance monitoring, and developing a long-term time series of the low-degree and order spherical harmonic coefficients of the Earth's gravity field. The weekly LAGEOS solutions in SINEX format are submitted to the DGFI combination center.

Facilities/Systems

The current computation facilities in the Geoscience Australia Space Geodesy Analysis Center consist of three multi-CPU HP L2000 workstations and a HP cluster composed of ten rx2600 servers. The processing system uses the Geodyn suite of programs for orbit determination and geodetic parameter estimation as the engine. NASA's SOLVE program and IGN Catref are used for the combination solutions. A suite of programs was developed in-house for analysis and re-formatting. Final results are provided in the SINEX format.

Analysis Activities during 2005-2006

- Solutions for the benchmark tests were submitted.
- Processing all LAGEOS-1 and LAGEOS-2 data for the period beginning 2003 to the end of 2006 was completed in compliance with ILRS AWG computation standards and submitted to the ILRS combination centers.
- Stella and Starlette data for the period beginning 1996 to the end of 2006 were processed.
- Etalon-1 (beginning 2000 to end 2006) and Etalon-2 (April 2001 to end 2006) data were processed.
- GLONASS-89 data for the period of March 2003 through the end of 2006 were processed.
- All GIOVE-A SLR data that were observed during the period May 2006 to end 2006 were processed for orbit determination.

The LAGEOS, Stella, and Starlette processing is resulting in a long-term time series for the motion of the Earth's center of mass and degree-two spherical harmonic coefficients of the Earth's gravity field.

Current Activities

- Completing the LAGEOS-1 and LAGEOS-2 time series for station coordinates, EOP and station performance from beginning 1983 to end 1992. These results are a contribution to the ILRS AWG project.
- Processing all GLONASS SLR data observed since 1997 and evaluating a combined solution of all SLR data observed to GNSS satellites.

Related Publications

Three papers were presented to the 15th International Workshop on Laser Ranging in Canberra, on GIOVE-A orbit determination, geocenter motion, and a global SLR network simulation.

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Japan Aerospace Exploration Agency (JAXA)

Shinichi Nakamura, Nobuo Kudo, Ryo Nakamura/Flight Dynamics Division, JAXA

Introduction

One of the tasks of the JAXA Associate Analysis Center is to provide the precise orbit determination for Ajisai, LAGEOS-1, and LAGEOS-2. In addition, JAXA has performed precise orbit determination experiments for ALOS using onboard GPS receiver data and its accuracy evaluation using SLR. JAXA has also been preparing for the ETS-8 experiment, a geostationary satellite launched on December 18, 2006.

Facilities/Systems

JAXA developed and completed a precise orbit determination system that incorporates both GPS data and SLR data. The JAXA SLR station, located at Tanegashima, was completed at the end of March 2004. In comparison with last year, JAXA made some modifications to our software, such as the addition of a solar radiation pressure model and a replacement of our observational model from the IERS 1996 standard to the IERS 2003 standard.

Current Activities

- Processing SLR tracking data of Ajisai, LAGEOS-1, and LAGEOS-2.
- Generating CPF for the above satellites.
- Processing GPS satellite data (QLNP and RINEX) for precise orbit determination. Comparison of our orbit determination results with those of the IGS analysis center shows that our precise orbit determination system has almost equivalent performance to IGS analysis center.
- Monitoring and evaluating SLR station performance. The results are available on our Web site: *http://god.tksc.jaxa.jp/slreport*.
- Analyzing the data obtained from ALOS. The analysis shows that our accuracy of orbit determination achieved within about 30cm (RMS) or 4cm (best record) for ALOS orbit.[1, 2]

Topics

ALOS

ALOS was launched by JAXA in 24 January 2006 and carries a dual frequency GPS receiver. JAXA performed precise orbit determination experiments using GPS data. Because the GPS receiver was a newly-developed one, JAXA evaluated the accuracy of the determined orbit using SLR.

ALOS carries two optical sensors (PRISM, AVNIR-2) that are vulnerable to a laser beam. JAXA requested the restricted operation of SLR to the supporting SLR stations [1, 2]. Precise orbit determination experiments and their accuracy evaluation were successfully performed. The success of the accuracy evaluation is largely due to the cooperation of the ILRS and the participating stations. The result of the experiments is as follows [1, 2].

- The orbit determination accuracy is 30cm (RMS) or 4cm (best record; Overlap Comparison Method; comparative evaluation).
- Eliminating the margin of error (30cm or so), the orbit precisely determined using GPS data is consistent with the orbit determined by SLR data (absolute evaluation).

ETS-8

ETS-8 is an advanced satellite being developed primarily to establish and verify the world's largest-class geostationary satellite bus technology, which is necessary for space missions at the beginning of the 21st century. ETS-8 was launched in December 2006 and will conduct orbital experiments on the Large-scale Deployable Reflector (for S-band), which is widely applicable to large-scale space structures, as well as the High-Power Transponder, and the On-Board Processor, which are all required to realize mobile satellite communications with hand-held terminals, similar to popular cellular phones. Moreover, the ETS-8 will carry the High Accuracy Clock (HAC) system and a Time Compare Equipment (TCE) system for the study of satellite positioning system. SLR data on ETS-8 is essential for these two experiments. SLR tracking can be performed to ETS-8 from the stations of WPLTN including the JAXA/Tanegashima station. JAXA carried out the link budget calculation in consideration of the station performance and checked the possibility of SLR. Consequently, Mt. Stromlo, Koganei, and Kunming became candidate tracking stations. JAXA will request that these stations range to ETS-8 once every two weeks [3].

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Mission Control Center (MCC) Analysis Center

Vladimir Glotov/Russian Mission Control Center

Introduction

The MCC has been involved in SLR data analysis since 1990 and is part of the MCC Navigation and Coordinate-Time Service. We have continued determination of standard EOP and SLR network quality control, studies to use SLR measurements of GLONASS satellites to check the quality of the available microwave-based orbital solutions, and support of the Russian SLR network.

Facilities/Systems

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

Current Activities

Weekly EOP Estimation and SLR Network Quality Control

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

In 1996, the MCC started a regular service of assessing performance of the SLR stations. All LAGEOS-1 and -2 data are analyzed to obtain values of time and range biases and RMS. The routine service requires two levels of data filtering: automatically excluding outliers and problem sessions and manually checking and correcting the results.

Since the end of 2006, the MCC uses ITRF2000 (the recommended by ILRS Analysis Working Group) as the basic coordinates set for standard analysis (i.e., in the frame of the ILRS activity).

GLONASS Orbit Determination and Verification

The global products from the IGS International GLONASS Service (IGLOS) should facilitate the use of combined GLONASS and GPS observations and analysis results for the civil scientific and engineering applications in the frame of the prototype Global Navigation Satellite System (GNSS). Particularly, there are many civil applications where navigation data from GPS are not adequate for the complete analysis. From this point of view, it is important to calibrate the geodetic base, the navigation signals accuracy, etc. for the GLONASS system as good as possible. SLR data are the source of calibration data for determination of satellite ephemerides, generation of an international geodetic base, and accuracy factor for improving GNSS, etc.

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

Future Plans

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

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Newcastle University, UK Associate Analysis Center

Philip Moore/Newcastle University.

The School of Engineering and Geosciences (CEG) at Newcastle University has continued its activity in space geodesy involving SLR, DORIS, VLBI, GPS and altimetry. SLR activities utilize our in-house software FAUST. Our ILRS Associate Analysis Center activities over the past two years have involved precise orbit determination of geodetic and altimetric satellites, calibration of the altimetric range and onboard microwave water radiometers, temporal variation in the Earth's gravity field and synergy of tracking techniques.

Precise orbits of LAGEOS-1 and LAGEOS-2 have been used to infer temporal variability for the lower order and degree harmonics. The study compared (1) degree 2 harmonics from ERPs and gravitation, and (2) LAGEOS excitation functions and geophysical data (mass + motion). In addition, an attempt was undertaken to investigate to what extent a unified approach is possible with current models for AM data and gravity mass change estimated from ERP within orbit determinations. The results show that there is some value in utilizing variability of J2 from Earth rotation to model the temporal gravitational force associated with the second-degree zonal harmonic. Other studies of temporal variability have combined SLR results with temporal variability recovered from GPS loading deformation with further comparison against the harmonics from the monthly GRACE solutions. Results to date have revealed that degree 2 harmonics from SLR complement the higher degree variability obtainable from GPS.

In collaboration with Graz University, Austria, reduced dynamic orbits for Envisat have been utilized with transponder altimetric ranges for precise transfer of height from the land to the oceanographic surface. The study identified that the quality of the orbital determination is an essential component for height recovery. With limited SLR geographical coverage for short-arc computations the reduced dynamic approach based on SLR and DORIS provided radial positioning at about the 3cm level for arcs over the transponder. Other studies utilizing precise SLR and DORIS orbits include absolute calibrations of the TOPEX/Poseidon, Jason-1, and Envisat altimetric ranges utilizing time series of sea-surface variability from UK tide gauges.

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National Institute of Information and Communications Technology (NICT)

Toshimichi Otsubo/NICT

Introduction

NICT has developed its own software package, ‘concerto v4’ for precise orbit determination. During the 2005-2006 period, this software was applied to SLR-related activities using the ILRS observation data.

Daily Quality Check Analysis

NICT (formerly called CRL) started the three-satellite (two LAGEOS and Ajisai) routine bias report in 1997 and enhanced it to the seven-satellite (by adding Starlette, Stella and two Etalon) analysis in 1999. This report was again significantly upgraded in May 2005.

First, we included additional satellites: ERS-2, Jason-1, Envisat, GPS-35, GPS-36, GLONASS-87, GLONASS-89 and GLONASS-95. Note that some of these satellites might be omitted from the analysis report in the case of failing certain criteria in terms of data quality and quantity. Nevertheless, the analysis reports consistently include more than ten satellites. The increased number of satellites and the variety of satellite altitudes will certainly help the ILRS stations easily identify any problem and its cause.

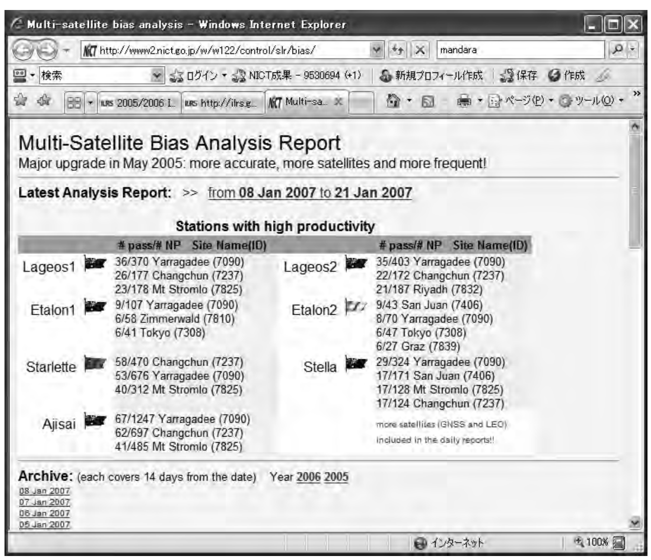

Figure 12-10. Multi-satellite bias analysis Web page at NICT (http://www.nict.go.jp/w/w122/control/slr/bias).

We have switched the orbit analysis software from ‘concerto v3’ to ‘concerto v4’. The new version is nearly compatible to the physical models recommended in IERS Conventions (2003). The station coordinates were basically unchanged from ITRF2000, but those of new or significantly improved stations after the year 2000 were readjusted. As a result the quality of the analysis reports should be more accurate.

We now publish the bias report daily; prior to May 2005 the report was issued weekly. The report timing was also improved from 48-hour delay to 24-hour delay. Every morning, in Japanese Standard Time (around 0 to 1 hr UT), a report covering up to two days before is released. Such a quick reporting scheme became possible thanks to the rapid submission (typically within a few hours after the observation) and archive service of normal point data.

Simulation Studies for Future Space-VLBI Satellite, ASTRO-G

The next space VLBI observation program, implemented as the ASTRO-G satellite, relies upon highly accurate orbit determination up to a few cm. This requirement is challenging especially because its orbit is highly elliptic with the altitude ranging from 1,000 to 25,000 km. The simulation studies for estimating orbit determination precision are currently ongoing at NICT, in collaboration with JAXA. Onboard GPS receivers are likely to be the primary instruments that should constrain the orbits at least around the perigee. We also consider that satellite laser ranging plays an important role because it is expected to significantly improve the estimation precision especially in the transverse direction, even with a small amount of observations.

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Observatoire de la Côte d'Azur (OCA)/GEMINI

Pierre Exertier, Philippe Berio, Pascal Bonnefond Florent Deleflie, Dominique Féraudy, Olivier Laurain/OCA/CERGA

Introduction

Besides its involvement in the SLR data acquisition through operation of the Grasse stations (LLR, high altitude satellites, and the Moon), and the FTLRS deployed on Corsica Island during the year 2005, the OCA/GEMINI department is actively contributing to the ILRS as an Associate Analysis Center (AAC).

We have participated in:

- The analysis of LAGEOS (-1 and -2) SLR data for carefully producing site coordinate and EOP time series (processing method in development); we have computed benchmarks in view of becoming one of the official ILRS Analysis Centers.
- The analysis of SLR data for calibration/validation (cal/val) activities (Jason-1, essentially).
- The combination of the raw observations of multiple space geodesy techniques is still in the research domain and necessitates more development and improvement, which is underway. We note however that some groups have started to produce solutions as results from the combination at the observation level.

Facilities/Systems

The current computation facilities in the OCA/GEMINI consist of two Opteron (PC computers) with a bi-processor. The processing system uses the GINS (GRGS/CNES) software for orbit determination and a suite of locally developed codes (MATELO, OCA, and IGN/LAREG) for space geodesy analysis.

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

- Laser ranging stations: FTLRS, and LLR in re-development (see the French station report about the T2000 project, same issue)
- In 2005, the SLR station was stopped definitively. Now, we are working to improve the LLR capabilities for: low earth satellite tracking (a greater velocity of Az. and El. axes), and very long distance one- and two-way telemetry (a greater stability of the telescope).

Background

The activities of the OCA AAC have been focused on two main points discussed below.

Solution Improvements

In 2004-2005, the primary objectives (and organization) of OCA AAC were to improve our solution (precise orbit determination strategy, and reference system), based on SLR. Although it is hard to assess the origin accuracy of the single ILRS solution that was submitted to ITRF2005, we attempted, however, to evaluate its consistency with respect to ITRF2000. Figure 12-11 shows the three translation time variations with respect to ITRF2000, using a reference set of twelve stations. Given their observation history and good performance, these are the only stations that are usable to link the combined SLR TRF resulting from the stacking of the time series to the ITRF2000 frame (see Figure 12-12). Because the estimated transformation parameters are heavily sensitive to the network geometry, the distribution of the reference set of 12 stations is far from being optimal; only two of them are in the southern hemisphere (Yarragadee, Australia and Arequipa, Peru).

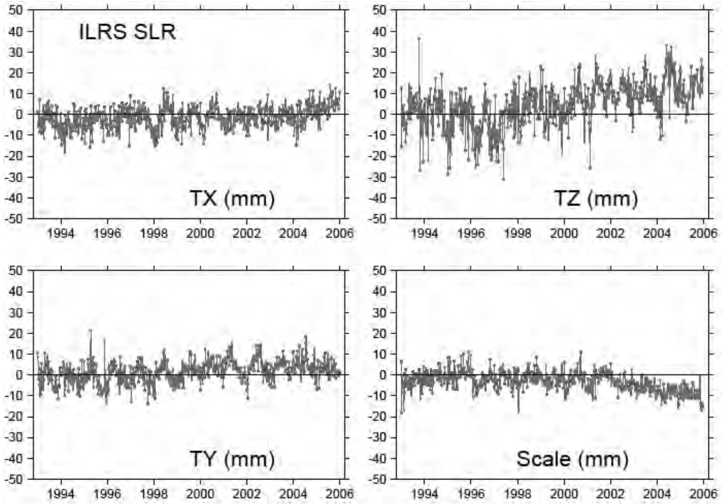

Figure 12-11. Translations and scale variations with respect to ITRF2000 of the ILRS SLR time series submitted to ITRF2005P.

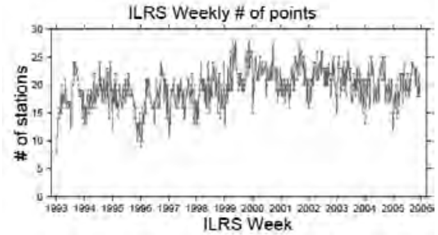

Figure 12-12. Number of stations included in the weekly ILRS SLR time series submitted to the ITRF2005.

Combination Activities

Combination, and implicit comparison of multiple solutions of geodetic products of a single or several techniques is considered to be an efficient tool to both bring to the fore discrepancies between solutions/techniques and to yield a more reliable combined product, gathering the strengths of the combined solutions/techniques.

The combination of the raw observations of multiple space geodesy techniques method consists of combining directly the raw geodetic observables that are measured by various techniques. Although some research groups carry out such a combination and some results are already available, the experience of such computations is very recent, compared to that of the combination at the product level. Regarding this second combination method, the work that has been realized is mainly illustrated by the experiment carried out by the French Groupe de Recherche en Géodésie Spatiale (GRGS) in 2004-2005 (see the Proceedings of the GGOS 2006 workshop, in October, Munich, Germany).

The approach that is currently adopted for the combination of various TRF solutions provided by a single or several space geodesy techniques is built on the construction of a unique (combined) TRF, making use of the mathematical Helmert transformation formula. It considers defining the combined TRF at a given (arbitrary) reference epoch and adopting a TRF time evolution law that is supposed to be linear (secular). Consequently, 14 degrees of freedom are always necessary to completely ensure the TRF datum definition: six for the TRF origin and its rate (time derivative), two for the scale and its rate, and six for the orientation and its rate.

The inclusion of EOPs into the combination requires additional equations where the link between the TRF and EOPs is ensured via the six orientation parameters. The combination model considered here (as the one used by the ITRF Product Center) allows the estimation of station positions and velocities, transformation parameters of each individual TRF solution with respect to the combined TRF and, if included, consistent series of EOPs. The input solutions usually used in this kind of combination are either (1) time series of station positions and EOPs or (2) long-term solutions composed by station positions and velocities and EOPs. In the first case where the combination amounts to rigorously stacking the time series, the un-modeled non-linear part of geodetic parameters are implicitly embedded in the combination output: possible seasonal (e.g., annual or semi-annual) station or/and geocenter motions are respectively left in the output time series of station residuals and the transformation parameters.

Current Activities

The current activities of the OCA AAC are:

- Computation of SLR purely solutions (EOPs and station coordinates),
- Research in view of improving the combination method (raw data),
- Participation in the Jason-1 cal/val program and deployment of the FTLRS in Australia at the end of 2007,
- Preparation of future campaigns and data reduction schemes for T2L2/Jason-2 (Time Transfer).

Future Plans

OCA AAC will continue laser data analysis development. Our activities for 2007-2008 will be centered on:

- Realization and data processing of Jason-2 cal/val campaign(s),
- Computation of laser EOP and station coordinate time series and distribution of products to ILRS,
- Organization of the T2L2 (Time Transfer by Laser Link, on board Jason-2 in 2008) data process, and campaigns (time transfer) with the FTLRS.

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Shanghai Astronomical Observatory

Cheng Huang, Yuanlan Zhu/Shanghai Astronomical Observatory

Recent Activities

During 2005-2006, we started the pre-processing and analysis of LAGEOS-1 and -2 data on a weekly basis. We provided ranging accuracies, range biases, and time biases for more than 50 SLR stations, which were published on SLReport and on the ILRS Web site.

The astronomical constants, reference coordinate systems, measurement models, and orbital models for the processing were adopted according to the IERS 2000 conventions as follows:

- Reference coordinate systems

Inertial:	J2000.0
Terrestrial:	ITRF2000
Precession:	IAU 1976
Nutation:	IAU 1980 plus IERS-revised
Earth Orientation Parameters:	Estimated

- Measurement models

Satellites used:	LAGEOS-1and -2
Data editing:	3.5 sigma editing
Troposphere	Marini-Murray model
Satellite center of mass:	LAGEOS: 0.251 m
Station coordinate correction:	IERS 2000 conventions

- Orbital models

Third-body:	Moon and Sun
Ephemeris:	JPL DE403/LE403
Geopotential:	JGM3
Solid earth tides:	IERS 2000 conventions model
Ocean tides:	IERS 2000 conventions model
Solar radiation pressure:	Direct and albedo radiations applied (Cr estimated)
Drag-like:	Drag coefficient Cd estimated
General relativity:	IERS 2000 Conventions model
Experience forces:	estimation of empirical (constant and once-per-rev) along-track and (once-per-rev) cross-track accelerations

We also processed SLR observation data from the Chinese network's mobile SLR station and from Shanghai SLR station during its relocation, obtaining their positions to centimeter accuracy.

In addition, the two-wavelength (846nm and 423nm) SLR observation data from the Zimmerwald station (7810) have been processed for two years; the results were also submitted to SLReport and the ILRS Web site on a weekly basis.

A new comprehensive orbit determination and parameter analysis software (COMPASS) for processing multi-satellite and multi-sensor observation data was developed during the past two years. The software can be used to estimate satellite orbit, dynamical, and geodetic parameters, such as EOPs, solar radiation pressure coefficients, atmospheric drag coefficients, and station coordinates, based on a multistage-multiarc procedure. At present, the software works well and can obtain an accuracy of 1-2cm for 30-day LAGEOS SLR data processing, and obtain more accurate EOPs from multi-satellite data than single satellite data when re-estimating EOPs using 1998-2006 SLR data.

Future Plans

We will continue to explore the application of multi-satellite analysis to the long time series of EOP, station coordinates and velocities, and the position variation of the Earth's mass center using COMPASS software.

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Lunar Associate Analysis Center Reports

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

Institut Fuer Erdmessung (IFE)/Forschungseinrichtung Satellitengeodaesie (FESG)

Jürgen Müller, Liliane Biskupek/IfE

Status

At the IfE (Institute of Geodesy) in spring 2005 the software to analyze the LLR data was converted from Fortran 77 to Fortran 90 (Koch 2005). Another activity was the implementation of a new integrator for the numerical integration of the ephemerides of the main solar system bodies and the dynamical partials with sufficient accuracy. With the new software package, standard solutions for the determination of the unknown parameters were carried out using all LLR measurements between 1970 and 2005, about 16,000 normal points. Besides the 'Newtonian' parameters of the Earth-Moon system, many relativistic effects were investigated such as the validity of the equivalence principle and predictions of alternative theories of gravity. To better understand the effect of the various relativistic quantities on the Earth-Moon distance and their correlations, sensitivity studies were performed by computing

$$\Delta r_{em}^{p} = \frac{\delta r_{em}}{\delta p} \Delta p$$

Δr_{em}^{p} is the perturbation of the Earth-Moon distance caused by p, e.g., a relativistic parameter. $\delta r_{em}^{p} / \delta p$ is the partial derivative of the Earth-Moon distance with respect to p, obtained by numerical differentiation. is a small value indicating the variation in p. As an example, Figure 12-13 represents the sensitivity of the Earth-Moon distance with respect to a possible temporal variation of the gravitational constant in the order of 7 * 10-13 1/yr, the present accuracy of that parameter. It seems as if perturbations of up to 1.2 meter are still caused, but this range (compared to the LLR ranging accuracy at the cm level) cannot be fully exploited, because the lunar tidal acceleration perturbation is similar. Corresponding studies for the other gravitational physics parameters have been published in Müller et al. (2006 a, b).

In May 2006 a new LLR project started at a German research unit of the DFG (German Research Foundation) dedicated to "Earth rotation and global dynamic processes". The LLR data have been further analyzed. Accuracy studies were made by considering different time spans of the data in neglecting the LLR data of the first 5 and 15 years, respectively. We could show that the increase of the weighted post-fit residuals (observed-computed Earth-Moon distance) obvious since 2000 is not caused by deficiencies in the numerical integration, but probably by model limitations and reduced quality of the LLR data. The comparison of the RMS residuals computed from data of two different time spans is shown in Figure 12-14.

In cooperation with U. Schreiber, Wettzell, and J. Oberst, DLR, we started to investigate the poor observational conditions in LLR and to consider possible improvements by new installations on the Moon. In this respect, we performed investigations as to how the various reference frames are affected (Müller et al. 2007).

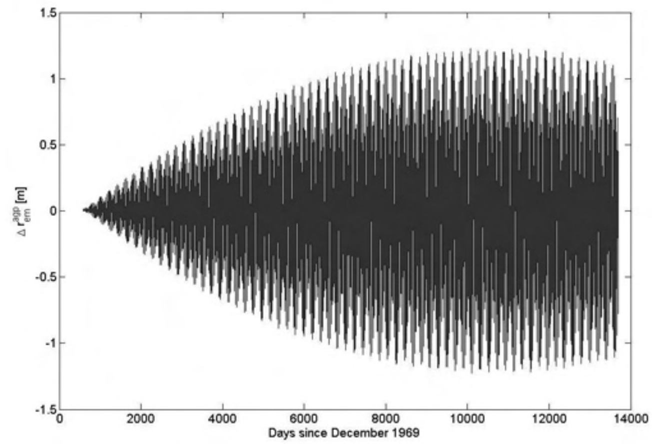

Figure 12-13: Sensitivity of the Earth-Moon distance with respect to G/G

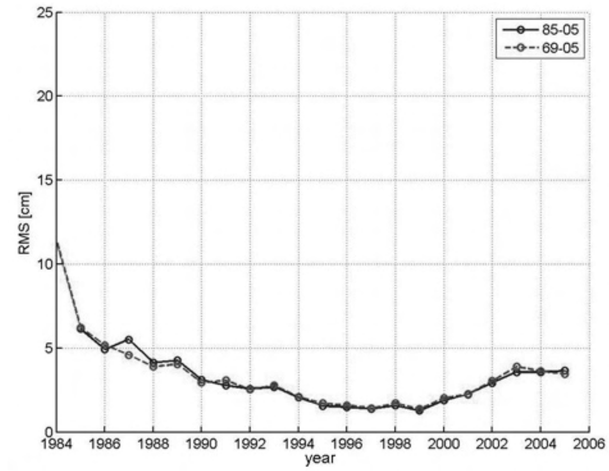

Figure 12-14: Weighted residuals annually averaged

Current Activities and Future Plans

We continued to determine gravitational physics parameters, where we concentrated on temporal and spatial variations of the gravitational constant G.

In December 2006, we started to include the data of the new LLR station APOLLO in New Mexico USA. This station is able to provide data with millimeter accuracy; first results look promising.

As future work extensions and improvements of the LLR model are planned, which comprise e.g., the gravity field of Earth and Moon, consideration of the effects of asteroids and the interior of the Moon. Investigations of Earth rotation and further tests of relativity are also foreseen.

We plan to enhance out activities to provide LLR results to a larger user community via ILRS and IERS.

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Jet Propulsion Laboratory (JPL) Lunar Associate Analysis Center

James G. Williams, Dale H. Boggs, Slava G. Turyshev, Jean O. Dickey, J. Todd Ratcliff/JPL

Analysis Activities

The Lunar Laser Ranging (LLR) data analysis activity has analyzed the first fully accurate operational data from Apache Point Observatory in addition to the extensive operational data sets from the McDonald and Observatoire de la Cote d'Azur (Grasse) sites and historical data from Haleakala. Retroreflector arrays include those installed by the Apollo-11, -14, and -15 and Lunokhod-2 missions.

The computer code for lunar laser ranging data analysis continues to be reviewed and upgraded. A major improvement was new code for fluid-core/solid-mantle boundary (CMB) oblateness, both numerically integrated physical librations and partial derivatives, along with a revision of the code for fluid core dynamics. The solution for the lunar CMB oblateness gives a significant detection.

Standard solution parameters now include ranging station coordinates and motions, Earth orientation parameters, lunar orbit, tidal acceleration, GM of Earth+Moon, lunar rotation, Love numbers, tidal Qs, fluid core dissipation, fluid-core/solid-mantle boundary (CMB) oblateness, gravity coefficients and retroreflector array positions. In addition, solutions were made for any equivalence principle violation (related to PPN beta and gamma), dG/dt and geodetic precession. Gravitational physics results are in agreement with general relativity. Daily UT0 and variation of latitude solutions have been made for a 37 year LLR data span.

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Paris Observatory Lunar Analysis Center (POLAC)

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

Introduction

The POLAC Lunar Analysis Center is located at the SYRTE Laboratory of "Observatoire de Paris" (France). It works in cooperation with the two IERS centers based also at SYRTE (EOP and ICRS centers) and with the LLR-SLR staff of "Observatoire de la Côte d'Azur" OCA/GEMINI (Grasse, France). The analyses of Lunar Laser Ranging (LLR) have various applications in astronomy, geodynamics, geodesy and especially in the determination of parameters involved with the lunar motions and the dynamics of the Earth-Moon system.

Lunar Laser Ranging

Lunar laser observations (LLR normal points) consist of measurements of the round-trip travel time of light between a terrestrial station and a lunar reflector. There are more than 17,000 LLR normal points provided between 1969 and 2006 by three stations: McDonald (Fort Davis, Texas) 1969-2006, Observatoire de la Côte d'Azur (Grasse, France) 1984-2005, Haleakala (Maui, Hawaii) 1987-1990. The observations supplied by McDonald and OCA since 1987 represent 70% of the whole set of available normal points. Between 1969 and 1973 five lunar reflectors have been placed on the lunar ground: three by American astronauts (Apollo missions 11, 14 and 15) and two by Russian lunar vehicles (Lunakhod 1 and 2). The observations of McDonald Laser Range Station (MLRS) have decreased since 2003. The OCA station at Grasse stopped temporarily its LLR activities on September 2005 for renovation. The APOLLO observations (Apache Point Observatory, New Mexico) are not yet available on the ILRS Web site. With the exception of Lunakhod 1, lost after landing, all lunar reflectors are still operational.

Activities

Several analyses have been performed on LLR data. The values of residuals between observed and computed values depend on the number and the nature of the selected parameters. The global root mean square of the post-fit residuals on the distance station-reflector over the interval [1995-2006] is 4.2cm for McDonald observations and 3.8cm for OCA observations.

- The fit of lunar orbital parameters during the period 1969-2006 has improved the lunar analytical solution, elaborated at Paris observatory, and consequently the accuracy of lunar ephemerides. These parameters are the mean longitude of the Moon and the Earth-Moon barycenter, the mean longitudes of the lunar perigee and ascending node, the inclination and the eccentricity of the lunar orbit and the eccentricity of the Earth-Moon barycenter. In particular, the tidal part of the quadratic term of the mean longitude (half of tidal secular acceleration) has been evaluated to -12.94"/cent2.
- The fitted rotational parameters of the Moon are the amplitude of the three main terms of the free libration and their respective arguments. The lunar libration theory developed at SYRTE laboratory has been compared to various numerical ephemerides of JPL (DE245, DE403, DE405), which use different gravitational and tidal models. The analytical form of the theory allowed passing from a model to another with the addition of short Fourier series after referring them in the same reference frame. The fit of the free libration parameters to LLR data has been performed with the analytical solution of the lunar libration completed by numerical series. A method has also been found to maintain an internal precision of the solution of about 0.01" on the libration angles over several centuries.
- The fit of the reflector coordinates to the LLR observations in the selenodesic system of axes referred to the principal moments of inertia, have allowed correcting the initial values of these coordinates (IERS convention 1992) by several tens of meters. The error estimated by the least squares method is centimetric but basically the accuracy depends on the physical libration model. The contribution of each reflector in the whole set of

observations is not evenly distributed. All the observations made up to now come 80% from Apollo15, which is very close to the median axis of the lunar disk, 9% from each of the other two Apollo reflectors (11 and 14) and only 2% from Lunakhod 2, respectively.

- LLR analyses allow determination of the orientation of the dynamical reference frame with respect to other reference systems, in particular the International Celestial Reference Frame (ICRF). The inclination e of the dynamical mean ecliptic (epoch J2000) to the equator of ICRF, and the angle f between the origin of right ascensions on the equator ICRF and the dynamical equinox in J2000, have been evaluated. The correction Dp to IAU1976 precession constant has also been estimated. The fits realised over the period [1969-2006] gave the following values:

  e = 23° 26' 21.411" ± 0.001"
  f = -0.055" ± 0.001"
  Dp = -0.307"/cent ± 0.004"/cent

- The few number of LLR stations poses a difficulty for improving the accuracy of their terrestrial coordinates with LLR data. Investigations have been done to determine how the LLR residuals could be improved by using time series of station positions provided by the Satellite Laser Ranging technique, which has a better global tracking network. In the case of OCA station, where the LAGEOS satellite and LLR observations have been realized at the same site, the same instrument, and the same laser ranging technique, the implementation of SLR time series in the LLR analyses over the common period (1998-2004) has reduced by 2 mm/year the derivative of LLR residuals during these seven years. More significant improvements on the LLR residuals are expected with a new SLR time series.

Conclusion

Over the last 35 years the accuracy of LLR measurements has regularly improved from 25cm on the distance station-reflector in the1970's to 10-15cm in the 1980's and 2-3cm in the 1990's. In the early 2000's, the staff of the Observatoire de la Côte d'Azur (OCA) station estimated that they had an instrumental internal precision of 30-60 picoseconds in the round-trip between transmitter and reflector (5-10mm in distance). Therefore, we are still more limited by the modelling than by the observations and some effects have to be modelled with more accuracy. This is the case for the lunar libration in correlation with the orientation of the reflectors and for some corrections like the effects of the troposphere. The sub-centimetric accuracy of the future data and the high quality of the first LLR results of Apache Point Observatory justify the continuation and the extension of Lunar Laser Ranging.

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Section 13
ILRS Station Reports

Section 13

ILRS Station Reports

Arequipa, Peru

David Carter/NASA GSFC, Julie Horvath and Scott Wetzel/HTSI

Figure 13-1. TLRS-3 system in Arequipa Peru (the DORIS antenna is located on the left).

Figure 13-2. TLRS-3 administrative and program personnel.

Following the NASA budget reductions of 2004, the Transportable Laser Ranging System (TLRS)-3 system, operated by the Universidad Nacional de San Agustin (UNSA), was forced to close after the 13th year of SLR operations at the site in Arequipa, Peru. The system was packed but remained in Arequipa, pending final disposition. During this time the TLRS-3 system remained without power to the system and thus, without any environmental control or protection.

In 2005, NASA Headquarters determined it was necessary to re-open the station. Following a new agreement between NASA and UNSA, Honeywell Technology Solutions Inc. (HTSI) was tasked, under the SLR contract, to reopen TLRS-3. Efforts began in the fall of 2005, and the first onsite inspection occurred in January 2006.

After two full years of no environmental control or maintenance at the TLRS-3 site, the system required significant repairs, maintenance, and upgrades. Upon the first site visit, HTSI staff determined that every major subsystem required a rigorous process of careful inspection, thorough cleaning, and evaluation as to whether maintenance or replacement/upgrade would be performed on-site or at the HTSI facility.

As a result, the telescope and computers were sent to the HTSI facility in Maryland. There, the hardware was disassembled and cleaned, inspected for failures, repaired or upgraded, then reassembled and tested prior to delivery back to the station. Additionally, all software updates since 2004 were loaded on the computers, including the restricted tracking and 4pps upgrades.

In Arequipa, the TLRS-3 crew, under the supervision of Dr. Raul Yanyachi, began the laborious job of cleaning and inspecting all surfaces of the system. Major facilities repairs were performed on the heating, ventilating, air conditioning (HVAC) system, generators, and the uninterruptible power supply (UPS).

All hardware upgrades since the TLRS-3 closure, including the recent TLRS-4 upgrades, were sent to Arequipa for inclusion. Following multiple site visits by HTSI engineers, the system saw its first satellite returns on September 29, 2006.

Before completing the return to full operations, a complete set of System Operations Verification Tests (SOVTs) was performed. An issue with the gimbal was discovered during the testing and, while not completely repaired, was made operable. The gimbal subsystem will remain in this state until resources are made available to complete the repair.

By the end of 2006, TLRS-3 tracked a total of 294 passes and achieved a total of 2517 normal points.

Figure 13-3. NASA presentation to UNSA Vice-Rector.

Figure 13-4. ILRS presentation to UNSA Vice-Rector.

Figure 13-5. U.S. Ambassador to Peru, James Curtis Struble (center).

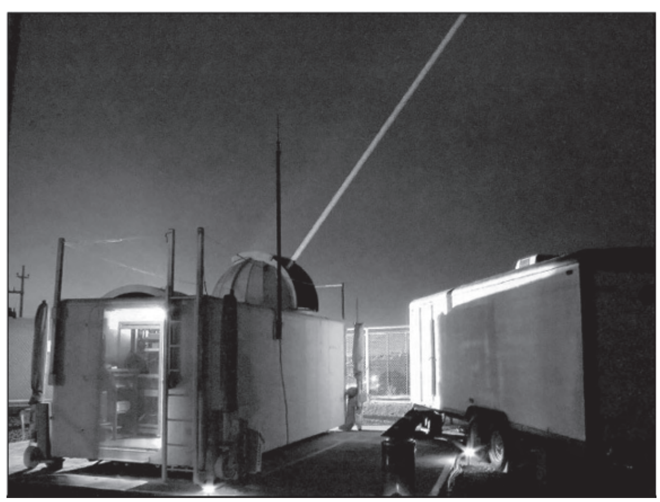

Figure 13-6. Laser demonstration at TLRS-3 ceremony.

On February 12, 2007, NASA and UNSA performed a formal re-dedication ceremony, officially celebrating the return of SLR operations to Arequipa, Peru. Many local dignitaries, including the U.S. Ambassador to Peru, participated in the festivities.

Crew at TLRS-3: Dr. Raul Yanyachi (Station Manager), Janet Caceres, Jorge Valverde, Mariano Gomez, Manuel Yanyachi, Modesto Cañari, Wilberto Cañari, Dante Corrales, Marco Higueras, and Kevynn Rodriguez.

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Installation of SLR System in San Juan Argentina

The most important event during 2005-2006 at the Beijing station was the packing, shipment, installation, and debugging of the new SLR system in San Juan, Argentina. This new SLR system is the result of the scientific and technology cooperation between the National Astronomical Observatories (NAO), the Chinese Academy of Sciences, and the San Juan National University of Argentina. The Ministries of Science and Technology of the two countries provided support and investment for the project. The system was designed and developed from 2000 to 2003 by personnel from the Beijing SLR station (operated by the Chinese Academy of Surveying and Mapping, CASM). The system was completely developed, validated, and accepted by the sponsor, NAO, on January 12, 2004. For more than one year we waited for completion of the SLR building in Argentina; we prepared for shipment in the beginning of 2004 and filled two shipping containers with the equipment in April of 2005. On July 21, 2005 these two shipping containers began their journey to Argentina and arrived in San Juan city on August 6, 2005. On September 12, Mr. Liu Weidong and Mr. Huang Dongping from NAO and Mr. Xiang Qingge from the CASM Beijing SLR station traveled to Argentina for the installation of the SLR system. On November 14, Prof. Wang Tanqiang/CASM from the Beijing SLR station and Prof. Guo Tangyong left for Argentina for the installation and debugging of the system. This process began on November 18 and was completed on February 23, 2006, at which time the new San Juan station was operational. To date, three staff members, Mr. Liu Weidong, Huang Dongping/NAO, and Mr. Xiang Qingge/CASM remain on duty at the San Juan station for daily maintenance and station observations. More information on the San Juan station can be found later in the station section of this ILRS report.

Figure 13-7. Disassembly of the SLR system for shipment.

Figure 13-8. Parts of SLR system packed ready for shipment to Argentina.

System Upgrade Experiments

During 2005-2006, upgrades of the Beijing SLR system concentrated on efforts to achieve daylight tracking capabilities. Daylight ranging is necessary and important for every SLR station and many stations in the world can acquire daylight observation data. Daylight tracking can increase the number of passes and observations, improving orbital coverage and discovery of systematic errors in data processing.

To achieve the goal of daylight tracking in Beijing, our efforts included adjustment of the telescope pointing, star tracking calibration for the telescope, enhancement of the resolving power of the range gate, purchase of a narrow band filter, and fabrication of a constant temperature oven for the filter for receiving returns in the telescope, etc.

All efforts were performed on a stable laser system at the station. In recent years, the developments in diode-pumped all solid-state lasers (DPSSLs) have made remarkable headway in output power, beam quality, new wavelength, narrowing pulse width, etc. As a result, DPSSLs are in widespread use today. A very successful use of the DPSSL is probably in SLR for kHz ranging. Therefore, during 2005-2006, we developed a sub-DPSSL laser system that will be easily upgradeable to DPSSL, for our daylight tracking capability and the updating of our SLR system to kHz ranging in the near future (within 2007). A schematic and photo of the sub-DPSSL laser are shown in Figures 13-9 and -10.

The new laser system was developed with the help of the Beijing Industrial University; the seed light of the laser is output from a SESAM Mode-locked laser from EOS of Australia. This laser has the following technical specifications: 1064nm wave length, 10ps pulse width, 100MHz frequency and more than 100mW average power. The laser output beam travels into a flash pumped regenerative amplifier and becomes a stable single pulse with 10ps pulse width, with about 1.5mj energy. Using two flash pumped amplifiers and a double frequency crystal BBO we obtained the uniformity single pulse laser with 532nm wave length, 10ps pulse width, 30mj single pulse energy and 1 to 10Hz repetition.

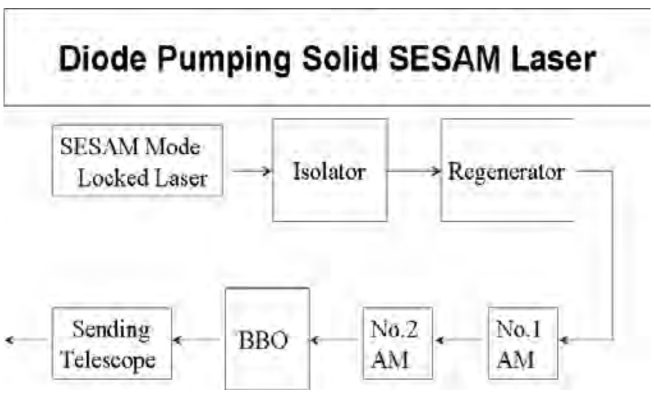

Figure 13-9. The diagram of sub-DPSSL laser.

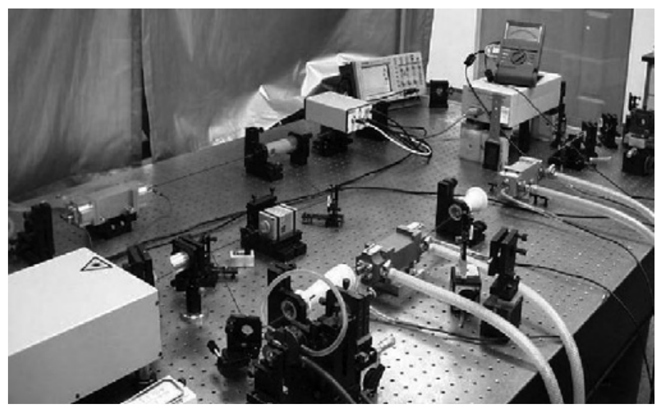

Figure 13-10. A photo of sub-DPSSL laser in daily use.

Operation

The Beijing SLR station operated continuously during 2005 and 2006 without major problems. We acquired 1,815 passes/19,616 normal points in 2005 and 1,642 passes/ 24,364 normal points in 2006. The number of passes was strongly limited by the weather and air pollution and the lack of daytime operation capability at the station. Due to some laser communication experiments, 2005 proved to be the second most successful year in quantity and quality of the data in the history of continuous activity at the Beijing SLR station, following the year 2004. In 2006, we performed some system upgrade experiments with our laser and daytime ranging capacity so the number of successful passes was reduced over 2005.

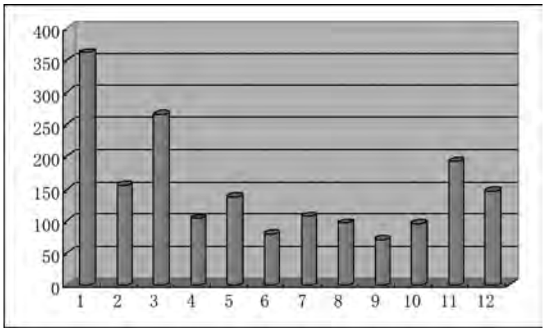

Figure 13-11. Passes for all satellites in 2005.

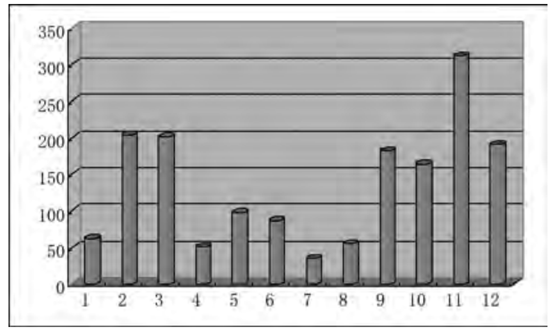

Figure 13-12. Passes for all satellites in 2006.

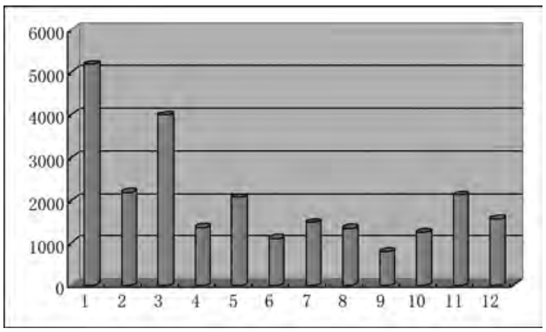

Figure 13-13. Normal Points for all satellites in 2005.

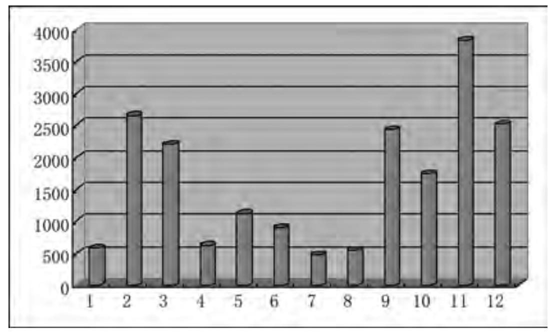

Figure 13-14. Normal Points for all satellites in 2006.

Future Plans

Currently we are at the start of a major hardware and software upgrade program through the support of the Chinese Crustal Movement Observation Network. As was mentioned above, we will upgrade the sub-DPSSL to a DPSSL. This added capability would enable the next stage of the upgrade, namely daylight tracking and kHz laser ranging. The ranging policy will remain that of working strictly at the single photon level, so the single shot jitter will continue to be dominated by satellite signature effects. However, normal point precision will improve by virtue of the increased numbers of observations that will be available by kHz tracking.

Figure 13-15. The Beijing SLR Station staff (left to right): Bohui Cheng, Jian Ding, Liping Ji, Chunmei Zhao, Nailing Liu, Feng Quzhibin Wei, Tanqiang Wang, and Qian Li.

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Borowiec, Poland

Stanislaw Schillak/ Space Research Centre, Polish Academy of Sciences

During 2005-2006, the satellite laser ranging station in the Astrogeodynamic Observatory of the Space Research Centre, Polish Academy of Sciences in Borowiec (7811) produced, collected, and delivered over 27,000 normal points to the scientific user community, tracking 1,824 successful passes from twenty satellites. The lower number of passes in comparison to previous years was caused by a two-month break in activity in November and December 2006 due to renovation of the laser building. The number of passes was strongly limited by weather conditions (68% clouds) and nighttime operations only. Since August 2006, we successfully returned to high-satellite ranging. The data quality in the form of an average 2005-2006 single shot RMS, normal points RMS, and analysis centers short term stability (ILRS Global Performance Report Cards) was equal to 22 mm, 4 mm and 14 mm, respectively. The single shot RMS was slightly degraded in the second half of 2006 due to problems with stability of the laser pulse. A detailed laser adjustment will be performed in the first quarter of 2007.

Several system upgrades were made during 2005-2006. The most important were tests of a new transmitting telescope with a system permitting the change of the laser beam divergence (in the second half of 2006). Successful ranging to high orbiting satellites (GLONASS, Etalon) was the result of this system upgrading. This work will continue in 2007 with the main goal of a ranging capability to the Galileo satellites. The software changes include implementation of a new version of a post-observation program which has a new method of polynomial fitting (from July 2005) and installation of software to utilize the Consolidated Prediction Format (CPF) (June 2006).

The future plans for Borowiec consist of several tasks: improvement in range and efficiency of the observations, tests of daylight tracking, increase of the data quality and quantity, and participation in the Time Transfer by Laser Link (T2L2) project in 2008. For realization of these tasks, the new transmitting and receiving optics, including a new cover for the main mirror of the telescope, a new 30% QE HAMAMATSU PMT-MCP, an indoor target, a new control system in 2007, and an event timer, will be installed in 2007-2008.

The onsite orbital analysis of SLR data with the NASA GEODYN-II program continues. The positions and velocities of all SLR stations in 1999.0 through 2004.0 were determined. In addition to the SLR system operations, the Borowiec site is a permanent IGS station (BOR1) operating a TurboROGUE SNR 8000 receiver and high-quality time service equipped with a cesium frequency standard HP-5071A, a two nanosecond Time Transfer System TTS-2 and two-way system with an accuracy 500 ps for time scales comparison. Gravity measurements were made with an absolute gravimeter in November 2006.

Figure 13-16. The Borowiec SLR building after renovation (January 2007). Borowiec SLR staff (left to right): Piotr Michalek, Pawel Lejba, Stanislaw Zapasnik, Danuta Schillak, Stanislaw Schillak, Jacek Bartoszak, (Daniel Kucharski was working at Graz SLR).

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A032-ET Experimental Results

There are many advantages of a kHz SLR system, and there are several stations working in this firing frequency rate, such as Graz and Herstmonceux. Some systems are under development; Changchun is one of these stations. We planned to use an event timer to increase firing frequency to 10Hz and even higher so as to increase the data quantity. After analyzing all event timers, the A032-ET was chosen for the Changchun experiment; Figure 13-17 shows the A032-ET.

Figure 13-17. A032-ET.

Since October 23, 2006, the A032-ET has been used routinely in satellite laser ranging at the Changchun station for all satellites tracked with the firing frequency rate of 10Hz. This event timer works very well and the experiment has been very successful. Next, we plan to increase to kHz observation if the laser source is available.

System Improvement and GIOVE-A Observations

GIOVE-A was launched on December 28, 2005, into an orbital altitude of 23,260 kilometers. Performance of the on-board atomic clocks, antenna infrastructure, and signal properties has been evaluated through precise orbit determination, supported by SLR. The Changchun station was selected among the Chinese stations contributing to the ILRS because it had demonstrated strong satellite tracking, co-location with an existing International GNSS Service (IGS) station, and good weather conditions. In order to track the Galileo satellites and obtain more SLR data with high precision, the following things were done in preparation:

- The primary mirror and second mirror of the receiving telescope were recoated, tested, adjusted and calibrated. These modifications resulted in higher transparency of the receiving optics.
- A new type photoelectric encoder was installed in the tracking mount to replace the old one. This new encoder will improve the resolution of the angular sensor of the tracking mount.
- A new type of servo driver was used to improve the telescope tracking performance thus heightening the tracking precision.
- The old laser components were replaced in order to increase the laser output energy up to 70-100mj and to improve output stability. These modifications will greatly increase the number of photons reflected back from the satellites.

After these system improvements, tracking speed and stability of the system greatly improved and output laser energy increased. Ranging ability obviously increased and points and passes from high satellites increased. Figures 13-18 through 13-21 below show the new components of the Changchun laser system.

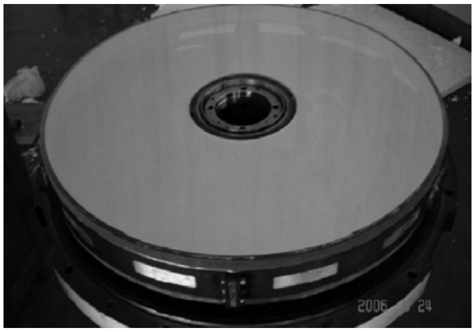

Figure 13-18. Recoated primary mirror.

Figure 13-19. New operation console.

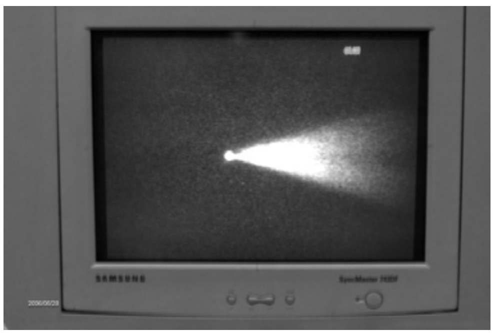

Figure 13-20. Laser output on monitor.

Figure 13-21. New encoder system.

Since December 12, 2006, 28 GIOVE-A passes and 12 GPS-35, -36 passes have been tracked. The observations performed by Changchun at the time of the GIOVE-A tracking campaign were included in the data set as the data were of high value for the analysis carried out. The geographical location of Changchun (Figure 13-22) was of primary importance in providing better laser ranging coverage of GIOVE-A.

Figure 13-22. World map showing geographical distribution of the first GIOVE-A ranging campaign.

Preparation for Daylight Tracking

Nearly all requirements for daylight tracking, including hardware and software, have been ready since the end of 2005. Due to the cold weather, we decided to perform testing at the beginning of 2006. Furthermore, because of the Galileo project, we had to change our plans and daylight tracking tests were delayed. The first phase of the Galileo project has been completed, and we will try daylight tracking in the near future.

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Bernd Sierk/BKG

The SLR station of the Transportable Integrated Geodetic Observatory (TIGO) underwent substantial changes in 2005 and 2006, with respect to both staff and technical equipment. Bernd Sierk replaced Stefan Riepl as station manager; Riepl returned to Wettzell to be the project leader for BKG's upcoming SOS-W site. Two more operators were hired to facilitate a 24 hour/7 days a week operation. In April/May 2006 the entire laser system was replaced by a state-of-the art Ti:Sapphire oscillator based on SESAM technology and 100% diode pumped amplifiers. In addition, the event timer was upgraded to enable 100Hz repetition rate tracking of all satellites (including LEO). The main characteristics of the upgraded SLR system are:

- passively mode locked Ti:Sapphire oscillator operating at 847 nm
- regenerative and multipass amplifiers pumped by a diode pumped Nd:YAG system
- 40 ps pulse width (847 nm)
- 1.5 W output power at 100 Hz repetition rate (15 mJ pulse energy)
- two-wavelength operation (847 nm and 423.5 nm)

The new SLR system became operational in June 2006 and greatly improved the productivity of the station. A much improved system stability and the continuous operation resulted in a significant increase in data yield and quality. Figure 13-23 depicts the passes per month measured in 2006, a total of 1,902 satellite passes were acquired that year. In addition to LEO missions like CHAMP and GRACE, which have been difficult to measure before, GNSS satellites (GPS, GLONASS, and GIOVE) are now tracked on a regular basis.

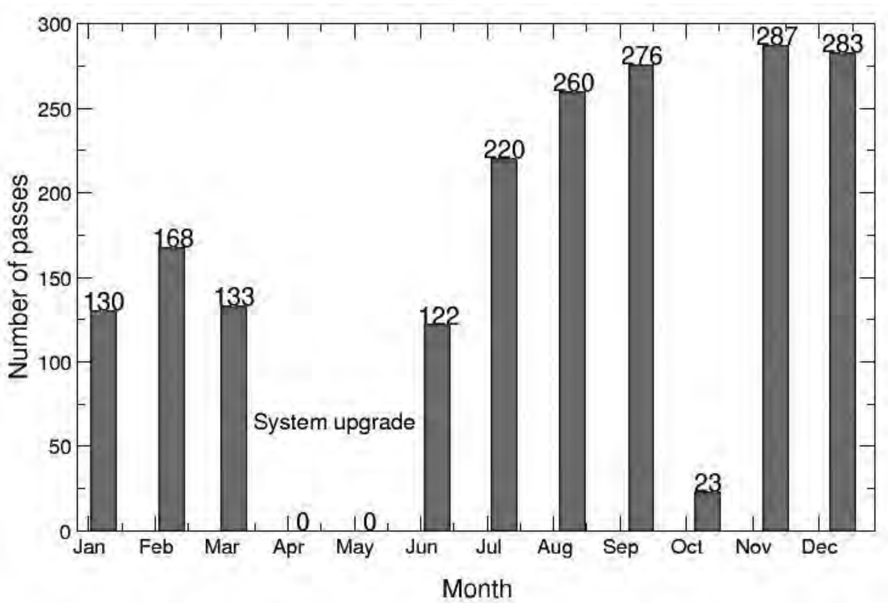

Figure 13-23: Number of passes per months measured at CONL in 2006. Note the increase of data productivity after the system upgrade in April/May.

Figure 13-24: The TIGO-SLR crew (left to right): Víctor Mora, Alejandro Fernández, César Guaitiao, Marcos Avendaño, Bernd Sierk, and Iván Cona.

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Grasse and FTLRS

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Grasse

Grasse laser staff: D. Albanese, E. Cuot, D. Feraudy, M. Furia, Laplanche, G. Martinot, F. Para, J. Paris, M. Pierron, E. Samain, JM. Torre, P. Vrancken, J. Weick

A very important project, in terms of buildings and technology for telescopes, mount and dome, was started at the Grasse Observatory in September 2005. A new laboratory has been built in place of the historical SLR fixed station (7835) to receive the mobile SLR system (FTLRS) for upgrade, development, and operations between field missions.

The current LLR station (7845), renamed MeO (for Metrology and Optics), is being completely rebuilt to track and range from LEO satellites to the Moon and even further to support new missions in the solar system

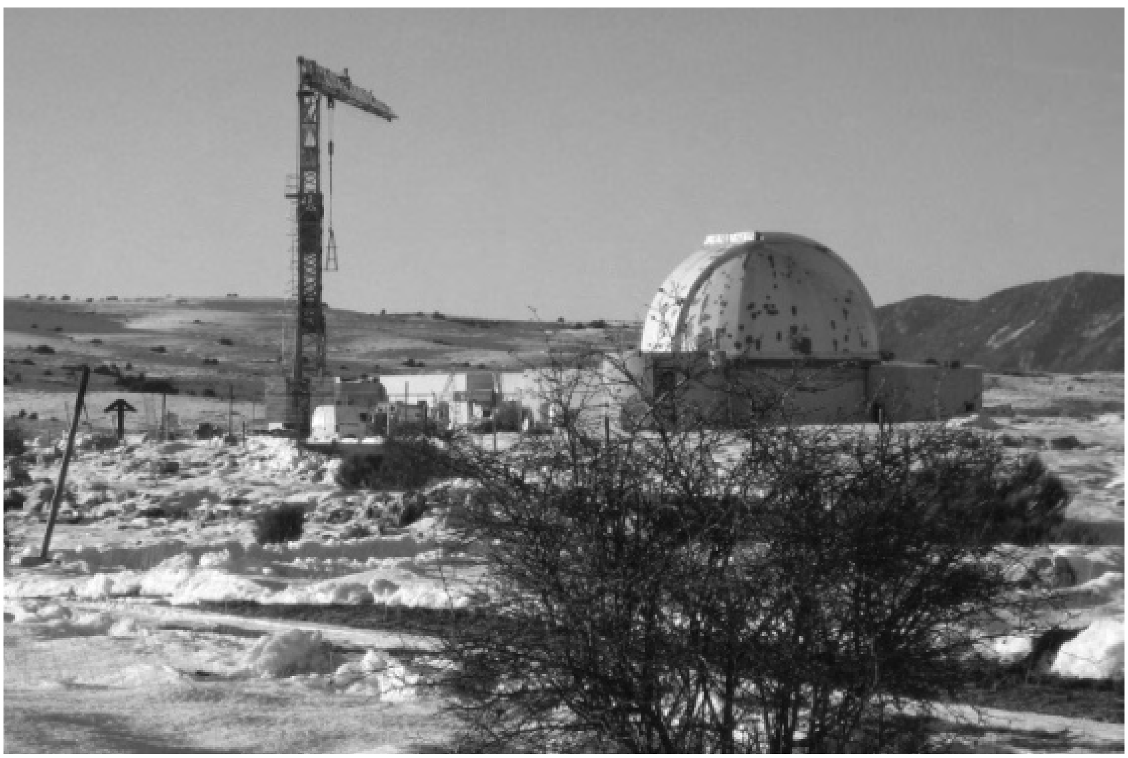

Figure 13-25. LLR and FTLRS laboratories under construction at Grasse (12/2005).

Operations

Ranging to the Moon in 2005

Before operations were stopped in summer 2005, the OCA station performed very well from January to July 2005 with 284 normal points on the Moon. The validated OCA LLR data are still available both through the ILRS data centers and the local OCA Web site with a monthly update. The Paris Observatory Lunar Analysis group is continuously processing the data for studies in Earth rotation, reference frame, and dynamic of the Moon.

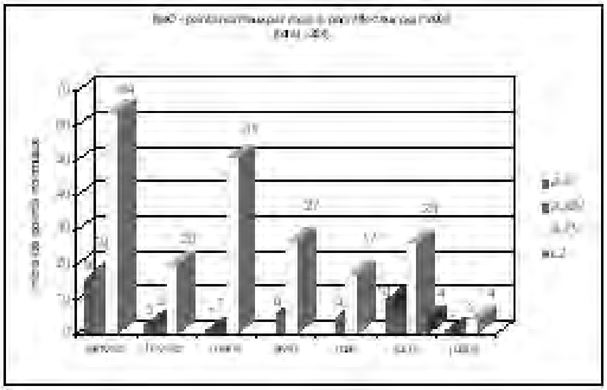

Figure 13-26. Grasse lunar ranging in 2005.

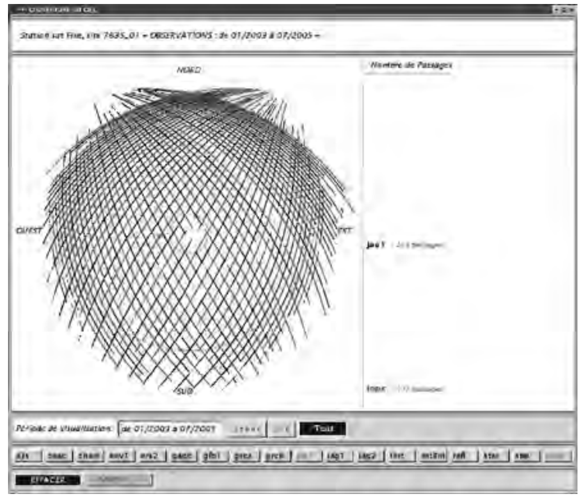

Figure 13-27. Sky coverage for Jason/TOPEX.

FTLRS Jason-1 cal/val campaign in Corsica May-October 2005

- Successful calibration passes: 10
- Total passes: 1719
- Total normal points: 30,000
- Stella, Starlette, LAGEOS-1, -2
- Jason/TOPEX, ERS-2/Envisat
- Bias and stability: at the several mm level
- Number of people on staff: 14
- Very good reliability

Figure 13-28. FTLRS onsite for Jason/TOPEX tracking (with rainbow).

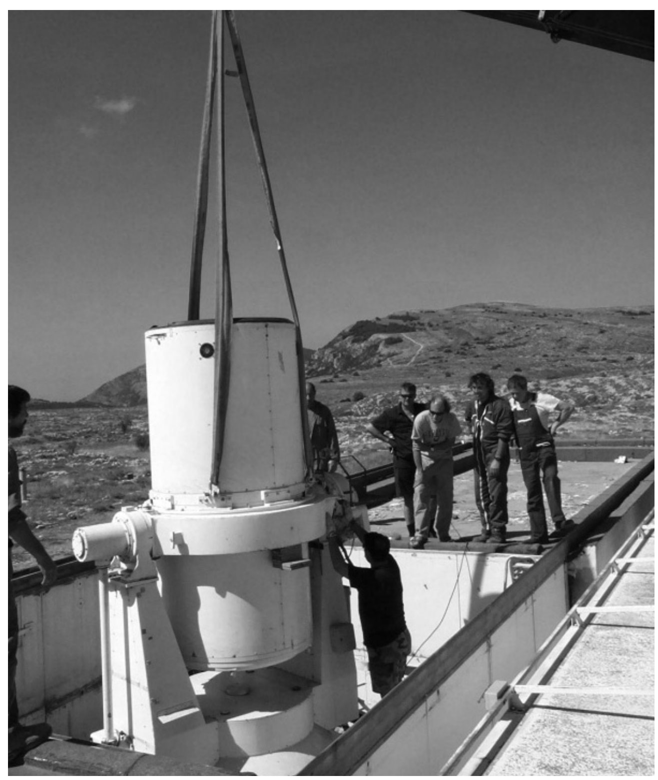

Figure 13-29. Removal of Grasse telescope and mount.

New and Future Developments

Historical SLR station stopped operations

The Grasse SLR station was in service for thirty years with regular upgrades and very fruitful operations, contributing more than 35,000 passes. In September 2005, the telescope and mount were dismantled and temporarily installed in the old trailer waiting for future shipment to South Africa for a space geodesy project.

New laboratory for FTLRS developments and operations replacing old telescope

In place of the old one-meter telescope, we built a new laboratory perfectly suited to host the mobile system between field campaigns. The configuration of the setup has very original features. The group laser/mount/telescope was installed on a platform elevator with two possible positions as shown in Figures 13-30 and 13-31 below.

Figures 13-30-a and -b. Down position in the laboratory to perform technical developments, tuning, and maintenance in good conditions.

Figures 13-31-a and -b. Alternative configuration, 1.40m higher with the roof open and the telescope able to view the sky and to achieve operations on satellites in normal conditions with operator control facilities inside the building.

LLR station renamed to MEO and completely rebuilt

- A new generation laser station:
    - o From 400 km to the Moon
    - o Solar system probes
    - o Highly automated

- Research and development facility:
    - o New optical links
    - o Time transfer experiments
    - o One-way interplanetary missions

The recent and planned technical upgrades (shown in Figures 13-32 and -33) are:

- Buildings and laboratories (June 2006)
- Laser (2006): Integration on new, common optical bench (laser and detection) 20 ps – 200 ps – 1 ns
- Motorization (end 2007): Two torque motors (F = 800 mm___), direct encoders
- Dome (end 2007): Renovation, motorization, and guidance
- Optics (2007): Common optical path and laser commutation

Figure 13-32. Future MEO system.

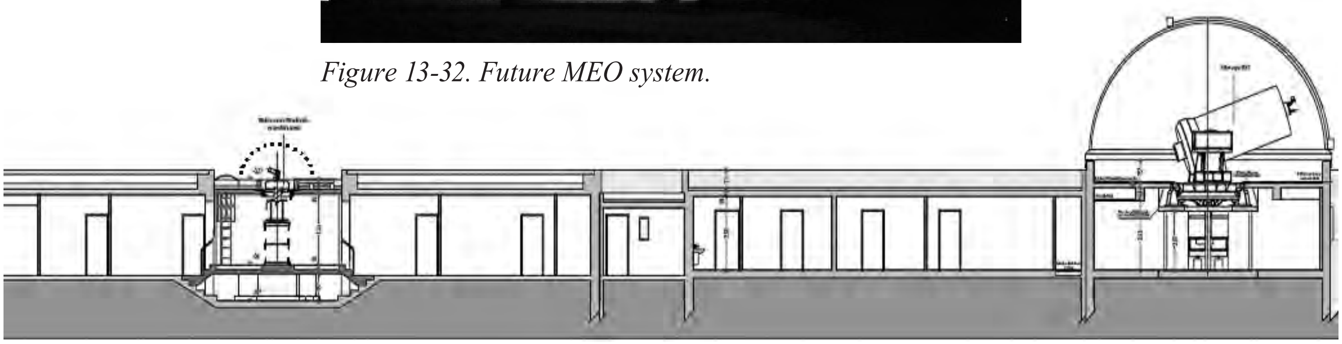

Figure 13-33. Diagram of future MEO system configuration.

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The kHz SLR System in Graz

The Graz kHz SLR station was fully operational during 2005 and 2006; the laser itself operated without major problems. We are still using the same pump diodes (working now for more than 10,000 hours). The selected parameters of the kHz system are still the optimal choice for us:

- 400µJ per pulse: Enough for all satellites up to GLONASS/Etalon/GPS;
- 2000Hz: A very good compromise for hardware (our ET allows maximal 2500 Hz) and software (a standard PC can handle it without problems);
- 10ps pulse width: Allows excellent single shot accuracy, makes single retroreflectors visible, allows determination of satellite spin parameters etc.

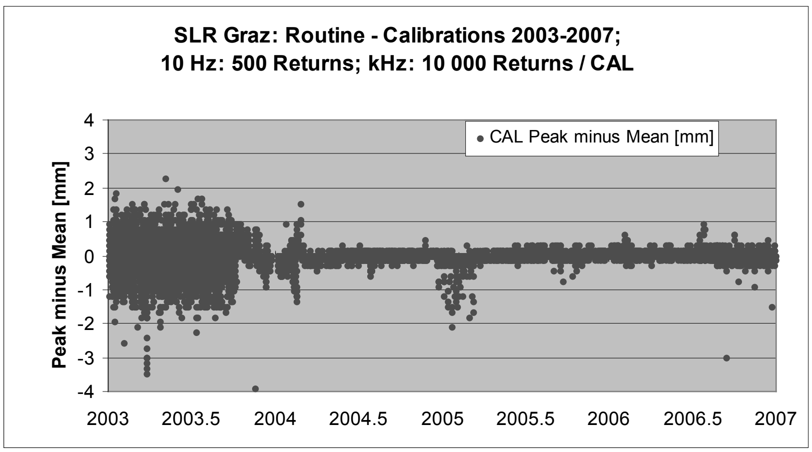

Figure 13-34. The improvement due to switching to kHz laser (end of 2003) is significant.

The stability of the total system — as measured from one calibration to the next, usually in intervals of about 1 hour — is in the order of a few picoseconds; the statistics of the routine kHz calibration of the last years show the improvements in determination of calibration values (Figure 34).

Determination of Satellite Spin Parameters

With the 2 kHz SLR system and 10 ps laser pulses, we are scanning the satellite's surface with good accuracy; this allows us to detect spin parameters of several satellites. Table 13-1 shows a summary of this work. For some of these satellites, kHz SLR is the ONLY technique to determine these spin parameters.

Table 13-1. Satellite with Spin Parameters determined by Graz kHz SLR

Satellite	Spin Period	Remarks
Ajisai	~ 2 s	Spin period, spin direction, spin axis orientation
ANDE-RR	~ 21 s	Spin period
Etalon	~ 66 s	Period only; even with < 0.1 % return rates possible
GP-B	~ 77 s	Spin period, spin direction, spin axis orientation
LAGEOS-1	~ 6000 s	Spin period, spin axis orientation/selected passes

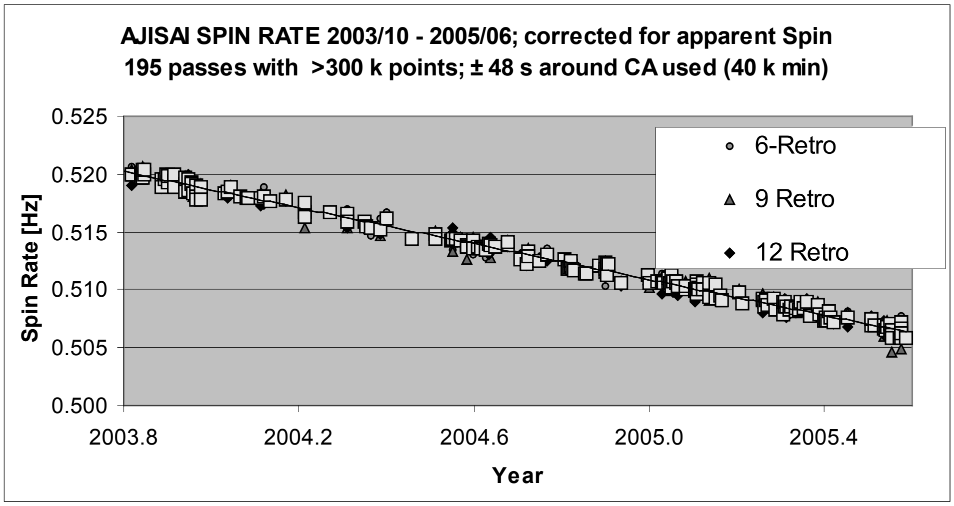

Figure 13-35. Spin rate slow down of Ajisai: -0.0077497 ± 0.000403 Hz/year.

Other work

- "Seeing" values are determined, using laser pointing jitter during actual SLR measurements;
- Using the Hartmann-Shack method, we also measure seeing values, observing UMI Alpha;
- A simple beam monitor records the laser beam pointing stability.

More details can be found in the proceedings of the Canberra 2006 Laser Ranging Workshop.

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Figure 13-36. MOBLAS-7 located at NASA GSFC in Greenbelt, MD.

In 2005-2006, the MOBLAS-7 supplied SLR tracking data from the Goddard Space Flight Center (GSFC) in Greenbelt, Maryland for its 23rd and 24th years.

Data volume decreased significantly in these years due to the budgetary reductions in early 2004. The system now operates a 1 shift, 5 day per week schedule, and in 2005-2006, provided just over 4,600 passes. The system continues to be among the leaders in SLR data quality with an average single shot RMS under 1cm.

Because MOBLAS-7 is the engineering standard for the NASA network, much of the station time in 2005 was utilized for simultaneous tracking for the intercomparison effort supporting the TLRS-4 system upgrade prior to its transfer to Maui, Hawaii. During this time, and for months after the transfer to the summit of Haleakala, the MOBLAS-7 station manager, Maceo Blount, was also tasked to manage the TLRS-4 system. This required additional assistance on the MOBLAS-7 system by current and former HTSI/SLR employees, Jay Steigleman and Grandeville Priest. The MOBLAS-7 crew was instrumental in bringing a high quality SLR system back to the NASA SLR network by determining bias information that may never have been discovered without the NASA co-location technique.

In 2006, MOBLAS-7 was used for testing the SLR2000 prototype system, by tracking satellites as the SLR2000 system received the MOBLAS-7 returns (test of the prototype receiver). This became an essential part of successful ranging efforts from SLR2000 to LAGEOS (for the first time) by the end of 2006.

MOBLAS-7 was also one of the first systems to utilize and test the restricted tracking software designed for a more sophisticated go/nogo safety net for satellites that have sensors too sensitive for laser illumination, such as ICESat and ALOS. Written by Randy Ricklefs of the University of Texas, Center for Space Research, and modified and installed by Michael Heinick of HTSI, all MOBLAS systems were prepared for ICESat and ALOS restricted campaigns in mid-2006.

By the end of 2006, MOBLAS-7, along with our MOBLAS-5 partners, tested the Consolidated Predication Format (CPF) upgrade. All major tracking and processing software are affected by the new prediction format, and therefore will be benchmarked for quality assurance. MOBLAS-7 is the NASA SLR test-bed for all software modifications scheduled for distribution to the NASA systems.

Crew at MOBLAS-7: Maceo Blount

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Figure 13-37. TLRS-4 system located at Haleakala, HI.

After the June 2004 closure and disassembly of the HOLLAS LURE Observatory, located at the Haleakala Observatory on Maui, Hawaii, a great void was left in the global distribution of SLR stations, specifically in the Pacific Region. NASA searched for a way to bring back a critical geodetic SLR data point to the SLR analysis community. In March 2005, NASA Headquarters tasked Goddard Space Flight Center to return the Transportable Laser Ranging System – 4 (TLRS-4) to operational status for the purpose of filling the hole that was left by the absence of the HOLLAS system. The TLRS-4 system had been maintained in caretaker status at the GGAO by HTSI since 1995, where it was often used as a test-bed to support SLR engineering projects. TLRS-4 was also frequently used for spare parts to support operational stations. The system required a major engineering effort to return it to regular operations.

Because the system was used more in support of operational NASA systems, TLRS-4 was inoperable, lacking both hardware and software upgrades that had been installed into other systems in the NASA network. Significant repairs and upgrades were required to every major subsystem of TLRS-4. The laser subsystem required new oscillator and amplifier heads, a solid state pulse slicer, a laser interlock system, a laser collimation lens, dye pump power supply, calibration transmit filter, laser bracket, and a laser warning light. The telescope/optics subsystem required a new 10Å daylight filter, a complete upper deck upgrade, and a disassembly and cleaning and re-alignment of the telescope. The transmit/receive (T/R) subsystem required upgrades or repairs to the T/R switch, the Photek MCP, and low loss receive cable. The computer subsystem required upgrades or replacements to the processing, controller, and administration computers and upgraded Internet communications. The console subsystem required upgrades or replacements to the trackball system, a new tracking scope, and a new HP5370B time interval counter. The timing subsystem required upgrades to the time code generator and auto switch for 4pps, and an updated CNS clock software package. The facility subsystem was upgraded with dome control sensors, weather protection, a new remote operated dome shutter, and complete refurbishment of the instrumentation van and support trailer. The safety subsystem was completely overhauled and coordinated through GSFC Code 250 for laser safety compliance.

In July 2005, following all system upgrades and repairs, HTSI began system operations verification tests (SOVTs) for each subsystem. SOVTs historically have been performed on all NASA systems subsequent to each relocation and prior to any laser system beginning operational support. All TLRS-4 SOVTs were successfully completed on July 15, 2005.

The TLRS-4 was then co-located with MOBLAS-7 with analysis performed using POLYQUICK and by orbit comparisons using GEODYN. NASA has been using this verification method since the mid 1980's to validate new or modified systems.

The TLRS-4/MOBLAS-7 intercomparison produced some of the best intercomparison results ever achieved by a NASA system. The TLRS-4 system exceeded every intercomparison requirement, and the TLRS-4 to MOBLAS-7 bias offset far exceeded the +/-15 mm bias requirement. The TLRS-4 system was declared an operational system on September 15th, 2005, after the NASA Operational Readiness Review, which included a panel of experts. TLRS-4 was deployed to Maui, Hawaii on April 19th, 2006 and was then moved to the summit of Mt. Haleakala on September 7th, 2006, to a site within 60 meters of the old HOLLAS site. Prior to the occupation, modifications were made to the station pad, and calibration piers were installed. After station setup in late September, a survey was performed with site tie measurements to the former HOLLAS station and GPS sites. A new SOVT was then performed to validate operability following the move to the new location.

TLRS-4 achieved first data on October 23rd, 2006, and by the end of 2006 had ranged to over 154 passes. Maceo Blount, from HTSI, left the island in the middle of November 2006, and turned the system operations over to the University of Hawaii Institute for Astronomy. The station manager, Craig Forman, and Jake Kamibayashi, working with Dan O'Gara, resumed SLR operations at the Haleakala Observatory.

On January 28th, 2007, a ceremony was performed in the tradition of the Hawaiian Islands to bless the TLRS-4 system, and to celebrate the return of NASA SLR to the Pacific Region.

Figure 13-38. Blessing of the TLRS-4 system.

Figure 13-39. NASA presentation to the University of Hawaii, Institute for Astronomy.

Figure 13-40. ILRS presentation to the University of Hawaii, Institute for Astronomy.

Crew at TLRS-3: Craig Foreman (Station Manager), Jake Kamibayashi

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The MOBLAS-6 satellite laser ranging activities started at Hartebeeshoek Radio Astronomy Observatory (HartRAO) in 2001 in collaboration with NASA; the system is shown in Figure 13-41.

MOBLAS-6

The MOBLAS-6 satellite laser ranging capability is 24-hour 5-day and 8-hour 2-day per week and is ranked among the global SLR leaders in terms of providing high quality and volume data on a consistent basis. The station crew at MOBLAS-6 is: Johan Bernhardt (station manager), Willy Moralo, Sammy Tshefu, and Gert Agenbag (student).

Figure 13-41. MOBLAS-6 located at Hartebeeshoek Radio Astronomy Observatory in South Africa.

Upgrades

The following upgrades were performed during 2005-2006:

- Old administration computer and printer replaced with new ones
- Telescope boom anti-interference mechanism installed to prevent cable and boom obstructing laser beam path
- Sun shutter installed on CCTV camera
- Device installed to monitor laser clean room access
- New amplifier-head assembly installed on laser table

Repairs

The following repairs were performed during 2005-2006:

- Burned amplifier rod replaced
- Faulty telescope roof-top wheels replaced
- Batteries for UPS and timing systems replaced
- Laser system and telescope steer electronics repaired

A preventative maintenance and upgrade plan implemented during the past two years has reduced equipment failures and repair times. Despite the degradation in weather conditions over the last two years, MOBLAS-6 has maintained its high volume of data output (see Figure 13-42).

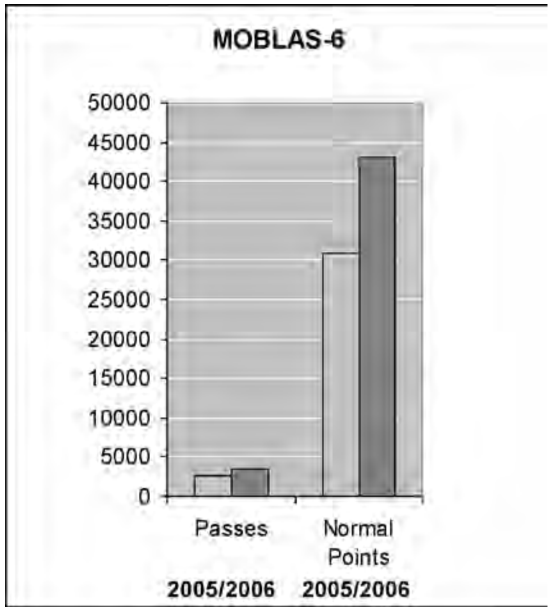

Figure 13-42. MOBLAS-6 station performance for 2005 and 2006.

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Helwan, Egypt

Makram Ibrahim, Magdy El-Saftawy, Makram Ibrahim Khalil Ibrahim/NRIAG

Satellite laser ranging activities commenced at Helwan (National Research Institute of Astronomy and Geophysics, NRIAG) with the cooperation of the Czech Technical University of Prague (TUP), the Russian Academy of Sciences (RAS), and the Smithsonian Astrophysical Observatory (SAO) in 1974. The Helwan satellite laser ranging station is part of the Space Research Laboratory of the NRIAG.

The TUP group operated the Helwan station until 1997. Since the beginning of 1998, the station has been operated by the Egyptian scientists with technical help from TUP. During 1999, there were 1,391 observed passes on low orbiting satellites as well as for LAGEOS-1 and -2. In 2000, there were 426 observed passes and in 2001, there were 140 observed passes. The total number of passes of the satellites observed during 2004 and 2005 are 163 and 360 respectively. There were only 18 satellite passes observed during 2006 due to the preparations of the station for external modifications.

Helwan SLR Station Staff

- Associate Prof. Dr. Khalil Ibrahim Khalil, head of Space Science Laboratory
- Associate Prof. Dr. Magdy El-Saftawy, principal chief of the Helwan SLR station; now teaching at a university in Saudi Arabia
- Associate Prof. Dr. Makram Ibrahim Khalil Ibrahim; principal chief of the Helwan SLR station
- Mr. Hany Mahmoud Mohamed, Assistant Researcher
- Mr. Abd El-Rahman Ahmed, Electric Engineering
- Mr. Mohamed Yehya, scientific staff
- Mr. Sami Fath-allah, technician

Figure 13-43. The staff of the Helwan SLR station (from left to right) Dr. Magdy El-Saftawy, Dr. Makram Ibrahim, Mr. Mohamed Yehya, Mr. Sami Fath-allah, Mr. AbdEl-Rahman Ahmed, and Dr. Khalil Ibrahim Khalil

Figure 13-44. Czech colleagues who work with the Egyptian staff at the Helwan SLR station (from left to right): Dr. Antonin Novotny, Dr. Miroslav Cech, Dr. Helina Jelinkova, Dr. Ivan Prochazka, Dr. Josef Blazei, and Dr. Petr Matlas.

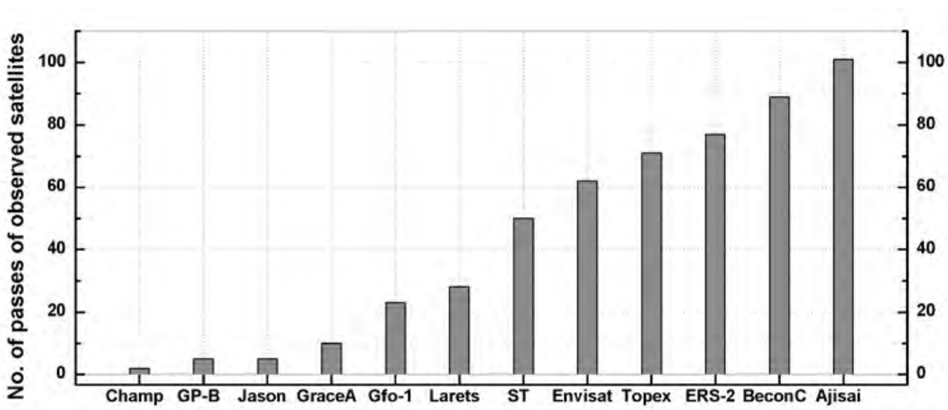

Figure 13-45. The total number of observed satellite passes during 2004 and 2005.

Figure 13-46-a, -b, -c. Telescope mount, power supplies for the laser, and station control room.

Recent Upgrades

Some recent modifications have been applied to the station:

- The roof of the station is motorized to be opened and closed via the remote control. TUP provided funding for this activity.
- The outside of the building has been modified, improving its external appearance.

Future Plans

The Hamamatsu H6533 PMT box with PMT tube 4998 has been used in the Helwan system since 1998. This component consists of a PMT tube and a high voltage (HV) supply with precise divider. The Tennelec TC 952A high voltage power supply with stable 2500 volts is used as a source for the PMT, to obtain standard parameters. An EG&G Ortec 1GHz pre-amplifier Model 9306 is used as a four-stage preamplifier. Due to the extended use of this PMT, its sensitivity had been decreased and thus a PMT change will soon be required.

Equally important are the three power supplies for the laser oscillator and amplifiers. These power supplies are very old and we often experience problems. Changing these power supplies are an important future task.

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Space Geodesy Facility (SGF), Herstmonceux, UK

Philip Gibbs, David Benham, Christopher Potter, Robert Sherwood, Vicki Smith, Matthew Wilkinson, Graham Appleby/NSGF

Introduction

This report lists the main achievements at SGF during the last two years. Besides outlining work on the laser ranging upgrade program, we also discuss the GNSS, gravimeter, and LIDAR activities at the station.

Satellite Laser Ranging

'Standard' SLR activities

The Herstmonceux station remains extremely productive, with good tracking coverage of all the ILRS priority targets. Operations are scheduled on a seven-days-a-week basis, with shifts arranged around pass times of the major geodetic and altimeter satellites. Prior to the GIOVE-A campaign organized by ESA and the ILRS in June 2006, SGF was asked by the prime contractor (SSTL, UK) to attempt ranging; first returns were obtained in April 2006, as detailed in the Inside GNSS report from SGF at *http://ilrs.gsfc.nasa.gov/docs/IG0606-appleby-v2GG2.pdf*.

Progress towards kHz rate ranging

A bid for laser upgrade funding was successful and in early 2005 a 2kHz, 10ps pulse-length laser was purchased and mechanically and optically integrated. Additionally, an accurate event timer (HxET) was assembled in-house and integrated into the operational 10Hz system by August 2006. This step permitted a re-calibration of the pre-HxET measurements over the entire range of from a few meters for the calibration targets out to 23,000 km for GIOVE-A. As a result, we have characterized the illusive non-linear behavior of our Stanford counters at the short ranges to the local targets, and showed that all SGF satellite ranges over the period 1994 to date are short by 8.5±2 mm, in addition to the satellite-dependent range corrections announced in January 2002 in SLRMail 0891. This bias will disappear, of course, once the HxET is in routine use at a date to be determined in early 2007 and announced to the community. Rapid progress has since been made to achieve experimental laser ranging at 2,000 shots per second, with ranges to all the major satellites obtained by early October 2006. The radar and manual interrupts have been fully integrated and work is ongoing to include the automatic eye-safe control for calibration ranging and to develop a robust pre-processing system that will not insert a discontinuity into the Herstmonceux data. It will also be necessary to develop a camera system to view the fainter kHz laser backscatter during daytime to optimize pointing.

Local target

Range observations using the HxET to the in-dome calibration target provide for the first time, and at a level of accuracy of 1mm, an independent check on the standard range calibration value derived from the external calibration target. Non-linearities present in the Stanford counters had previously confused this issue, despite our confidence in the target surveys.

GNSS

The HERS and HERT IGS stations continue in routine continuous operation, with HERT also configured for Internet streaming in support of the expanding EUREF real-time GNSS over Internet Pilot Project. More worrisome was the apparent lack of use within IGS analysis centers of these systems for routine daily ITRF and EOP work, despite their current demonstrably good performance. However, a recent communication from the IGS does show that at least two IGS analysis centers currently process data from both systems.

Gravimetry

In collaboration with the Proudman Oceanographic Laboratory and University College London, SGF has purchased an FG5 absolute gravimeter (AG). The instrument, shown in Figure 13-47 is installed in an existing, refurbished basement at the facility, and has been fully operational since mid-October 2006. A measurement campaign is underway to produce mean gravity values at mid-GPS-week intervals. An example of the hourly mean-value results is shown in the plot in Figure 13-48 below; daily mean values have 1-sigma standard errors of about 1_gal, equivalent to a height change sensitivity of better than 4mm.

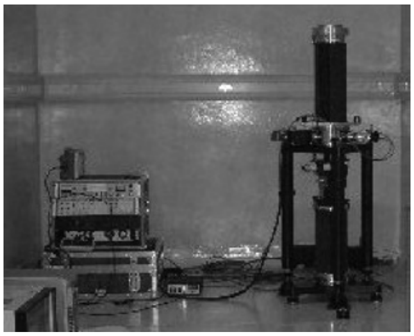

Figure 13-47. FG5 absolute gravimeter in its basement laboratory.

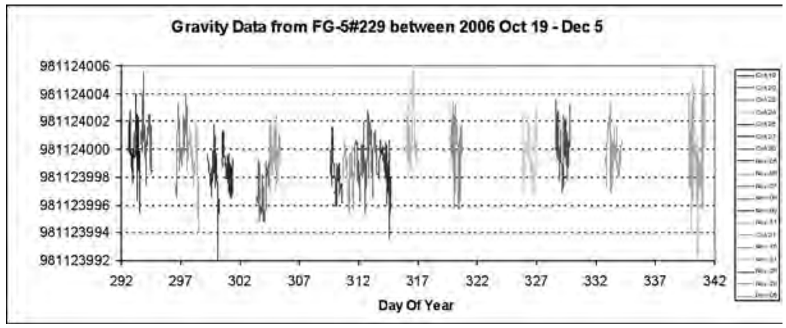

Figure 13-48. Hourly mean-value results from Herstmonceux absolute gravimeter.

LIDAR

Software has been written to enable collection and analysis of atmospheric backscatter observations during short, dedicated LIDAR observing sessions. The software moves the C-SPAD gate from close-range up to the tropopause, at a height of approximately 12km. Initial results are encouraging in terms of detection of haze and boundary layers, and plans are underway to develop a dedicated, PMT-based system that will work simultaneously with standard SLR observing. Laser ranging through aircraft contrails and cirrus, which looks to be a promising and novel way of estimating their optical densities, will also be pursued.

Staffing

Shown in the picture in Figures 13-49 are members of the team marking David Benham's formal (but temporary) retirement.

Figure 13-49. SGF staff members attending David Benham's retirement celebration.

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Katzively, Ukraine

Yury Kokurin/Crimean Laser Observatory Main Astronomical Observatory of the National Academy of Sciences of Ukraine

The Katzively Laser Ranging station (number 1893) began second-generation operations on LAGEOS in August 1984. Over the next several years, efforts were undertaken to improve station performance to a level necessary for ranging to the Moon. Unfortunately, due to financial and technical difficulties this work was stopped in 1990. Routine observations of satellites resumed in 1988 and continue today. In 1990, the Katzively station began operations with an upgraded system giving a single-shot RMS of about 5cm and a normal point accuracy of 1-2cm.

Figure 13-50. The Katzively SLR station.

In 2006, the station was operational with the following laser transmitter configuration:

- Wavelength of radiation 532nm;
- Pulse duration: ≤ 200ps;
- Pulse energy: ≈ 100mJ;
- Beam diameter: 8mm;
- Divergence 3.5 angular minutes;
- Pulses repetition rate: 3-10Hz.

RMS analysis was performed on LAGEOS-1 and -2 2005-2006 normal point data from the CDDIS; 94% of these data were used in the analysis. As seen in Figure 13-51, the average RMS value was 15.9±8.5 in 2005 and 13.7±6.0 mm in 2006. Improvement is the result of upgrading the laser transmitter characteristics.

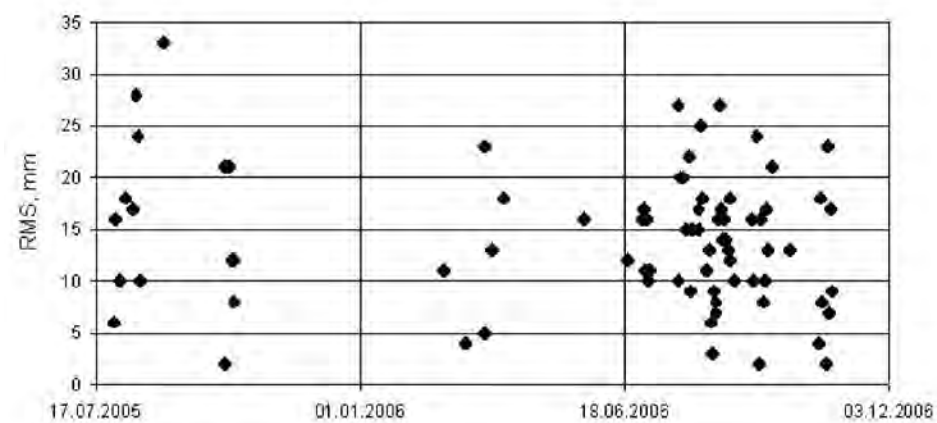

Figure 13-51. RMS analysis on LAGEOS-1 and -2 data from Katzively.

In 2005, the surface of the telescope mirror was also re-aluminized. The photo in Figure 13-52 shows the installation of the mirror; the photo Figure 13-53 shows the mirror after the recoating process.

During 2005-2006 the station crew was expanded to increase observing time and, as a consequence, the quantity of observations. At the same time the question with qualified personnel is an issue due to station personnel turnover. The station tracked 971 satellites passes with 14,850 normal points.

Figure 13-52. Installation of mirror.

Figure 13-53. Mirror in box after transportation.

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During 2006, all systems on the station were modernized. The new laser system was modified with the following parameters:

- semitrain oscillation
- pulse duration - 50ps
- output energy at 532nm - 15mJ
- repetition rate - 10Hz

The new time "gate" was installed with a resolution 20ns. Efforts with a new receiving channel continue. A new receiving telescope was placed on the main telescope (see Figure 13-55 below). The calibration result is 300ps RMS (with old PMT FEU-79). An improved PMT is undergoing testing. A new guide system has been tested. It is now possible to observe sky objects with magnitude 14 with this system. Our system is now ready for the routine ranging operations.

Figure 13-54. The main telescope with guide and receiving telescope in dome.

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Kunming, China

Xiong Yaoheng, Zheng Xiangming, Fu Honglin/Yunnan Observatory

The Kunming station, operational from 1998 through March 2003, utilized a 1.2 meter telescope and had the following characteristics:

- Telescope mounting: alt-az
- Focus: Coudé focus afocal + an imaging lens
- Field of view: 3´
- Axis accuracy: < 1¨
- Pointing accuracy: ± 1¨
- Drive mode: torque motor through friction disk for az. directly for alt.
- Tracking accuracy: ±1¨

The Kunming station has undergone a system upgrade from mid-2003 through 2006. The new system utilizes the 1.2m telescope (shown in Figure 13-55) and has the following components:

- Drive and servo-control system (accuracy ~10¨ for racking LEO satellites)
- Acquisition and tracking system (detected star for close loop M=8m.0)
- Slit-ring
- Optical system
    - o Primary mirror accuracy: l /20 rms
    - o Secondary mirror accuracy: l/40 rms
- Tip-tilt tracking system
- Telescope dome
- Optical benches
    - o SLR (3.5m¥1.5m)
    - o LLR (3.5m¥1.8m)
    - o Adaptive optics (3m¥1.8m)
    - o Image processing (3m¥1.5m)

The 1.2m Kunming laser ranging system characteristics:

- Range: 400 ~ 20,000km
- Accuracy: ±3cm
- Nd:YAG Laser: 532nm,50-80mj/p,200ps,1-4Hz
- Timing: GPS
- Timing interval counter: SR620
- Detector: SPAD
- Low efficiency detector, unstable laser power

Plans are to resume operations of the Kunming station in 2007 using a low efficiency detector and unstable laser power, which will hopefully be upgraded in the future.

A series of Chinese lunar missions are planned, starting with the launch of a satellite orbiting the moon in 2007. Later stages include installation of a retroreflector array on the moon (2012). The refurbished Kunming station

(Figure 13-56) plans to be part of these activities by submitting a proposal to the Chinese National Science Foundation for performing further upgrades to permit lunar ranging. The proposal would include the following upgraded components:

- Laser upgrade: 0.05j/p_2j/p, 5-7ns, 8Hz
- Event timer
- New SPAD
- Local Telescope Pointing Model: ± 1≤
- Filtering (spectral, spatial, temporal)
- Compensation laser beam on LLR

We propose to test the system by conducting experimental ranging to the Apollo 15 retroreflectors with an accuracy of 20cm.

Figure 13-55. Kunming telescope.

Figure 13-56. New Kunming SLR system facility.

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During 2005-2006 the station acquired 550 satellite passes (138 LAGEOS passes) with the corresponding mean accuracies: 14.1mm calibration, 48.8mm LEO, 53.9mm LAGEOS [1].

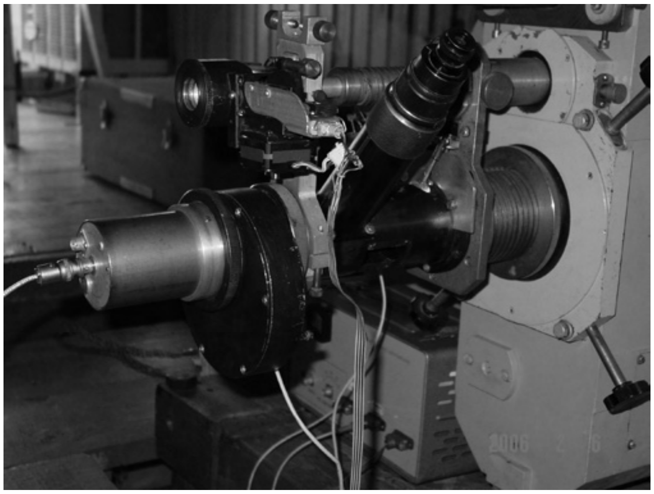

Figure 13-57. Modernized receive channel.

Figure 13-58. Modernized telescope finder "Uran-9".

During this time, partial equipment modernization and upgrades were performed (shown in Figures 13-57 and 13-58):

- A neutral filters block was developed and produced. We can now perform some tests and work on its mounting in the receive channel of the telescope.
- A new rotating shutter, with a dead time of about 5ms, was developed.
- Work on the installation of a new PMT H6780-20 (Hamamatsu).
- Upgrade of meteorological station. We now use a new computerized met-station WS-3600.
- Continue work on the software updates and modernization [2].
- In 2006, we conducted a complex research of the telescope optical-mechanical systems. This allowed us to improve tracking capabilities. We will now perform test tracking of satellites not illuminated by the Sun (evening and night tracking).
- The standard telescope finder was changed to a fast lens objective equipped with a LCL902K CCD TV camera. It is used as a wide field telescope and as well as other goals, e.g., positional observations, etc.

In the near future we plan to purchase a new modern event timer (currently we use the timer A911 developed by Latvian University). At the same time we plan to modernize our receiving system by replacing rotating mirrors with a system of fixed optics.

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1. ILRS Global Report Cards, *http://ilrs.gsfc.nasa.gov/reports*.
2. Bilinsky A., Melekh B. Control of the laser ranger in Real-time Linux, "Problems of the control and informatics", 2 (2005), p.103-106 (in Russian).

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Matera, Italy

Giuseppe Bianco/ASI

During the years 2005-2006, the MLRO (Matera Laser Ranging Observatory) has, for the most part, been in a routine operations phase. The photograph below shows the current MLRO engineering and operations crew.

Figure 13-59. MLRO operations and engineering staff.

Unfortunately, due to financial constrains starting in January 2006, the MLRO has not been operating a weekend shift. The same financial difficulties have caused several problems, such as preventing or delaying the procurement of a number of crucial spare parts, including a new photomultiplier, laser optics, electronic components, etc. As a result, the overall efficiency of the system has decreased significantly, not permitting lunar observations to be carried out. At the end of 2006 a new MCP/PMT was received from Photek, and a new solid state laser seeder was ordered from High-Q Lasers Austria. Finally, the 1.5 m main mirror of the MLRO telescope will soon require recoating.

Other than routine SLR operations, the MLRO has been involved in an interesting optical telecommunication experiment in cooperation with the Universities of Vienna and Padova, whose results have recently been submitted for publication.

In spite of the financial limitations and the reduced observing time, the data production of MLRO has been relatively good, particularly in the year 2006, as shown in the following table which reports, for each satellite, the number of tracked passes as well as the number of normal points produced in years 2005 and 2006.

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Table 13-2. MLRO Data Production for 2005-2006

		2005		2006	
Satellite	SIC	**# Passes**	**# NPs**	**# Passes**	**# NPs**
Beacon-C	317	402	1247	359	6894
Etalon-1	525	22	60	69	348
Stella	643	129	130	173	1274
Starlette	1134	445	603	509	4687
LAGEOS-1	1155	354	573	525	4635
Ajisai	1500	609	1275	615	8414
OICETS	1578			1	9
GPS-35	3535	2	14	5	18
GPS-36	3636	2	4	5	16
Etalon-2	4146	29	71	94	526
TOPEX	4377	393	484		
Jason-1	4378	326	1407	299	6013
METEOR-3M	5555				
Larets	5557	69	54	120	657
LAGEOS-2	5986	383	668	553	5305
ERS-2	6178	136	359	190	2683
Envisat	6179	140	319	196	2603
GIOVE A	7001			18	101
CHAMP	8002	10	10	13	127
GRACE-A	8003	13	43	21	338
GRACE-B	8004	20	112	49	815
GFO-1	8501	98	250	168	2036
GP-B	8603	35	128	15	124
GLONASS-84	9084	21	0		
GLONASS-87	9087	30	40	62	328
GLONASS-89	9089	26	34	42	193
GLONASS-84	9095	3	8	6	24
Totals		3697	7893	4107	48168

McDonald Laser Ranging Station (MLRS)

Peter Shelus/University of Texas at Austin, CSR

The McDonald Laser Ranging Station (MLRS) is located at McDonald Observatory in the Davis Mountains of west Texas, near the town of Fort Davis (USA). In addition to its artificial satellite laser ranging (SLR) responsibilities, the station continues its lunar laser ranging (LLR) activities as a part of the ILRS laser ranging network. It is one of only two laser ranging stations in the world that has had routine LLR activity over the past several years. SLR funding continues to be provided through an operations contract from NASA and LLR support comes from the National Science Foundation. NASA support for LLR was discontinued several years ago. LLR data volume from the MLRS continues to be less than optimal, due to the reduction in manpower that has been forced by a sequence of funding cuts. In addition, the station is showing its age with many components suffering from failure and degradation. The station is in need of serious upgrade and refurbishment. Activity is directed toward keeping the station operational and in a data-gathering mode. All MLRS LLR data are available through the data centers of the ILRS. These data are transmitted to the data centers in near real-time, using standard laser ranging formats.

Peter J. Shelus serves as the Project Manager for the MLRS. Mr. Randall L. Ricklefs is the Software Manager and Mr. Jerry R. Wiant is the Project Engineer. Mr. Windell L. Williams, a member of LLR operations at McDonald Observatory since the late 1960's has retired. Mr. Kenny T. Harned and Mr. Anthony R. Garcia, observers, are each partially funded for LLR operations by the NSF Grant. Ms. Rachel M. Green serves as a part-time Technical Assistant.

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Metsähovi, Finland

Markku Poutanen/Finnish Geodetic Institute

The Metsähovi research station was founded in the mid-1970s, and over the years it has become an essential part of the activities of the Finnish Geodetic Institute. The instrumentation of the station serves both the Institute's own research and the international scientific community. The following instruments are currently installed at the Metsähovi research station: satellite laser ranging (SLR), geodetic Very Long Baseline Interferometry (VLBI) in co-operation with the Helsinki University of Technology, GPS and GLONASS receivers, DORIS beacon, and a superconducting gravimeter. Absolute gravity is regularly measured in the gravimetric laboratory where the national reference point of gravity exists. The University of Helsinki also operates a seismometer at the site. Metsähovi is one of the few fundamental stations in the world where all major geodetic observing instruments are installed in the same site.

The original satellite laser ranging system, operational through the middle of 2005, was acquired in 1994. It consisted of a 1-meter telescope, made by the University of Latvia in Riga, and a mode-locked Nd:YAG laser with less than 50 ps pulse length. Ranging data showed a precision of about ± 20 mm. The system was designed and constructed by the late Dr. Matti Paunonen. Maintenance of the old system became more and more difficult and in 2005 a decision was made to replace the laser with a more modern one.

Renewal of the laser was started in mid-2005 and therefore observations were possible only during the first half of the year. The plan was to make a temporary improvement in the system until a new laser could be procured. Discussions with Georg Kirchner of the Graz Lustbühel Observatory led to a new solution: the old Graz laser was transferred to Metsähovi. This renewal process, however, was delayed because the person in-charge became ill and was unavailable.

Due to the unexpected delay, the Finnish Geodetic Institute decided to advance the planned purchase of a modern kHz laser. A contract was made with the High Q Laser Production GmbH of Austria in mid-2006. A diode-pumped Nd:VAN solid-state laser with the pulse rate up to 2kHz and the pulse energy > 0.5mJ is now on order. This laser is the same type that Graz and Herstmonceux are currently using.

The installation of the new laser will begin in the first half of the year 2007 with a new person hired in Metsähovi. Some modifications of the telescope, and renewal of timing and control systems are needed but we hope to return to operational status before the end of 2007.

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Monument Peak, CA

David Carter/NASA GSFC, Julie Horvath and Scott Wetzel/HTSI

Figure 13-60. MOBLAS-4 located on Monument Peak, CA.

Figure 13-61. DORIS antenna and monument located near MOBLAS-4.

In 2005 and 2006, MOBLAS-4, located on Monument Peak, Mt. Laguna, California, provided SLR tracking from for its 22nd and 23rd years. After the NASA funding cuts of 2004, the MOBLAS-4 operating schedule was reduced to a 3 shift, 5 days per week basis. MOBLAS-4 has continued to be a major contributor to the ILRS with over 10,800 high quality passes for these years.

During 2005, Ken Tribble assumed responsibility for MOBLAS-4 as the new station manager, and immediately began coordinating significant efforts to bring new capabilities to the site on Monument Peak. After the Goldstone DORIS site was closed due to lack of facility support, the DORIS network coordinator selected Monument Peak as the new location to host the DORIS antenna instrument because it resides in the same deformation zone of the San Andreas Fault as the Goldstone site, and also because of the good relationship between the DORIS and SLR networks.

The EarthScope project from the University of California at San Diego (UCSD) also expanded their existing experiments at the Monument Peak site about the same time that the DORIS construction began and construction for both efforts were completed in November 2005. MOBLAS-4 was surveyed as a result of the new construction, and a site tie was developed to the new DORIS hardware.

Also in 2005, the MOBLAS-4 received permission from the High Performance Wireless Research and Educational Network (HPWREN) to connect the MOBLAS-4 computers to their high-speed wireless network. This increased the Internet connection bandwidth of the system from 56 kilobytes/per second to multi-megabit levels.

In the middle of 2006, all NASA systems, including the MOBLAS-4, received a significant upgrade to their software system with the restricted tracking module; MOBLAS-4 was a major contributor to both the regular ICESat "laser turn-on" campaigns and the two ALOS campaigns in August and September of 2006.

Crew at MOBLAS-4: Ken Tribble (Station Manager), Ted Doroski, Ron Sebeny.

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Mount Stromlo, Australia

Chris Moore/EOS Space Systems Pty Ltd, Gary Johnston/Geoscience Australia

The Mt. Stromlo Space Research Center is a fundamental space geodesy site that currently consists of a high precision satellite laser ranging (SLR) station based on a 1m aperture telescope, and an experimental facility based on a 1.8m aperture telescope. The site is also home to IGS GPS and IGLOS GLONASS receivers, an IDS DORIS beacon, and a comprehensive local tie network.

Mt. Stromlo SLR Station (STL3, 7825)

Since the last report, the rebuilt Mt. Stromlo SLR station completed acceptance tests to the standard required under the contract to Geoscience Australia (GA) and has now been operating continuously since September 2004. It has contributed in excess of 7,000 passes per year, making it one of the most productive SLR stations.

Figure 13-62 shows a comparison of productivity from the original station (from primarily automated operations) and the new station (from manual operations). The current station has obtained data from at least 74% of all possible passes (i.e., during good weather, etc.) and at least 87% from all passes attempted.

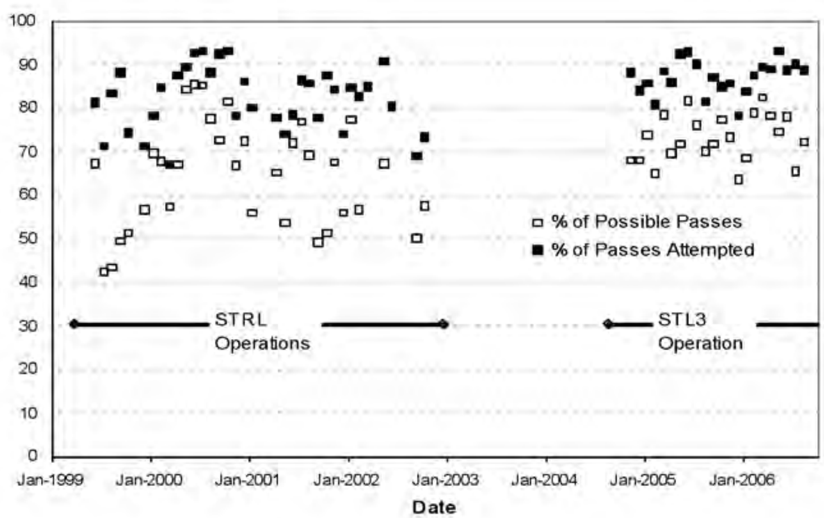

Figure 13-62. Productivity at Mt. Stromlo from the original and rebuilt SLR stations.

The current configuration of the Mt. Stromlo SLR station includes:

- 1.0 meter confocal paraboloid (Mersenne) telescope on Alt/Az mount, by EOS Technologies Inc. (EOST), Tucson AZ. Telescope pointing precision assessed by Star Calibrations is 0.9 seconds of arc with short-term prediction accuracy of 2.4 arcseconds
- PESO Consulting CSPAD with internally compensated time-walk
- passively mode-locked 100 MHz laser oscillator of EOS design, selected and amplified to 13 mJ at 30 Hz of 10 ps pulses at 532 nm
- event timing card to EOS design, 0.7 ps resolution, 5 ps precision
- fully enclosed Typhoon dome

Since 2004, the new station has been operated in manual mode while the capability for full autonomous operations was being developed. It is expected that the transition to fully automated operation will occur during 2007. At the same time, an increase in laser power by a factor of 2-3 is planned. This will be accomplished by modification to the laser and increasing the fire rate to 100Hz.

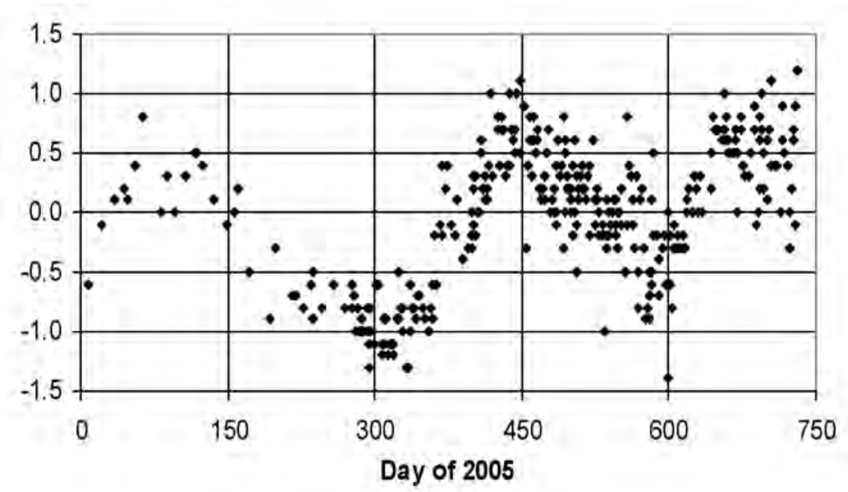

Figure 13-63. Calibration data from the NE cal target.

Stability of the timing and laser systems in the new station has been excellent. Calibration (single shot) rms is approximately 3mm while averages show less than 0.5mm scatter over short-term periods. This level of noise has allowed longer-term trends in calibration data to be identified, as shown in Figure 13-64. Trends of up to 1mm per year are currently being investigated (Luck 2006).

Mt. Stromlo Experimental Ranging Station (STRK, 7826)

A few months after the January 2003 firestorm, EOS completed the installation of a 1.8 meter EOST Az/El telescope in an IceStorm dome, the first stage of an experimental site that now includes finder telescopes for visually tracking space debris, a high energy laser for ranging to debris, and facilities for the development of guide star and ablation lasers (see *http://www.eos-aus.com* for more information). Also part of this system is an 8m high Differential Image Motion Monitor (DIMM) tower for measuring atmospheric seeing.

During 2006 the 1.8m system was used for investigating the potential for lunar laser ranging, initially assessing lunar predictions based on the new consolidated prediction format.

GNSS

The GPS site at Mt. Stromlo (STR1) continues to provide a variety of data products to the IGS including real time 1Hz data for a real time pilot project. A second GPS pillar has been installed awaiting the fit out of a new GNSS receiver/antenna set as backup to STR1 as recommended by IGS. The GLONASS receiver (STR2) continues to provide data to the IGLOS project under IGS.
Local Tie Survey

A full local tie survey was completed in 2006 including the connection to the 1.8m telescope and the new GPS mount. A report detailing the surveying is in preparation.

Gravimetry

The Japanese superconducting gravimeter installed in a basement at the Australian National University's Mt. Stromlo Observatory continues to operate in its old location. GA is planning to construct a special-purpose building in the hillside only a few dozen meters from the Stromlo SLR, capable of holding six absolute and one superconducting gravimeters. An FG5 machine from Kyoto University made some measurements at Mt. Stromlo in Feb/Mar 2004, and made comparisons in Canberra with Geoscience Australia's A10 roving absolute gravimeter. There were no occupations of the gravimetry hut at Yarragadee during the reporting period.

15th International Laser Ranging Workshop

EOS, GA, and the Mt. Stromlo SLR staff were involved in organizing and hosting the 15th International Laser Ranging Workshop, which was held in Canberra October 15-20 2006. The workshop included a visit to the Mt. Stromlo Space Research Center. The photograph in Figure 13-60 shows the workshop participants outside the Canberra Convention center.

Figure 13-64. Participants in the 15th International Laser Ranging Workshop.

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Figure 13-65. Nighttime view of station 7841 Potsdam in operation.

The Potsdam system (station 7841) has undergone routine operations during the period of 2005 through 2006 with emphasis on the tracking of LEO and LAGEOS satellites. More than 2,300 passes were obtained both in 2005 and 2006 under day and nighttime conditions. The use of the A031-ET event timer from the Latvian State University in Riga has considerably improved the ranging stability.

Besides the operation of the 7841 SLR system, GFZ Potsdam also supports the use of low-signature laser retroreflector arrays on LEO satellite missions. The LRRA for the German radar mission TerraSAR-X was built and qualified under supervision of GFZ in 2005. The 4-prism reflector of the CHAMP/GRACE type has been integrated into the spacecraft expecting launch in 2007. A similar array is under consideration for the upcoming radar satellite TanDEM-X due for launch in 2009.

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Main Activities (2005-2006)

Routine efforts in Riga resulted in the following achievements:

- In the year 2005 during 166 clear days-nights 1,791 passes were obtained, yielding a total of 2,389,235 data points from 18 satellites forming 1,796,545 full-rate data points and 35,422 normal points.
- In the year 2006 during 141 clear days-nights, 1,170 passes were tracked, yielding 1,714,783 data points from 19 satellites forming 1,203,054 full-rate data points and 24,270 normal points.
- In August 2006, the station participated in the ALOS tracking campaign under coordination by JAXA. All necessary software and hardware changes were made and installed. Weather conditions at the station allowed the station to track six passes of ALOS during the given ranging time interval.
- In February 2005, a new laser transmitter SL312SH from EKSPLA-Lithuania was installed. The transmitter has the following parameters: ranging frequency 10 Hz, output wavelength 532.0 nm, pulse energy 135mJ, pulse length 130ps, stability of output energy 3.8% (see Figures 13-66 and -67).
- In June 2006, a new event-timing unit was installed (Figure 13-68). The unit is based on the A032-ET Riga Event Timer system, supporting amplitude-range correction, two channel receiver system for daylight ranging, automatic satellite time-bias determination and correction, and a possibility to range to the Etalon and GPS satellites with 10 Hz ranging frequency. Since installation, this event timer is the basic system used by the station.
- As reported in 2004, significant changes in the laser telescope optical system (separation of transmit and receive channels) were planned but are not yet realized. Efforts on these modifications continue. Furthermore, daylight ranging under visual pointing is planned for 2007.

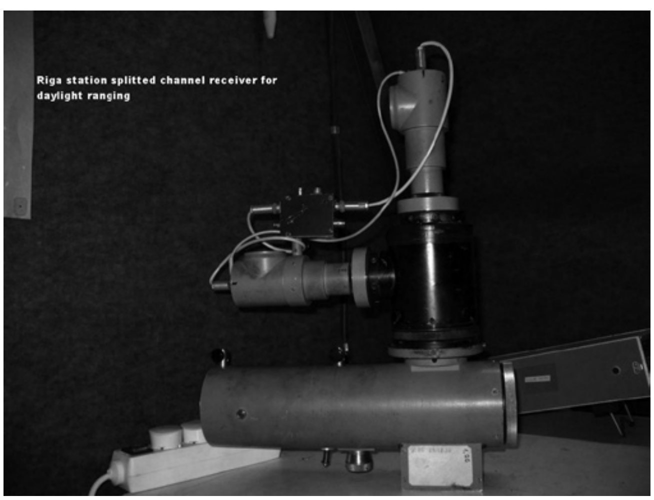

Figure 13-66. Riga station split channel receiver for daylight ranging.

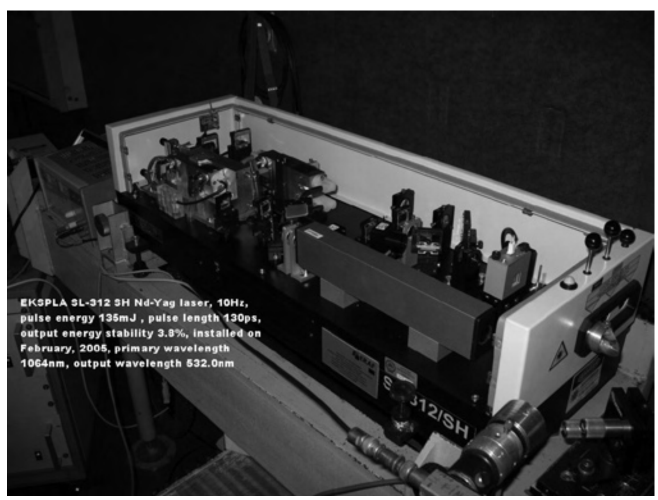

Figure 13-67. EKSPLA SL-312 SH Nd: YAG laser, 10Hz, pulse energy 135mJ, pulse length 130ps, output energy stability 3.8%, installed on February 2005, primary wavelength 1064 nm, output wavelength 532.0nm.

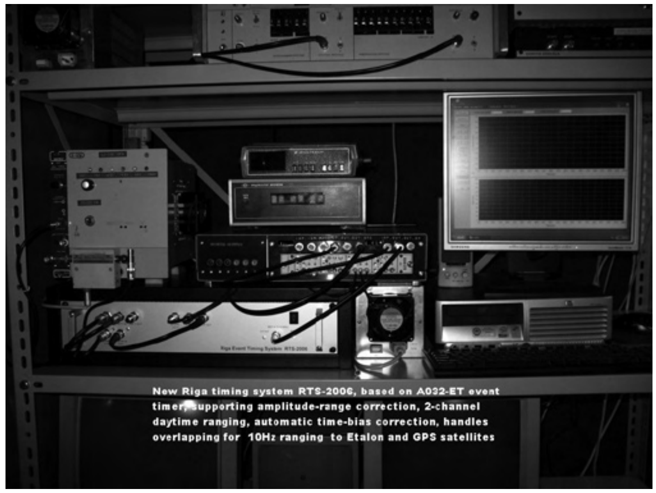

Figure 13-68. New Riga timing system RTS-2006, based on A032-ET event timer, supporting amplitude-range correction, two-channel daytime ranging, automatic time-bias correction, handles overlapping for 10Hz ranging to Etalon and GPS satellites.

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Riyadh, Saudi Arabia (SALRO)

John Guilfoyle/VPL

We are pleased to report that SALRO is continuing its stable and highly productive operation, as shown in Figure 13-69, due mainly to:

- KACST personnel acquiring significant operational skills,
- stability within the VPL O&M team,
- support from KACST management, and
- favorable site conditions.

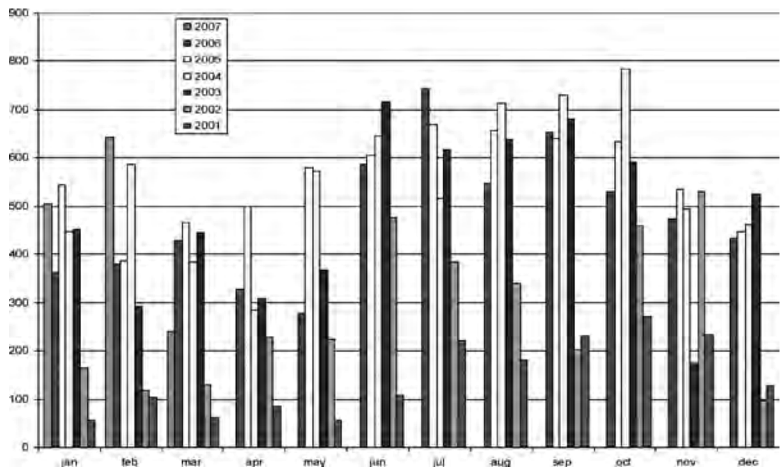

Figure 13-69. Monthly SLR acquisitions since 2001.

Other items worthy of note include:

- The survey, planned for a few years now, will take place in two phases, and soon. Phase 1 is to be a precision GPS survey as part of a national adjustment campaign. Phase 2 is determination of the telescope invariant point by traditional means. Both phases will be under the direction of Prof. Oglu, a well-known geodesist assisting the Saudi Military Survey group.
- KACST will be installing their aircraft detection radar within a few weeks.
- KACST is now considering an upgrade proposal that will take SLR operations into the kHz realm. This is particularly important because the system is still essentially as built in 1991, and replacement components are becoming difficult to find.
- VPL has also presented for consideration a revolutionary design that will allow SALRO to swap between SLR and LIDAR operations at the "flick of a switch". The design allows LIDAR operations to be seamlessly interleaved with SLR, thus extending the research capability of the site. Should the project go ahead, we expect to acquire one hour of both day and night profiling data, to easily fit within the SLR schedule.

There is much to look forward to at the Solar Village SALRO site.

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San Fernando, Spain

Jorge Gárate, Jose Martín Davila, Manuel Quijano, Carmelo Belza/Real Instituto y Observatorio Armada

From the beginning of 2005 until the end of 2006, the San Fernando SLR team has been working to make some improvements in the station. We were looking for two main goals. First of all we were interested in tracking LAGEOS during daylight. Secondly, we are also trying to track high satellites (Etalon or GNSS) in the nighttime.

The first objective has been achieved. As well as implementing some modifications on the tracking software in February 2005, a new two-Armstrong interferential filter was mounted to replace the old five-Armstrong filter. This enabled the facility to discriminate echoes from noise during daylight. However routine tracking has only been performed on one shift thus far; we are still tracking satellites every night. The system is scheduled to move to three shifts in the first half of 2007. In order to reach this goal, some satellites have been tracked during labor hours in order to train the staff on daylight procedures.

Additional modifications have been made to more easily track LAGEOS during daylight hours:

- Diaphragm: The old diaphragm was a wheel with a set of holes of different diameters. This model was replaced by a new one with a variable aperture diameter thus making alignment easier.
- Laser alignment was optimized to obtain echoes from the LAGEOS satellites.
- Laser beam daylight visualization device: A new shooting control board was designed to synchronize the shots with a light intensifier camera, which enables the laser beam visualization by the system operator during daylight operations.

The second goal mentioned above is to track high satellites. A new research project, funded by the Spanish National Research Council, started in the beginning of 2005. The main point of this project is to obtain a more accurate pointing system. Some modifications on the telescope mount will be made in order to equalize the weight over the system where a new emitter telescope will placed. Modifications to the control software are also required. Some pieces of software were developed to run under the DOS operating system; other pieces have been developed to run under Windows. The development of an interface started in late 2006 and is continuing.

A complete review of the optical system was made during the spring of 2006. We acknowledge the advice of Franco della Prugna, from the optical section at the Observatory of Merida Venezuela. He spent several weeks in San Fernando in May and June 2006, performing a complete review of the optical system for optimization. We learned a great deal from della Prugna during his stay.

Predictions using the consolidated prediction format were implemented. Some software modifications were required in order to enable the system to accept this new format.

Finally, during the fall of 2006, the EUROLAS Real Time communication software was also installed by connecting two computers running under different operating systems through a serial port.

Future efforts include the replacement of the SR620 time counter intervals by the Riga Event Timer A032-ET (already purchased). The unit has not yet been installed due to the requirement for a new interface (which has also been developed).

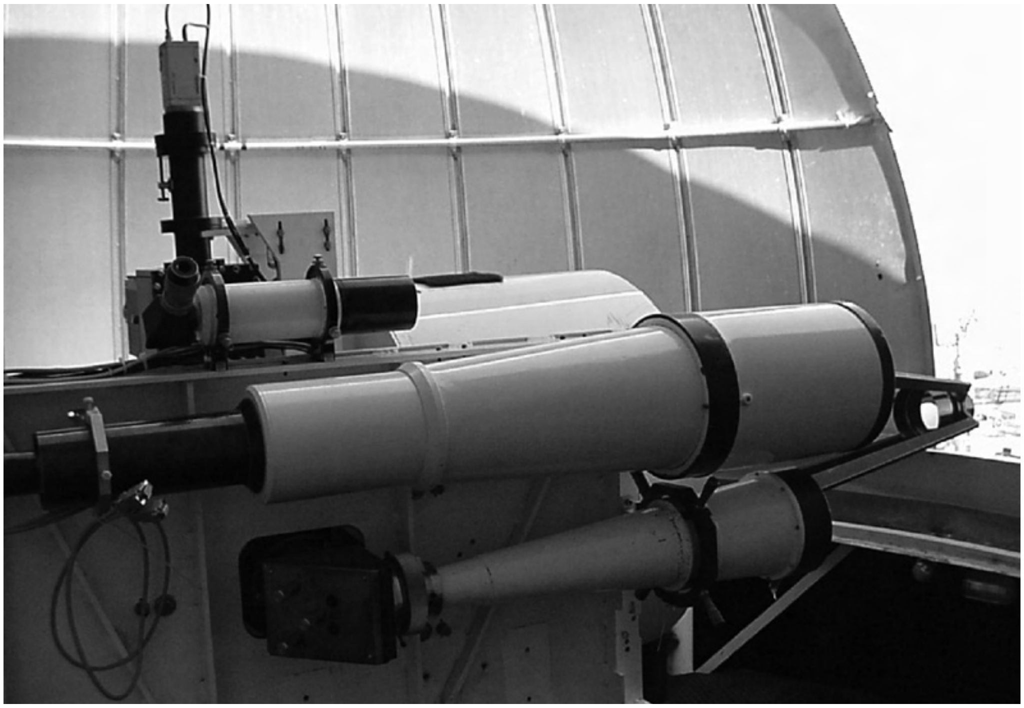

Figure 13-70. Telescope mount including emitter, receiver, finder and TV control telescope. Detector is located over the receiver.

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San Juan, Argentina (China and Argentina)

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Introduction

The new SLR system in San Juan, Argentina is based on a cooperative project in astronomy between the National Astronomical Observatories of Chinese Academy of Sciences (NAOC) and the National University of San Juan of Argentina (NUSJA). There has been a base of astronomical cooperation between NAOC and NUSJA. Because of the good weather, with approximately 300 clear nights per year in San Juan, a photoelectric astrolabe of NAOC was installed in an NUSJA observatory in 1992 for observations and research of the star catalog in the southern sky and astro-geodynamic. At the end of 20th century, NAOC and NUSJA held discussions to develop cooperation in SLR in order to improve the distribution of SLR stations in the world and adequately use the fine weather in San Juan. The Ministries of Science and Technology of the two countries, China and Argentina (MSTC and MSTA) supported the idea. NAOC obtained funds from MSTC to build the SLR system and NUSJA received funding to build the observational room. The Chinese Academy of Surveying and Mapping (CASM) and NAOC fabricated the SLR system under the cooperative agreement between NAOC and CASM. Prof. T.Q. Wang of CASM presided over the design, development, installation, and debugging of the system. The SLR system was completed at the end of 2003 and the observational room was completed in 2005. The system was moved to San Juan in the autumn of 2005.

Figure 13-71. San Juan SLR station.

Figure 13-72. San Juan SLR telescope.

About the Site

The San Juan SLR station is located in the observatory of NUSJA, about 10km from San Juan city. The small city is 1300km northwest of Buenos Aires, the capital of Argentina. The weather in the San Juan region can reach a high of 50˚C in the summer, with a very dry character of a desert climate. Thus, the observatory experiences about 300 clear nights per year making it an excellent site for SLR observation. The geographic position of the site is S 31° 30´ 31.050”, W 68° 37´ 23.377” and 727.22m elevation.

System Installation

The SLR equipment reached San Juan on September 6, 2005. We waited for Argentine customs inspection for one month and opened the cargo container on October 24. From this date to November 20, 2005, we waited for completion of the construction of the SLR buildings and for modifications to the base pillar of the telescope and the bottom platform of the laser. The installation of the SLR was completed on February 23, 2006, and the first LAGEOS pass was received on that date.

Figure 13-73-a, -b, -c. Installation and debugging of the San Juan station.

System Configuration

The telescope consists of a Cassegrain receiving telescope with a 60cm aperture and a separated Galilei Telescope that collimates the laser beam with an amplification factor of four. The control computer is a typical PC (a notebook can be used) running the Windows operating system. All programs, such as satellite predictions, target tracking, satellite ranging, data preprocessing, and data transmission, are run on the same computer. The laser system is a Nd:YAG passive mod-locked dye laser with 30ps pulse width and single pulse energy of 30mj in green light. The detector is C-SPAD from the Czech Technical University. We use the Stanford Counter SR-620 for receiving the signal and an ICCD camera to collect the star and laser beam image by the main receiving telescope. Timing and frequency is by HP58503A. Calibration is with short distance target inside the dome.

Operations

The San Juan station began routine operations on February 23, 2006. We acquired 5,981 passes and 70,946 normal points for all satellites during 2006 due to the excellent work of the observers from NAOC, NUSJA, and CASM under the direction of Prof. W.D. Liu of NAOC and Prof. V.G. Actis of NUSJA. The number of passes, however, was strongly limited by an unstable laser system in the station.

Figure 13-74. The San Juan SLR station team (left to right): R. Podesta (senior engineer), W. Liu (senior engineer), A. Gonzalez (senior engineer), Professor T. Wang, Q. Xiang (engineer), A. M. Pacheco (senior engineer), E. L. Actis (senior engineer), E. Alonso (senior engineer), D. Huang (senior engineer).

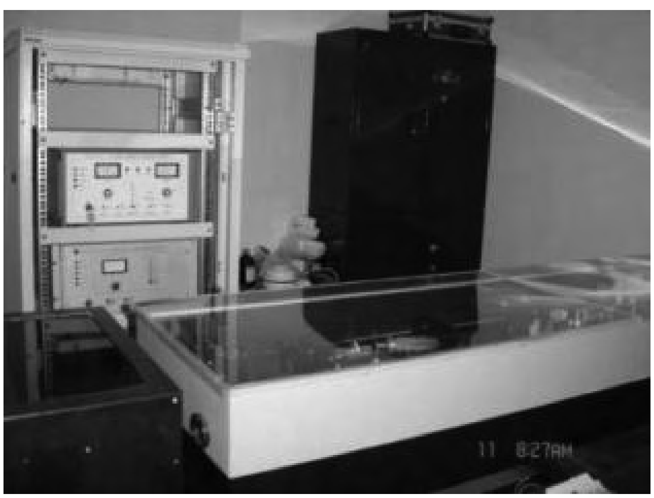

Figure 13-75. SLR system control room.

Figure 13-76. Laser system.

Future Plans

The NAOC, NUSJA, and CASM will continue cooperation in the San Juan SLR system. We will upgrade the system in the near future. The first step will be to change the laser system to a semiconductor pumped laser and thus bring the system to kHz and daytime ranging capabilities in order to obtain more high-quality data for the ILRS. Of course, our research will also continue.

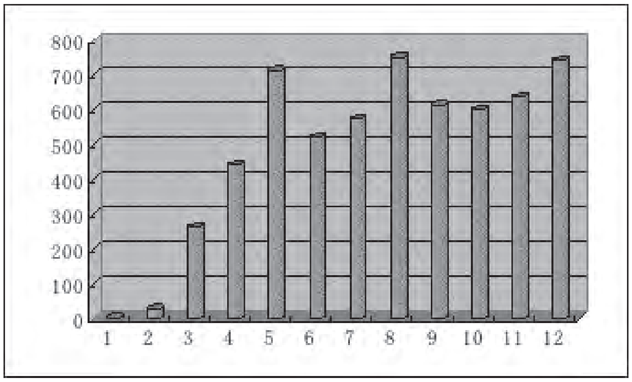

Figure 13-77. Number of passes (by month) from San Juan for all satellites in 2006.

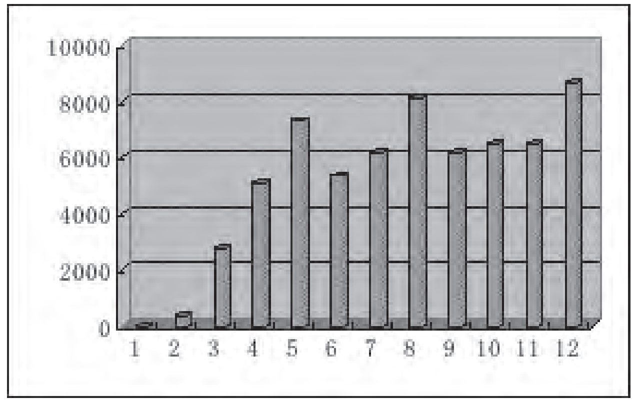

Figure 13-78. Number of normal points (by month) from San Juan for all satellites in 2006.

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Shanghai, China

Yang Fumin and Zhang Zhongping/CAS

The Shanghai SLR system moved to a new observation building in 2005. The old facility was located at the foot of the Sheshan hill and was built in 1983. During the last 22 years, the trees around the building seriously blocked observations. The new facility is near the top of the hill (Figure 13-79). Figures 13-80 and -81 show the telescope and the electronics.

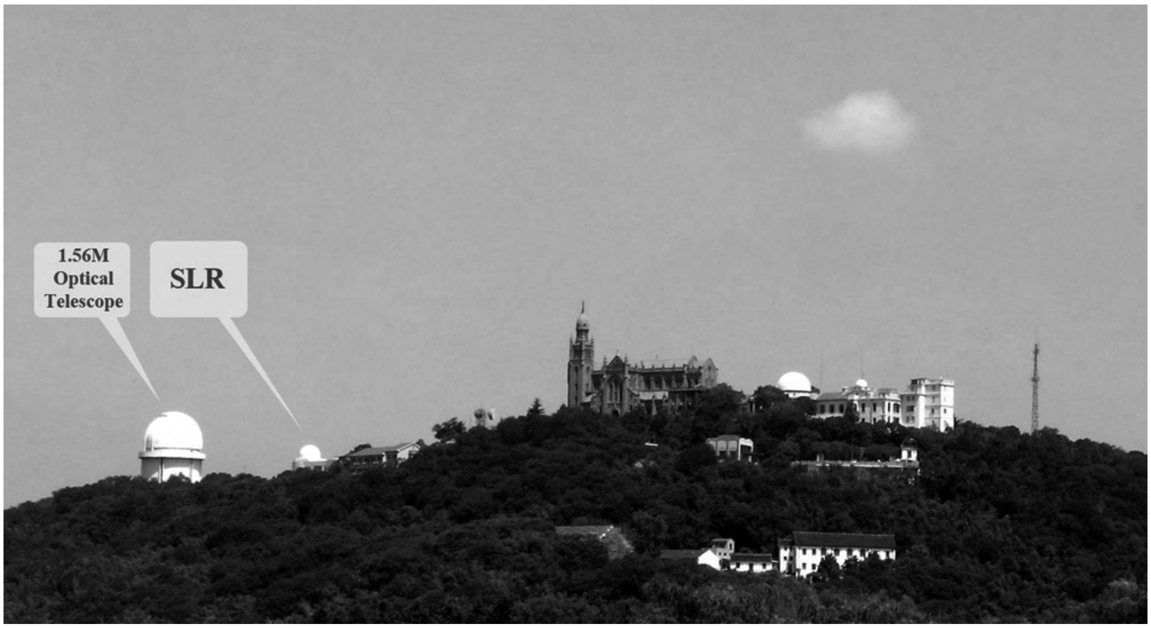

Figure 13-79. The optical observation site at Shanghai Observatory, China.

Figure 13-80. SLR telescope (aperture 600mm).

Figure 13-81. Electronics room.

The system components of the upgraded SLR system are as follows:

- SLR system:
    - o An aperture of 210mm transmitting telescope replaced the old one and will have better collimating beams for both high orbit satellites and space debris tracking.
    - o New controllers for the servo system of the telescope were installed.

- 40W Nd:YAG laser for experiments in laser ranging to space debris:
  The 40W Q-Switched laser with 2J (532nm), 10ns, and 20Hz was made by a Chinese institute for an experimental time period only. We are still working to obtain returns from space debris, without success to date.

- Laser Time Transfer (LTT) project:
  We have concentrated on developing the LTT EM and FM in collaboration with the China Academy of Space Technology and the Czech Technical University during the last two years. The LTT FM is waiting for launch. The first LTT experiment will be done at Changchun SLR station.

- Near future plans:
  The proposal for upgrading the performance of the entire Chinese SLR network has received approval primarily under the Monitoring Network for Structure Environment of China Mainland and will start in 2007. The main upgrades for most of the SLR stations in the network will be as follows:
    - o 1-2 kHz laser ranging
    - o Daylight tracking capability

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Introduction

Routine satellite laser ranging started at the Simeiz observatory in 1976 as part of the INTERKOSMOS network with a laser system installed by K. Hamal on a KRIPTON telescope. In 1988, the Crimean Astrophysical Observatory installed a new station near this older system and “Simeiz-1873” began operations in 1989; the system buildings are shown in Figures 13-82a and -82b. Co-locations with the IFAG (now BKG) MLTRS system were conducted in 1991. The Simeiz system is a one of four Ukrainian SLR stations (the others being GLSV-1824, Lviv-1831, and KTZL-1893).

Figures 13-82a and -82b. General views of the Simeiz SLR system.

A modernization program was undertaken in 2000 under a Civilian Research and Development Foundation (CRDF) grant (thanks to Michael Pearlman of CfA and Dan Nugent of HTSI). New angular encoders and a new time interval counter were installed at this time. After this modernization effort, we increased the amount of ranging data by approximately three times (see Figure 13-83). However, we have probably reached the limit of the equipment, due mainly to the shortcomings of the laser transmitter.

A permanent GPS receiver has been operating near the Simeiz SLR station since 2000. In 2004, this receiver (“GPS-CRAO”) became part of the IGS network. Recently we began processing GPS data using the GLOBK/GAMIT software. We have analyzed data obtained by our station for the period 2002-2005.

Current Activities

The current configuration of the Simeiz SLR system is given in Table 13-3. Modernization of the station continued in 2005-2006 with the following tasks:

- Implementation of the new CPF prediction format into the station software was fully completed in 2006;
- Installation of a new modern control system of engines;
- Update of optical system of a telescope for a new calibration target;
- Tests of ground calibration with the new target at 77m east;
- Processing of GPS data with GAMIT/GLOBK.

Table 13-3. Simeiz System Configuration

Element	Description
Mount	Alt-Az. 1m mirror
Angular encoders	FARRAND CONTROLS, 0.4”
Time interval counter	SR620
PMT	H6533
Time and frequency standard	TC-74, sec. from GPS
Laser	350 ps, 5Hz. (18 years old)
Software	GUI in JAVA, server in C++, low-level modules in C on LINUX
Ephemeredes	CPF (in F77)

SLR Ranging and GPS Processing

In 2006 we suffered appreciable downtime due to two failures in the laser power unit. As can be seen in Figure 13-83, data have increased with the modernization activities, but we have probably reached the limit with our equipment (the laser transmitter is 18 years old). A second problem is in tracking. In 2006 we purchased new servo-drivers for the stepper motors; we hope that this upgrade will help improve our tracking capability.

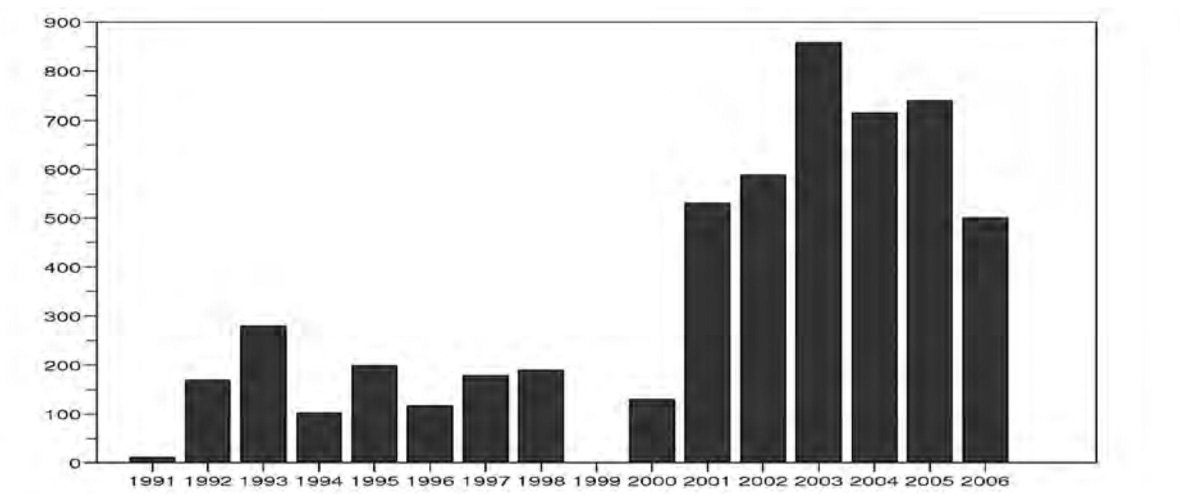

Figure 13-83. Amount of ranging data from Simeiz (1991-2006).

Analysis by two independent groups shows that the stability of the station SLR data still needs considerable work. Results from the Ukrainian Center of Determination of the Earth Orientation Parameters (Bolotina, 2006) are shown in Figure 13-84. S. Schillak found similar results by processing our LAGEOS ranging data for period 1999-2003 (see Schillak, 2004).

We have also processed GPS data with the GAMIT/GLOBK software on our station (Figure 13-85). In comparison, SLR coordinates (XYZ) were transformed for use by the GAMIT/GLOBK coordinates (NEU). These coordinates are defined as the distance from the equator, distance from Greenwich meridian along the small circle at the latitude of the site, and the height above the ellipsoid.

As can be seen in Figures 13-84 and -85, results from our SLR location are not comparable with results received by GPS. Furthermore, a trend is evident in the GPS results. In the SLR results (mean by year) a trend is ALSO visible (Figure 13-85, green) but possibly not precise. The ITRF2000 solution (Figure 13-85, black) is similar to the GPS results but not to SLR (especially in East offset).

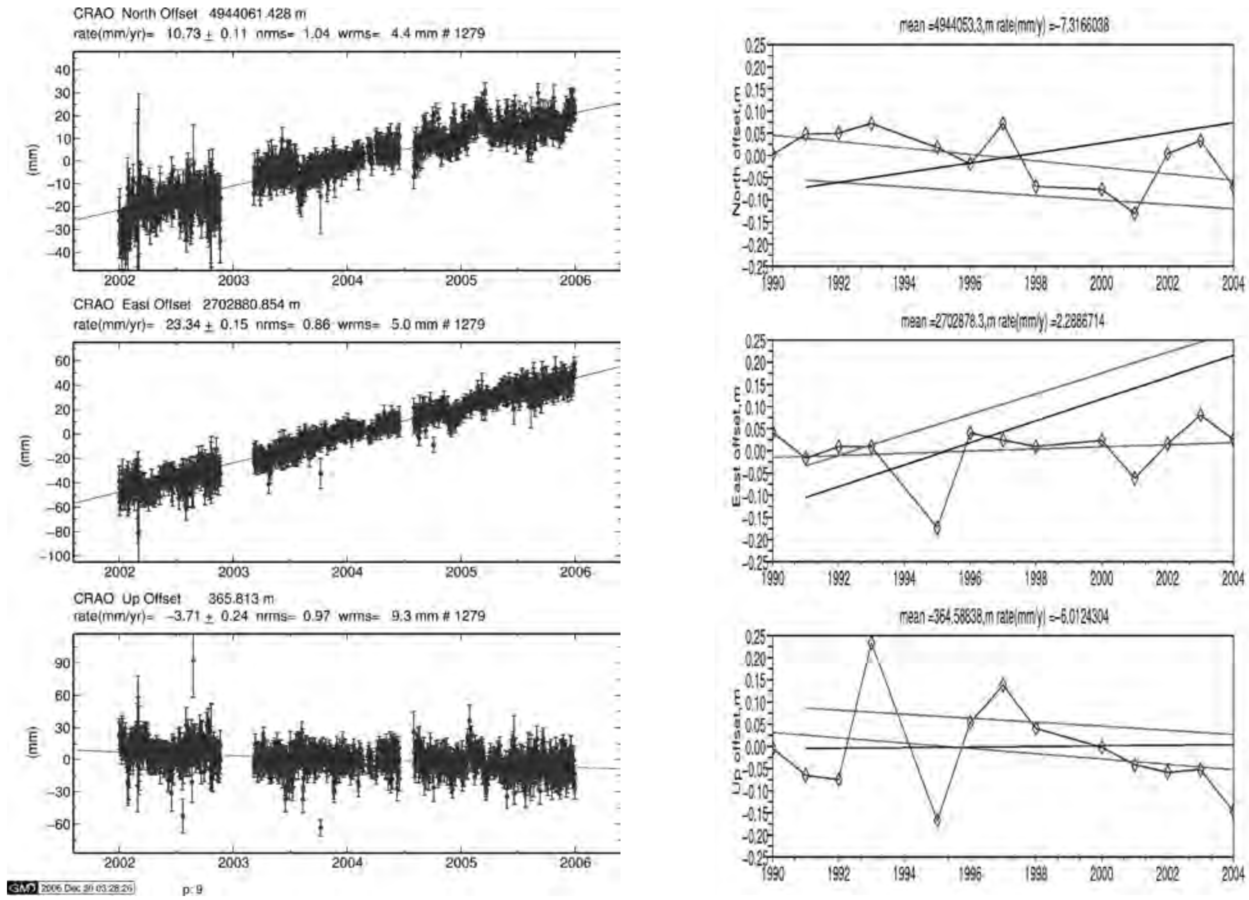

Figure 13-84 and 13-85. Topocentric ÅgNEUÅh coordinates (mean by year) obtained by SLR (13-84) for 1991-2005 (blue is a data, green is a trend, red is ITRF94 solution, black is ITRF2000 solution), meters; topocentric ÅgNEUÅh coordinates (delta from mean value) obtained by GPS (13-85) for 2002-2006, mm.

Summary

The analysis of SLR and GPS results has shown that we still have stability problems with the Simeiz ranging system; likely causes of the problems are the old laser transmitter, inadequacies in the calibration system, and greater breaks in ranging to LAGEOS because of equipment failure and poor weather.

The basic directions of our future work will be the creation of a new telescope mount model, better operations procedures, and hopefully, a replacement of the laser.

Acknowledgments

We acknowledge and thank Stanislaw Schillak and Olga Bolotina for providing the SLR results.

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Tadashi Ishikawa/Hydrographic and Oceanographic Department, Japan Coast Guard

The Simosato Hydrographic Observatory (Figure 13-86) is located to the south of Kii Mountain Range which was registered as a part of a UNESCO World Heritage site "Sacred Sites and Pilgrimage Routes" in July 2004; it is a bucolic area of central Japan and about four hours by train from Osaka, the second largest city of Japan. Since the site is close to the Pacific coast with a mountainous area located behind, the meteorological conditions do not always allow laser tracking.

Figure 13-86. The Simosato station's telescope.

The SLR tracking system undergoes regular maintenance by the professional staff six times a year and system upgrades are carried out in a step-by-step fashion. In May 2005, the C4258 photo-detector was replaced with a 1004-112B model.

Since July 2006, in order to reduce the time walk, the Simosato Hydrographic Observatory introduced two new techniques: Triple Threshold Screening (TTS) and Constant Mid-signal Detection (CMD).

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Tanegashima, Japan

Shinichi Nakamura, Nobuo Kudo, Ryo Nakamura/JAXA

Introduction

The Japan Aerospace Exploration Agency's (JAXA's) Satellite Laser Ranging system, called "GUTS-SLR" (GMSL, Tanegashima), was completed in the spring of 2004. The GUTS-SLR is located on Tanegashima Island, also the location of the Japanese launch site.

The GUTS-SLR is operated by remote control from the Tsukuba Space Center (TKSC). The distance between TKSC and the SLR station is approximately 1,100 km. Routine operations of the station commenced on September 1, 2004.

Figure 13-87. Tanegashima station in operation.

Facilities/Systems

GUTS-SLR is capable of ranging to satellites from low Earth orbit to geostationary orbit. The GUTS-SLR system is able to range to the LAGEOS satellites with a single-shot RMS of less than 10 mm and less than 20 mm RMS for ETS-8 (JAXA geostationary satellite). The GUTS-SLR station is operated almost automatically according to a predetermined sequence. An operator simply needs to turn on/off the initial power supply, manually operate the initial acquisition when the orbit prediction has an error, and perform regular maintenance on the system. The operational plan for the whole GUTS system is generated by the Master Control and Operation Planning Subsystem, which is called COPs. COPs also monitors operational conditions of each subsystem.

Current Activities

GUTS-SLR has tracked various satellites from low earth orbit to geostationary orbit, and successfully performed the restricted SLR operation for ALOS. GUTS-SLR also tracked ETS-8, which is the first time JAXA has successfully tracked a geostationary satellite using SLR. The ranging accuracy is about 16 mm RMS. GUTS-SLR is now preparing for more precise ranging of ETS-8 for HAC (High Accuracy Clock) experiments.

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Consolidated Space Tracking and
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Wettzell Laser Ranging System (WLRS), Germany

Stefan Riepl, Nik Brandl/BKG

The Satellite Observing System Wettzell (SOS-W) will be a highly autonomous SLR system providing support primarily for low earth orbiting satellites at kilohertz repetition rate lasers. Through 2005 and 2006, development of SOS-W continued on a steady basis; during October 2005, a five-meter dome was installed on the building selected to house the SOS-W telescope.

After lengthy negotiations with Zeiss Jena, the telescope plans were commissioned in early 2006, meeting all the specifications. As a consequence of the highly dynamic properties and weight of the telescope, the foreseen pier, which was already hosting the Wettzell Satellite Ranging System in former times, was subjected to a modal analysis, identifying the Eigen modes of the monument. Due to the analysis results, the telescope pier was re-enforced during the summer of 2006. After completion of the re-enforcement, the lowest Eigen frequency was identified to be well above 40Hz, providing now an ideal base for the telescope.

By the end of 2006, the Ti:SAP laser system was installed and commissioned. The system consists of an Nd:YLF pump laser providing excitation energy for a regenerative amplifier, which itself is seeded by a SESAM mode locked oscillator. The system is capable of delivering 40ps pulses with a pulse energy of 1.5mJ at a repetition rate of 1kHz and a wavelength of 850nm. The output may be frequency doubled to 425nm at a conversion rate of 50 percent. The future schedule calls for the integration of the individual system components, the assembly of the detector box, and the installation of the telescope, which is due in September 2007.

Figure 13-88: The inside and outside renovations of the building selected to host the SOS-W have been completed. The newly installed dome is ready to host the system's telescope.

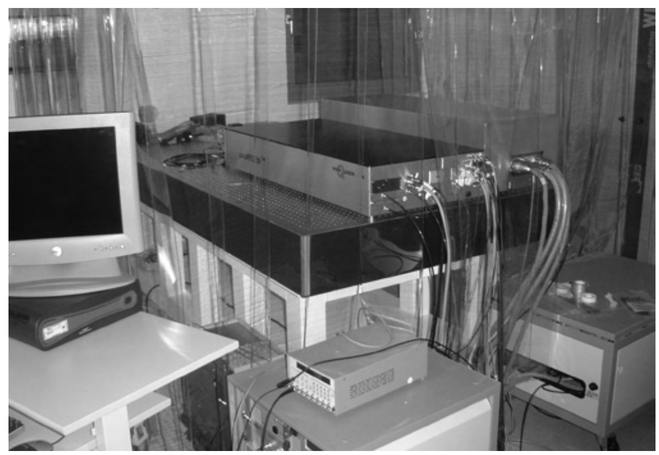

Figure 13-89: The recently installed Ti:SAP laser ready for operation.

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Yarragadee, Australia

Vince Noyes/EOS Space Systems Pty. Ltd.

General

MOBLAS-5 in Yarragadee has maintained its first place position as the most productive site in the ILRS network. The year 2005 found June to be the wettest month for 50 years, followed by the driest July on record, and finished with the coolest start to summer in 70 years. These strange weather patterns through 2005-06 have had a positive and negative effect on data collected. Approximately 11,400,000 data points were collected in 2006, up 10% from 2005, while the normal point total for 2006 was 213,192, a 1.7% reduction when compared with 2005 results. Tracking shifts are now 24/7, except for two full days per month. The Daily Operation Reporting (DOR) is now sent to Geoscience Australia (GA) via FTP.

Figure 13-90. MOBLAS 5 SLR station staff (left to right): Randall Carman, Peter Thomas, Jack Paff, Brian Rubery, Vince Noyes and Peter Bargewell.

System Changes/Upgrades/Faults

The site's 60KVA UPS system was fitted with a new air conditioner, which has significantly assisted reliability during the very hot summer months. A new GPS pier has been installed for GA with an associated antenna and receiver to be installed by late 2007. The Met-3 equipment was replaced as part of the NASA calibration program in July 2006. A new computer server was installed and, with fibre optic cable now available, has improved communications from 28Kbps to 512Kbps. Processor and tracking screens have been replaced with larger flat screen types. The main system software (processor and controller PC's) changes included: restricted tracking software for laser sensitive satellites (e.g., ALOS, ICESat), CPF handling software, and small scripts that also assist operators to process data faster on single man shifts.

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Griffith ACT 2603		
AUSTRALIA		

Zimmerwald, Switzerland

Werner Gurtner, Eugen Pop, Johannes Utzinger, Martin Ploner/Astronomical Institute of Bern

Figure 13-91. The Zimmerwald Observatory.

The efficiency of the SLR operations of the Zimmerwald satellite observatory was further improved during the last two years by increased reliability of the equipment and control software as well as extended periods of fully automated operation (several hours per day).

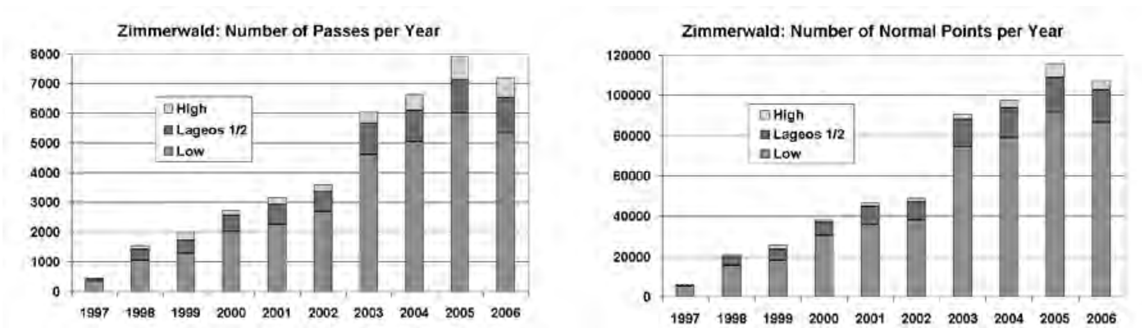

Figure 13-92. Number of passes and normal points per year at Zimmerwald.

In spring 2006 we introduced Riga A032ET event timers for the two observation channels (blue and infrared). In an initial phase they were operated in start/stop mode; on November 15, 2006 we switched to event mode. Now high satellites (GPS, GLONASS, Etalon, GIOVE-A) are also observed with 10Hz.

On June 21, 2006 we changed operational procedures by switching from internal to external calibration (external target distance about 600m) because we noted that there seems to be a problem in the internal calibration of the infrared observation channel. The pass-averaged differences between the blue (423nm) and infrared (846nm) calibrated and refraction-corrected ranges showed slowly varying biases of the order of +/-20 mm which could certainly not be attributed to errors in the refraction models used. Figure 13-93 shows these differences before and after June 21, 2006 for LAGEOS-1 and -2 passes. The reason for the infrared calibration problem is unknown; it did not disappear when we changed from Stanford counters to the Riga event timers. There still seems to be some systematic differences after the change, but on a significantly lower level (peak to peak about 15mm).

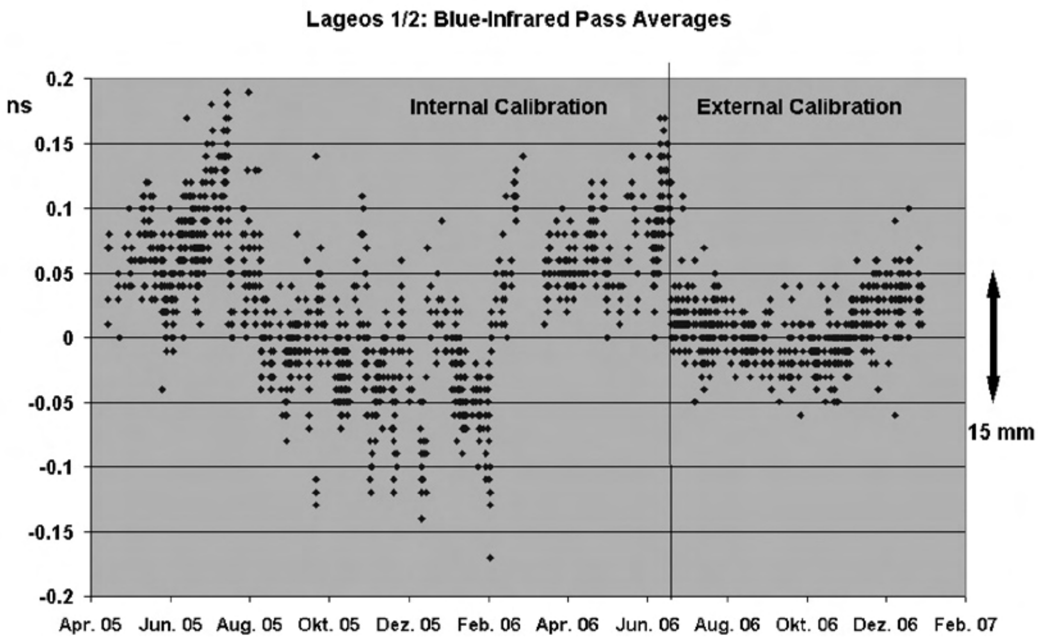

Figure 13-93. Inter-range biases.

Zimmerwald continued to track ICESat, the first vulnerable satellite (elevation cut-off at 70 degrees, test of Go-Nogo flag) and qualified for tracking ALOS, a Japanese Earth observing satellite with sensitive optical sensors, under the more complicated restriction scenario using pass segment information plus Go-Nogo flags.

The control software for optical observations by means of CCD cameras was improved to such a degree that CCD operations could run fully automatically, embedded into the SLR tracking by fast switching between SLR and CCD mode.

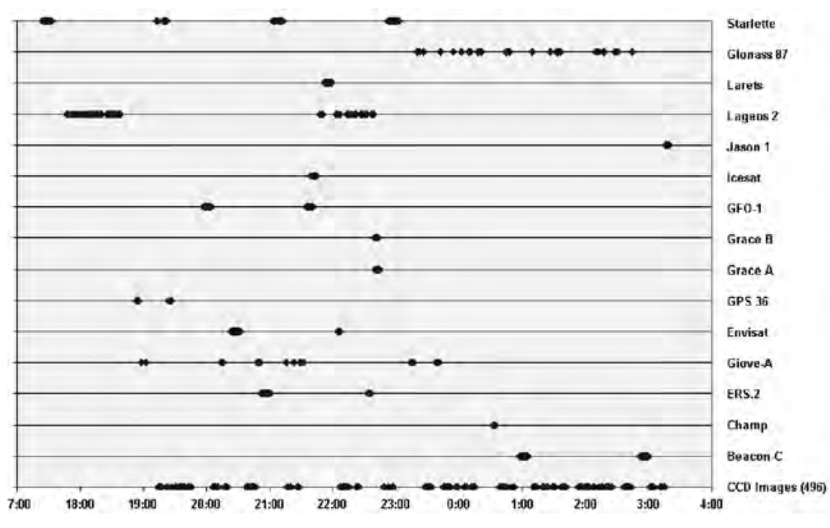

Figure 13-94. SLR/CCD interleaving.

Figure 13-94 shows a typical example of the distribution of SLR and CCD (bottom line) tracking during a night between 17:00 and 04:00 UT. Finally, in Figure 13-95 we show the number of CCD images taken each month between November 2004 and July 2006. A significantly higher number of observations could be collected in March 2005 during SLR system downtime.

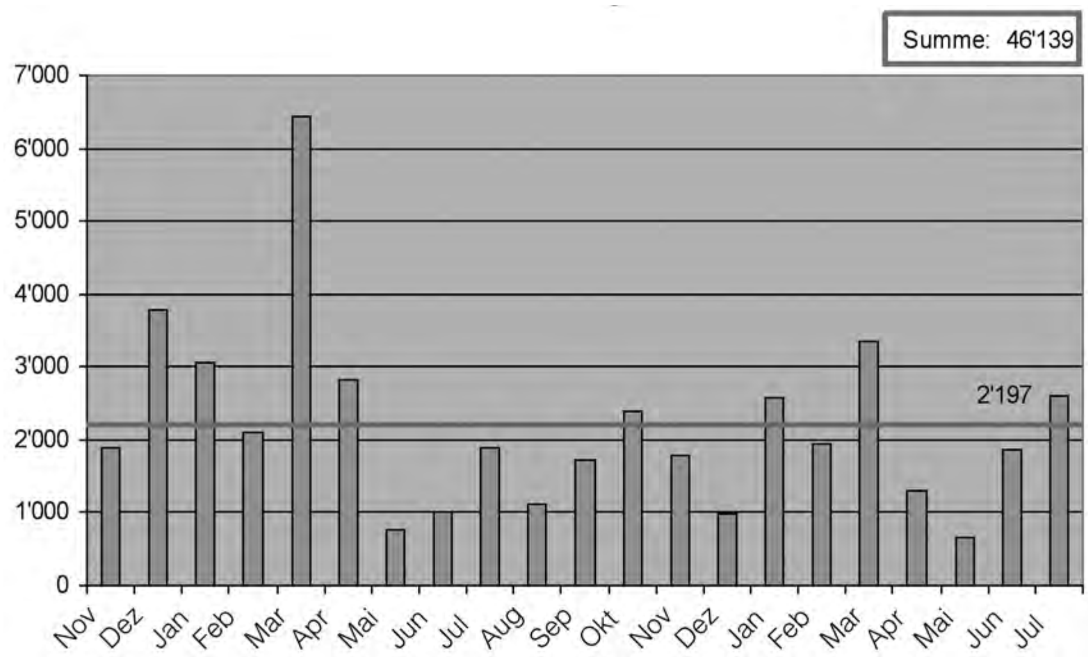

Figure 13-95. Monthly number of CCD images Nov. 2004-Jul. 2006.

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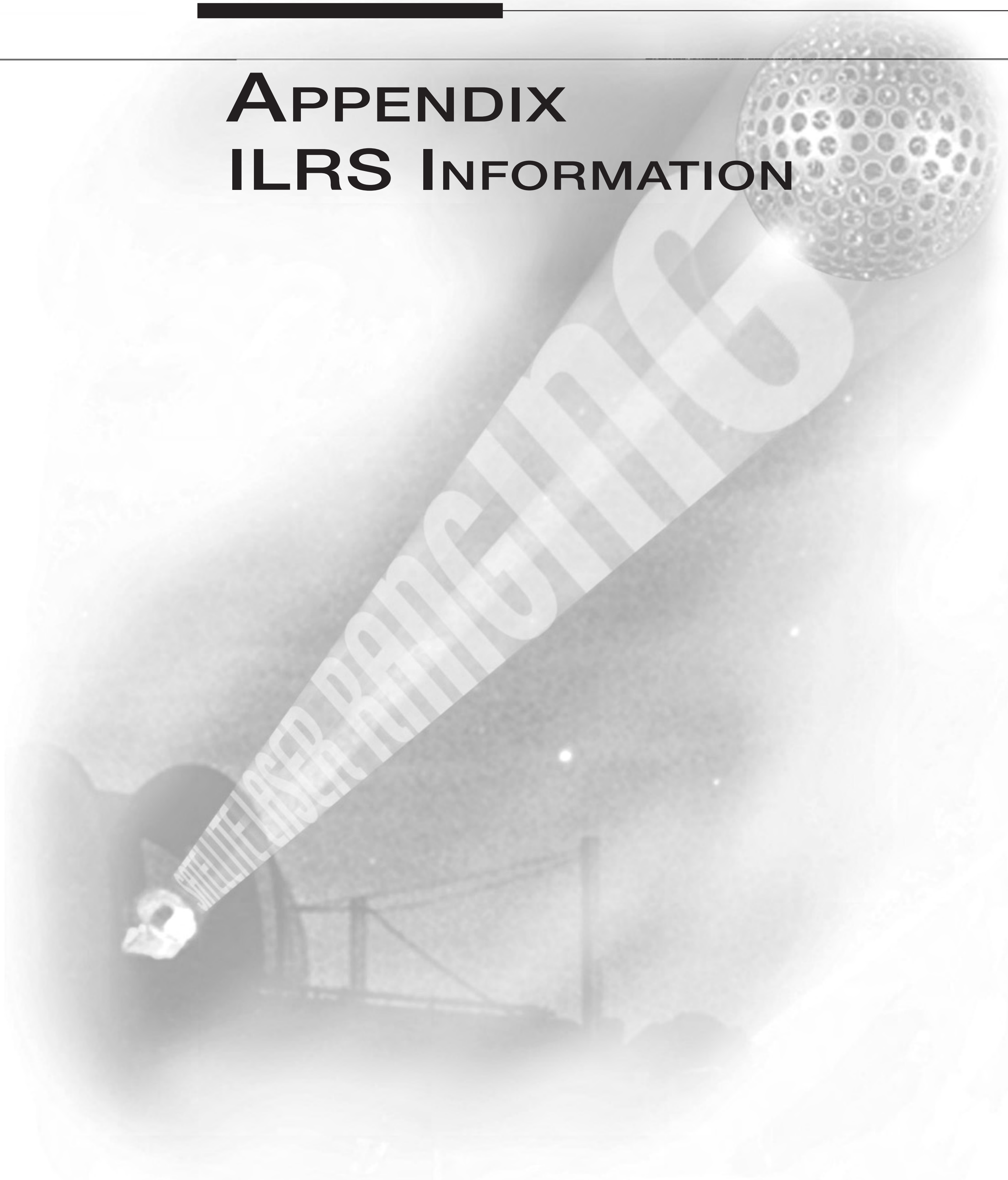
Appendix
ILRS Information



Appendix

ILRS Information

ILRS Contributing Organizations

Agency	Country
National University of San Juan of Argentina	Argentina
Geoscience Australia/National Mapping Division	Australia
EOS Space Systems Pty. Ltd.	Australia
Austrian Academy of Sciences	Austria
Central Laboratory for Geodesy, Bulgarian Academy	Bulgaria
Observatorio Geodetico TIGO, Universidad de Concepción	Chile
Academia Sinica	China
Chinese Academy of Surveying and Mapping	China
Institute of Seismology, China Seismological Bureau	China
National Astronomical Observatories of China (NAOC), Chinese Academy of Sciences (CAS)	China
State Seismological Bureau	China
Yunnan Observatory	China
Technical University of Prague	Czech Republic
National Research Institute of Astronomy and Geophysics (NRIAG)	Egypt
Finnish Geodetic Institute	Finland
Observatoire de la Côte d'Azur/Center d'Etudes et de Recherches Géodynamiques et Astrométrie (OCA/CERGA)	France
Observatoire de Paris	France
Tahiti Geodetic Observatory, University of French Polynesia (UFP)	French Polynesia
Bundesamt für Kartographie und Geodäsie (BKG)	Germany
Deutsches Geodätisches ForschungsInstitut (DGFI)	Germany
European Space Agency (ESA)	Germany
Forschungseinrichting SatellitenGeodasie/Institut fuer Erdmessung (FESG/IFE)	Germany
GeoForschungsZentrum (GFZ)	Germany
University of Hannover/Institut fuer Erdmessung	Germany
Italian Space Agency (ASI)	Italy
Hydrographic Department/Japan Coast Guard	Japan
Japan Aerospace Exploration Agency (JAXA)	Japan
National Institute of Information and Communications Technology (NICT)	Japan
Astronomical Observatory, University of Latvia	Latvia
Delft University of Technology (DUT)	The Netherlands
Division for Electronics, Forsvarets ForskningsInstitutt (FFI)	Norway
Universidad Nacional de San Augustin (UNSA)	Peru

Space Research Center of the Polish Academy of Sciences (PAS)	Poland
Institute of Applied Astronomy (IAA)	Russia
Institute of Astronomy of the Russian Academy of Sciences (INASAN)	Russia
Institute of Metrology for Time and Space (IMVP)	Russia
Mission Control Center (MCC)	Russia
Russian Space Agency (RSA)	Russia
Space Research Institute (SRI) for Precision Instrument Engineering	Russia
King Abdulaziz City for Science and Technology (KACST)	Saudi Arabia
Hartebeesthoek Radio Astronomy Observatory (HartRAO)	South Africa
Real Instituto y Observatorio de la Armada	Spain
Astronomical Institute, University of Berne (AIUB)	Switzerland
Astronomical Observatory of the Ivan Franko National University of Lviv	Ukraine
Crimean Astronomical Observatory	Ukraine
Lebedev Physical Institute in the Crimea	Ukraine
Main Astronomical Observatory (MAO) of the National Academy of Sciences of Ukraine (GAOUA)	Ukraine
Natural Environment Research Council (NERC)	United Kingdom
University of Newcastle Upon Tyne	United Kingdom
Harvard-Smithsonian Center for Astrophysics	USA
Jet Propulsion Laboratory (JPL)	USA
Joint Center for Earth System Technology (JCET), University of Maryland, Baltimore County	USA
National Aeronautics and Space Administration Goddard Space Flight Center (NASA GSFC)	USA
Naval Research Laboratory (NRL)	USA
University of Hawaii	USA
University of Texas at Austin	USA
University of Texas, Center for Space Research (CSR)	USA

List of Acronyms

AAC	Associate Analysis Center
AC	Analysis Center
ACES	Atomic Clock Ensemble in Space
ACT	Australian Capital Territory
ADEOS	Advanced Earth Observing Satellite
AG	Absolute Gravimeter
AGU	American Geophysical Union
AIUB	Astronomical Institute of Berne (Switzerland)
ALOS	Advanced Land Observing Satellite
Alt/Az	Altitude/Azimuth
ANDE	Atmospheric Neutral Density Experiment (USA)
ANDE-RR	Atmospheric Neutral Density Experiment Risk Reduction (USA)
ANSI	American National Standards Institute
APD	Avalanche Photodiodes
APOLLO	Apache Point Observatory Lunar Laser-ranging Operation (USA)
ARTEMIS	Advanced Relay And Technology Mission
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
AVNIR	Advanced Visible Near-Infrared Radiometer (Japan)
AWG	Analysis Working Group
Az-El	Azimuth-Elevation
BAS	Bulgarian Academy of Sciences
BBO	Beta Barium Borate
BE-C	Beacon Explorer C
BELA	BepiColombo Laser Altimeter
BIPM	International Bureau of Weights and Measures
BKG	Bundesamt für Kartographie und Geodäsie (Germany)
BNSC	British National Space Center
Cal/Val	Calibration/Validation
CAO	Central Aerological Observatory (Russia)
CAS	Chinese Academy of Sciences
CASM	Chinese Academy of Surveying and Mapping
CB	Central Bureau
CC	Combination Center
CCD	Charge-Coupled Device
CCR	Corner Cube Reflector

CCTV	Close Circuit Television
CDDIS	Crustal Dynamics Data Information System (USA)
CEG	School of Engineering and Geosciences, Newcastle University (UK)
CERGA	Centre d'Etudes et de Recherches Géodynamiques et Astrométrie (France)
CfA	Center for Astrophysics (USA)
CGS	Centro di Geodesia Spaziale (Italy)
CHAMP	CHAllenging Mini-Satellite Payload
CLG	Central Laboratory for Geodesy (Bulgaria)
CLS	Collecte, Localisation, Satellites (France)
CMB	Core Mantle Boundary
CMD	Constant Mid-signal Detection
CNES	Centre National d'Etudes Spatiales (France)
CNS	Communication, Navigation and Surveillance
CODE	Center for Orbit Determination in Europe
CoM	Center of Mass
COPs	Control Operation Planning Subsystem (Japan)
COSPAR	Committee on Space Research
CPF	Consolidated Prediction Format
CPP	Combination Pilot Project
CRD	Consolidated Laser Ranging Data format
CRDF	Civilian Research and Development Foundation (USA)
CRL	Communications Research Laboratory (Japan)
CSPAD	Compensated Single Photoelectron Avalanche Detector
C-SPAD	Compensated Single Photoelectron Avalanche Detector
CSR	Center for Space Research (USA)
CSRIFS	Combined Square Root Information Filter and Smoother (Finland)
CSTG	International Coordination of Space Techniques for Geodesy and Geodynamics
CTU	Czech Technical University (Czech Republic)
DEM	Digital Elevation Model
DEOS	Department of Earth Observation (The Netherlands)
DFG	German Research Foundation
DGFI	Deutsches Geodätisches ForschungsInstitut (Germany)
DIMM	Differential Image Motion Monitor
DLR	German Aerospace Center
DoD	Department of Defense (USA)
DOE	Diffractive Optical Element
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite

DPSSL	Diode Pumped Solid State Laser
DTOF	Differential Time of Flight
DUT	Delft University of Technology (The Netherlands)
ECMWF	European Centre for Medium-Range Weather Forecasts (UK)
EDC	EUROLAS Data Center (Germany)
EGU	European Geophysical Union
EO	Earth Observation
EOP	Earth Orientation Parameter
EOS	Earth Observing System (USA)
EOS	Electro Optical Systems (USA)
EOST	EOS Technologies, Inc. (Australia)
ERP	Earth Rotation Parameter
ERS	European Remote Sensing Satellite
Er:YAG	Erbium Yttrium Aluminum Garnet
ESA	European Space Agency
ESOC	ESA Space Operations Center
ET	Event Timer
ETS	Engineering Test Satellite
EU	European Union
EUREF	IAG Reference Frame Sub-Commission for Europe
EUROLAS	European Laser Consortium
FAA	Federal Aviation Administration (USA)
FESG	Forschungseinrichting Satellitengeodäsie (Research Facility for Space Geodesy, Germany)
FFI	Forsvarets ForskningsInstitutt (Norwegian Defense Research Establishment)
FOV	Field Of View
FPGA	Field Programmable Gate Array
FTLRS	French Transportable Laser Ranging System
FTP	File Transfer Protocol
GA	Geoscience Australia
GaAsP	Gallium Arsenide Photo Diode
GAOUA	Main Astronomical Observatory of the National Academy of Sciences of Ukraine
GB	Gigabyte
GeoDAF	Geodetical Data Archive Facility (Italy)
GEO	Group on Earth Observations
GEOS	Geodetic and Earth Orbiting Satellite
GEOSS	Global Earth Observation System of Systems

GFO	GEOSAT Follow-On (USA)
GFZ	GeoForschungsZentrum (Germany)
GGAO	Goddard Geophysical and Astronomical Observatory (USA)
GGM	Global Gravitational Model
GGOS	Global Geodetic Observing System
GGOS-D	Global Geodetic Observing System German Component
GIA	Glacial Isostatic Adjustment
GIOVE	Galileo in Orbit Validation Experiment
GIUB	Geographische Institut der Unversität Bonn (Germany)
GLAS	Geoscience Laser Altimeter System (USA)
GLONASS	Global Navigation Satellite System
GLONASS	Global’naya Navigatsionnay Sputnikovaya Sistema
GM	Gravitational Constant
GNSS	Global Navigation Satellite System
GOCE	Gravity Field and Steady-state Ocean Circulation Explorer
GP-B	Gravity Probe B
GPS	Global Positioning System
GRACE	Gravity Recovery And Climate Experiment
GRGS	Groupe de Recherches de Geodesie Speciale (France)
GSFC	Goddard Space Flight Center (USA)
GSTB	Galileo System Test Bed
GUTS	Global and High Accuracy Trajectory Determination System
H2A/LRE	Laser Ranging Experiment
HAC	High Accuracy Clock
HartRAO	Hartebeesthoek Radio Astronomy Observatory (South Africa)
HEO	High Earth Orbiter
HOLLAS	Haleakala Laser Station (USA)
HP	Hewlett-Packard
HPWREN	High Performance Wireless Research and Educational Network (USA)
HTSI	Honeywell Technology Solutions, Inc. (USA)
HV	High Voltage
HVAC	Heating, Ventilation, and Air Conditioning
HxET	Herstmonceux Event Timer
IAA	Institute of Applied Astronomy (Russia)
IABO	International Association for Biological Oceanography
IAG	International Association of Geodesy
IAPSO	International Association for the Physical Sciences of the Oceans

IA/RAS	Institute of Astronomy/Russian Academy of Sciences
IAU	International Astronomical Union
IBS	IAG Bibliographic Service
ICCD	Intensified Charged Coupled Device
ICESat	Ice Cloud and Land Elevation Satellite
ICET	International Center for Earth Tides
ICRF	International Celestial Reference Frame
IDS	International DORIS Service
IEEE	Institute of Electrical and Electronics Engineers
IERS	International Earth Rotation and Reference Systems Service
IFE	Institut für Erdmessung (Germany)
IGeS	International Geoid Service
IGFS	International Gravity Field Service
IGGOS	Integrated Global Geodetic Observing System
IGLOS	International GLONASS Service
IGN	Institut Geographique National (France)
IGOS	Integrated Global Observing Strategy
IGS	International GNSS Service
ILRS	International Laser Ranging Service
ILRSA	ILRS A solution
ILRSB	ILRS B solution
IMU	Inertial Measurement Unit
IMVP	Institute of Metrology for Time and Space (Russia)
INASAN	Institute of Astronomy of the Russian Academy of Sciences
InGaAs	Indium-Gallium-Arsenide
INGV	Istituto Nazionale di Geofisica (Italy)
InSAR	Interferometric Synthetic Aperture Radar
IOV	In Orbit Validation
IPIE	Science Research Institute for Precision Instrument Engineering (Russia)
IRS	Indian Research Satellite
IRV	Inter-Range Vector
ISGN	Integrated Space Geodetic Network
ISRO	Indian Space Research Organization
ISTRAC	ISRO Telemetry Tracking and Command Network (India)
ITRF	International Terrestrial Reference Frame
ITRS	International Terrestrial Reference System
IUGG	International Union of Geodesy and Geophysics

IVS	International VLBI Service for Geodesy and Astrometry
JAROS	Japan Resources Observation System Organization
JAXA	Japan Aerospace Exploration Agency
JCET	Joint Center for Earth Systems Technology (USA)
JGM	Joint Gravity Model
JGR	Journal of Geophysical Research
JIVE	Joint Institute for VLBI for Europe
JPL	Jet Propulsion Laboratory (USA)
KACST	King Abdulaziz City for Science and Technology (Saudi Arabia)
kHz	Kilohertz
LAGEOS	LAser GEOdynamics Satellite
LAREG	Laboratoire de Recherches en Géodésie (France)
LEO	Low Earth Orbit
LLR	Lunar Laser Ranging
LNU	Lviv National University (Ukraine)
LOD	Length Of Day
LOLA	Lunar Orbiter Laser Altimeter
LOS	Loss Of Signal
LOSSAM	LAGEOS Spin Axis Model
LOSTHERM	LageOS THERmal Model
LR	Laser Ranging
LRE	Laser Retroreflector Experiment
LRO	Lunar Reconnaissance Orbiter
LRO-LR	Lunar Reconnaissance Orbiter Laser Ranging
LRRA	Laser Retro Reflector Array
LRSO	Laser Ranging Safety Officer
LTT	Laser Time Transfer
LURE	LUnar Ranging Experiment
M-M	Marini-Murray
M-P	Mendes-Pavlis
MAO	Main Astronomical Observatory (Ukraine)
MCC	Mission Control Center (Russia)
MCP	Micro Channel Plate
MeO	Meteorology and Optics (France)
MEO	Medium Earth Orbit
MESSENGER	MErcury Surface, Space ENvironment, GEochemistry, and Ranging
MF	Mapping Function

MGS	Mars Global Surveyor
MHz	Megahertz
MLA	Mars Laser Altimeter
MLRO	Matera Laser Ranging Observatory (Italy)
MLRS	McDonald Laser Ranging System (USA)
M-M	Marini-Murray
MRR	Modulated Retro-Reflectors
MO	Master Oscillator
MOBLAS	MOBile LASer Ranging System
MOE	Medium Orbit Ephemerides
MOLA	Mars Orbiter Laser Altimeter
MSTA	Ministry of Science and Technology of Argentina
MSTC	Ministry of Science and Technology of China
NAO	National Astronomical Observatories (China)
NAOC	National Astronomical Observatories of Chinese Academy of Sciences
NASA	National Aeronautics and Space Administration (USA)
NASDA	National Space Development Agency (Japan)
NAS	National Academy of Sciences (Ukraine)
NASU	National Academy of Sciences of Ukraine
NCEP	National Centers for Environmental Prediction (USA)
NCL	University of Newcastle Upon Tyne (UK)
NCST	Naval Center for Space Technology (USA)
Nd:YAG	Neodymium Yttrium Aluminum Garnet
Nd:YLF	Neodymium: Yttrium Lithium Fluoride
NEAR	Near Earth Asteroid Rendezvous
NERC	Natural Environment Research Council (UK)
NGA	National Geospatial-Intelligence Agency (USA)
NICT	National Institute of Information and Communications Technology (Japan)
NOAA	National Oceanic and Atmospheric Administration (USA)
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NRIAG	National Research Institute of Astronomy and Geophysics (Egypt)
NRL	Naval Research Laboratory (USA)
NSF	National Science Foundation (USA)
NSGF	NERC Space Geodesy Facility (UK)
NUSJA	National University of San Juan of Argentina
OCA	Observatoire de la Côte d'Azur (France)
OGT	Observatoire Géodésique de Tahiti (French Polynesia)

OICETS	Optical Inter-orbit Communications Engineering Test Satellite (Japan)
OSTM	Ocean Surface Topography Mission
PALSAR	Phased Array L-band Synthetic Aperture Radar (Japan)
Pan-STARRS	Panoramic Survey Telescope and Rapid Response System (USA)
PAS	Polish Academy of Sciences
PCA	Point of Closest Approach
PDF	Portable Document Format
PMSL	Permanent Service for Mean Sea Level
PMT	Photo Multiplier Tube
POD	Precision Orbit Determination
POE	Precise Orbit Ephemerides
POL	Proudman Oceanographic Laboratory (UK)
POLAC	Paris Observatory Lunar Analysis Center (France)
PoliMi	Politecnico di Milano (Italy)
PPET	Portable Pico-Second Event Timer
PPN	Parameterized Post Newtonian
PRARE	Precise Range and Range-rate Equipment
PRISM	Panchromatic Remote-sensing Instrument for Stereo Mapping (Japan)
PROBA	Project for On-Board Autonomy
QC	Quality Control
Q/C	Quality Control
QE	Quantum Efficiency
QLDAC	Quick-Look Data Analysis Center (The Netherlands)
QLNP	Quick-Look Normal Point
R&D	Research and Development
RAS	Russian Academy of Sciences
RGO	Royal Greenwich Observatory (UK)
RINEX	Receiver Independent Exchange format
RIS	Reflector In Space
RITSS	Raytheon Information Technology and Scientific Services (USA)
RLEP	Robotic Lunar Exploration Program (USA)
RMS	Root Mean Square
ROA	Real Instituto y Observatorio de la Armada (Spain)
RRA	Retro Reflector Array
RSA	Russian Space Agency
RSG	Refraction Study Group
SAGE	Strategic Aerosol and Gas Experiment

SALRO	Saudi Arabian Laser Ranging Observatory
SAO	Smithsonian Astrophysical Observatory (USA)
SAR	Synthetic Aperture Radar
SCEG	School of Civil Engineering and Geosciences (UK)
SESAM	SEmiconductor Saturable Absorber Mirror
SGF	Space Geodesy Facility (UK)
SGT	Stinger Ghaffarian Technologies, Inc. (USA)
SINEX	Software Independent Exchange Format
SIRAL	SAR/Inteferometric Radar Altimeter
SLR	Satellite Laser Ranging
SLRP	Satellite Laser Ranging Processor
SNR	Signal-to-Noise Ratio
SOD	Site Occupation Designator
SOS-W	Satellite Observing System-Wettzell (Germany)
SOVT	System Operational Verification Test
SP3	Standard Product 3 (satellite orbit format)
SPAD	Single Photoelectron Avalanche Detector
SPIE	International Society for Optical Engineering
SRI	Space Research Institute (Russia)
SRIF	Square Root Information Filter
SSC	Set of Station Coordinates
SSV	Set of Station Velocities
SSN	Space Surveillance Network (USA)
SST	Satellite-to-Satellite Tracking
SSTL	Surrey Satellite Technology Ltd. (UK)
SYRTE	Systèmes de Référence Temps-Espace (France)
T2L2	Time Transfer by Laser Link
TC	Timer and Counter
TCE	Time Compare Equipment
TDC	Time-to-Digital Converter
TIGO	Transportable Integrated Geodetic Observatory
TIRV	Tuned Inter-Range Vector
Ti:Sap	Titanium Sapphire
Ti:Sapphire	Titanium Sapphire
TIU	Time Interval Unit
TKSC	Tskuba Space Center (Japan)
TLRS	Transportable Laser Ranging System

TOF	Time-Of-Flight
TOPEX	Ocean TOPography Experiment
ToR	Terms of Reference
TOR	Tracking, Occultation and Ranging
T/P	TOPEX/Poseidon
T/R	Transmit/Receive
TRF	Terrestrial Reference Frame
TROS	TRansportable Observation Station
TROS	Transportable Range Observation System
TTS	Triple Threshold Screening
TUP	Technical University of Prague (Czech Republic)
UCSD	University of California San Diego (USA)
UFP	Université de la Polynésie Française (French Polynesia)
UK	United Kingdom
UMBC	University of Maryland Baltimore County (USA)
UNAVCO	University NAVSTAR Consortium
UNESCO	United Nations Education, Scientific and Cultural Organization
UNSA	Universidad Nacional de San Augustin (Peru)
UPF	University of French Polynesia
UPS	Uninterruptible Power Supply
URL	Uniform Resource Locator
USA	United States of America
UT	University of Texas
UTC	Universal Coordinated Time
UV	Ultraviolet
VLBI	Very Long Baseline Interferometry
WESTPAC	Western Pacific Laser Tracking Network Satellite
WG	Working Group
WLRS	Wettzell Laser Ranging System (Germany)
WPLTN	Western Pacific Laser Tracking Network
YAG	Yttrium Aluminum Garnet
Yt:YAG	Ytterbium Yttrium Aluminum Garnet
ZD	Zenith Delay