The International Laser Ranging Service and Its Support for GGOS

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Abstract. The International Laser Ranging Service (ILRS) was established in September 1998 as a service within the IAG to support programs in geodetic, geophysical, and lunar research activities and to provide data products to the International Earth Rotation and Reference Systems Service (IERS) in support of its prime objectives. The ILRS develops the standards and specifications necessary for product consistency and the priorities and tracking strategies required to maximize network efficiency. This network consists of more than forty SLR stations, routinely tracking nearly thirty retroreflector-equipped satellites and the Moon in support of user needs. The Service collects, merges, analyzes, archives and distributes satellite and lunar laser ranging data to satisfy a variety of scientific, engineering, and operational needs and encourages the application of new technologies to enhance the quality, quantity, and cost effectiveness of its data products. The ILRS works with the global network to improve station performance, new satellite missions in the design and building of retroreflector targets to maximize data quality and quantity, and science programs to optimize scientific data yield. The ILRS Central Bureau maintains a comprehensive web site (http://ilrs.gsfc.nasa.gov) as the primary vehicle for the distribution of information within the ILRS community.

During the last few years, the ILRS has addressed very important challenges: (1) Data from the network stations are now submitted hourly and made available immediately through the data centers, (2) Tracking on low orbit satellites has been significantly improved through the sub-daily issuance of predictions, drag functions, and the real-time exchange of time biases, (3) Analysis products are now submitted in SINEX format for compatibility with the other space geodesy techniques, (4) The Analysis Working Group is now generating an operational station position and Earth Orientation Parameter (EOP) product, and (5) SLR has significantly increased its participation in the International Terrestrial Reference Frame (ITRF) activity.

Keywords. Space geodesy, satellite laser ranging (SLR), lunar laser ranging (LLR), International Laser Ranging Service (ILRS), terrestrial reference frame, GGOS.

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1 Role of Laser Ranging within GGOS

In early 2004, under its new reorganization, the International Association of Geodesy (IAG) established the Global Geodetic Observatory System (GGOS) project to coordinate geodetic research in support of scientific and applications disciplines. GGOS is intended to integrate different geodetic techniques, models and approaches to provide better consistency, long-term reliability, and understanding of geodetic, geodynamic, and global change processes. Through the IAG's measurement services (IGS, IVS, ILRS, IDS, and IGFS), GGOS will work to ensure the robustness of the three aspects of geodesy: geometry and kinematics, Earth orientation and rotation, and static and time varying gravity field. GGOS will identify geodetic products and establish requirements on accuracy, time resolution, and consistency. The project will work to coordinate an integrated global geodetic network and implement compatible standards, models, and parameters.

A fundamental aspect of GGOS is the establishment of a global network of stations with collocated techniques, working together to provide the strongest reference system. The ILRS will be one of the service participants in GGOS, bringing its unique strengths to the geodetic complex.

1.1 The Global Terrestrial Reference Frame

The terrestrial reference system is the basis through which we connect and compare measurements over space, time, and evolving technologies. It is the means by which we know that measured change over time is real and not corrupted with instabilities in our measurement technique.

One of the best-known scientific realizations of a global terrestrial reference system is the International Terrestrial Reference Frame (ITRF), updated every few years by the International Earth Rotation and Reference Systems Service (IERS). It is based on contributions from the four different space geodetic techniques, consisting of solutions for the positions and velocities of all participating tracking stations in an Earth-fixed geocentric coordinate system. The most important contributions of the laser ranging technique to the reference frame are the fixing of its origin (defined with respect to the center-of-mass of the Earth, including oceans and atmosphere) and its scale (defined by the speed of light, realized mainly through the measurement of the time of propagation, i.e., the ranges to satellites). Origin and scale are crucial elements, not only for “classical” referencing purposes (i.e., crustal deformation studies), but also as providers of an absolute reference for investigations on sea level change, ice budget, etc. ILRS contributions come either as multiyear solutions based on ranges to the geodynamic satellites LAGEOS-1 and -2 or, within the current IERS Combination Pilot Project, as time-series of weekly solutions. The latter are combinations of the individual solutions from several ILRS Analysis Centers to generate one "best" technique-specific submission for the IERS.

1.2 Earth in Space

The connection between the terrestrial and the celestial reference systems is given by the current position of the Earth’s body with respect to its current axis of rotation (polar motion), its orientation in space (UT1) or the change of its orientation (angular velocity, length-of-day), and the orientation of the axis of rotation in space (precession and nutation). One of the official ILRS products is the time-series of polar motion and length-of-day, submitted weekly to the IERS for combination with the time-series generated by the other space geodetic techniques.

1.3 Models of Earth's Gravity Field

Until recently global gravity field models were based on a combination of ground-based satellite tracking and surface measurements, with SLR playing a very major role. New, dedicated gravity satellite missions including new types of observations like satellite-to-satellite tracking, in-orbit observation of derivatives of the gravity field, and ocean-surface altimetry have provided much higher spatial and temporal resolution of the gravity field. However, lower-degree terms of this field and their secular changes (e.g., of the dynamic flattening of the Earth) are best observed by laser ranging. Also in view of the long time-history of the solutions, SLR provides extremely valuable information on (changes in) the overall mass distribution of the Earth. In this way, SLR provides extremely valuable information on (changes in) the overall mass distribution of the Earth.

1.4 Precise Orbit Determination and Verification

SLR provides routine precise orbit determination for some missions and verification and calibration of precise orbits determined with other tracking techniques such as GPS or DORIS for others. The high accuracy and unambiguous nature of SLR data makes it an independent source of quality control and calibration for other tracking techniques. In particular, SLR has been used in all of the recent ocean and ice topography missions to support altimeter measurements and for a number of special engineering activities (e.g., altimeter calibration).

SLR, with its totally passive spaceborne reflectors, also acts as a backup for active tracking techniques. It has saved satellite missions (ERS-1, GFO-1, TOPEX/Poseidon, and Meteor-3M) after the failure of the primary tracking system.

The ILRS continues to encourage new missions with high precision orbit requirements to include retroreflectors as a fail-safe backup tracking system, to improve or strengthen overall orbit precision, and to provide important intercomparison and calibration data with onboard microwave navigation systems.

1.5 Lunar Laser Ranging

The two ILRS stations currently capable of routinely tracking the four lunar targets have a long history of providing LLR data: the McDonald Observatory in Texas has been in operation since the Apollo 12 mission (since 1985 with the current system), whereas the Grasse Observatory in France started lunar laser ranging in 1987. Several stations have demonstrated lunar capability while others have tracked the Moon for some periods of time (e.g., Maui, Hawaii, 1984-1990). A number of stations (e.g., Matera, Italy, and Mount Stromlo, Australia) are planning to include lunar tracking in their future activities. Applications in gravitational physics include: testing of the Equivalence Principle; (limits for) time-variation of the gravity constant G; and the assessment of the geodetic precession. Applications in lunar science include the determination or the improvement of lunar ephemerides and rotation; dissipation-caused (negative) acceleration; and an assessment of the interior and the Lunar Love numbers.

More details about current SLR/LLR contributions to science can be found e.g., in the proceedings from the Science Session of the 2002 International Workshop on Laser Ranging (Noomen et al, (2003)).

2 The ILRS Organization

The ILRS is organized into the following components: Tracking Stations and Subnetworks, Operations Centers, Global Data Centers, Analysis and Associate Analysis Centers, a Central Bureau, Working Groups, and a Governing Board (see Figure 1 and Pearlman et al (2002) and Gurtner et al (2005)).

Stations in the ILRS Tracking Network range to the approved constellation of artificial satellites and the Moon and transmit their data in near-real time to the ILRS Data Centers. The full network currently consists of about forty SLR stations as shown in Figure 2. The ILRS has given strong encouragement to the development of Fundamental Reference Stations, where a combination of several space geodetic techniques including SLR, VLBI, GPS, DORIS, and absolute gravimetry are collocated to strengthen reference system constraints and system synergy. The majority of ILRS stations have a collocated GPS receiver that adheres to International GPS Service (IGS) standards.

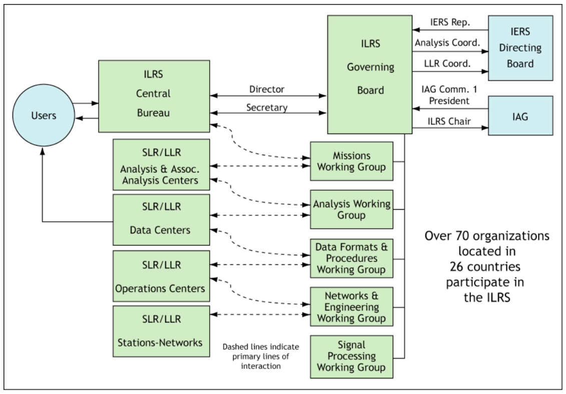

Fig. 1. Organization of the ILRS

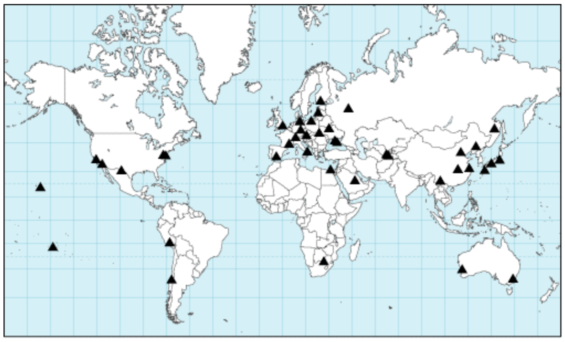

Fig. 2. ILRS Tracking Network (as of July 2005)

ILRS Operations Centers collect and merge the data from the tracking sites, provide initial quality checks on these incoming data, reformat and compress the data if necessary, and relay the data to an ILRS Data Center.

Two Global Data Centers archive all the ranging data and auxiliary data (e.g., station log files and satellite orbit predictions), make the data available to the ILRS Analysis Centers and external users of the data, and act as distribution centers for the primary ILRS products.

The Analysis and Associate Analysis Centers routinely generate the official ILRS products (station coordinates and derivatives at one-week intervals, EOP at one-day intervals) as well as special products, such as satellite predictions, time-bias information, precise orbits for special-purpose satellites, or scientific data products of a mission-specific nature. Lunar Analysis Centers process ranging data to the targets on the Moon and produce lunar-specific data products. There are currently about thirty ILRS Analysis and Associate Centers.

The Central Bureau (CB) is responsible for the daily coordination and management of the ILRS. The CB maintains the ILRS web site (http://ilrs.gsfc.nasa.gov), a source for all SLR- and LLR-related information, details about the organization and operation of ILRS, and also an entry point to the data and products stored at the Data Centers. The CB maintains the ILRS documentation, organizes meetings and workshops, and issues service reports.

The ILRS has four standing Working Groups that provide the expertise necessary to make technical decisions, to plan programmatic courses of action and are responsible for reviewing and approving the content of technical and scientific databases maintained by the Central Bureau. They are:

- Missions Working Group reviews requests for laser tracking and recommends the relative tracking priority with respect to other approved satellites.
- Data Formats and Procedures Working Group develops and maintains formats and standardized procedures.
- Networks and Engineering Working Group facilitates the generation, collection and distribution of data to the user community in a timely and efficient manner, and examines new technologies to improve network performance.
- Analysis Working Group (AWG) provides feedback to the network regarding data quality, maintains standards for methods of analysis, provides quality control on the analysis products, and organizes and coordinates activities for the official ILRS analysis products.

An ad hoc Working Group on Signal Processing studies the effects introduced by the satellite retroreflector arrays on ranging accuracy.

The ILRS Governing Board (GB) is responsible for the general direction of the service and defines official ILRS policy and products, determines satellite-tracking priorities, and develops standards and procedures. The sixteen-member body interacts with other services and organizations and is selected from ILRS associates representing all components of the service.

3 Tracked Satellites

Since its inception, SLR has tracked more than fifty satellites with retroreflectors. Currently, the ILRS tracks 28 satellites for geodynamics, remote sensing (altimeter, SAR, etc.), gravity field determination, general relativity, verification of global navigation systems satellite orbits, and engineering tests. Altitudes range from a few hundreds of kilometers to GPS altitude (20,000 km). Two stations, Grasse, France and McDonald, USA, routinely range to four targets on the Moon. Satellites are added and deleted from the ILRS tracking roster as new programs are approved by the GB and old programs are completed.

The ILRS assigns satellite tracking priorities in an attempt to maximize data yield on the full satellite complex while at the same time placing greatest emphasis on the most immediate data needs. Nominally, tracking priorities decrease with increasing orbital altitude and increasing orbital inclination (at a given altitude). Priorities of some satellites are then increased to intensify support for active missions (such as altimetry), special campaigns, and post-launch intensive tracking campaigns. Finally, daily priority adjustments are made based on actual data yield over the previous ten days.

New missions scheduled for ILRS tracking support over the next year include ALOS and OICETS, and the first two engineering versions of the Galileo satellites (GSTB-V2A and GSTB-V2B). It is anticipated that the full thirty satellite Galileo complex, to be launched between 2007 and 2008, will require, at least intermittent, SLR tracking.

The ILRS supports space engineering studies on some rather unique missions. The Russian Reflector satellite included retroreflectors over its nearly 1.5 meter length (Figure 3). Differences in the laser return time-of-arrival were used to interpret the orientation and dynamics of the satellite (Figure 4). Another mission, the Naval Research Laboratory's Tether Physics and Survivability satellite, (TiPS) with retroreflector arrays on two satellites separated by a four-kilometer tether was tracked by SLR to study tether dynamics in space.

4 Network Performance

Laser ranging stations use short pulse lasers to measure the distance to passive targets on satellites and the Moon. The measured range is the roundtrip travel time corrected for optical refraction, spacecraft center-of-mass, and relativistic effects. The prime data product from the ILRS stations are normal points, which are full-rate ranging data averaged over time intervals ranging from fifteen seconds to five minutes depending upon the satellite altitude. Absolute accuracy is typically better than a centimeter. Data are archived and available to the user on a pass-by-pass basis.

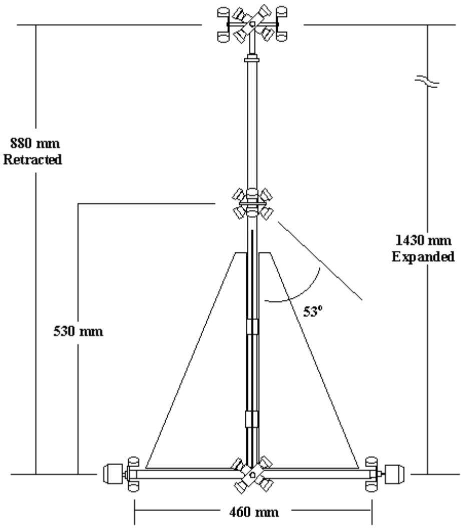

Fig. 3. Schematic of Reflector Satellite

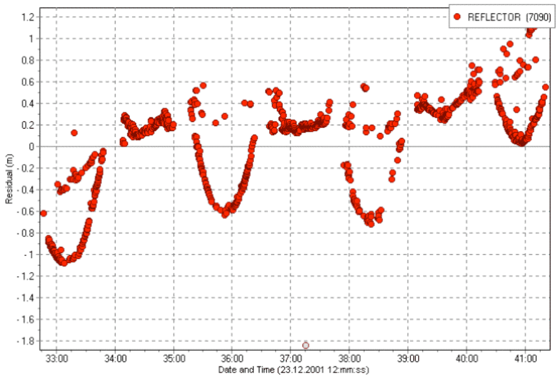

Fig. 4. Range residual pattern from Reflector sastellite observed at Yarragadee (Courtesy of N. Parkhomenko, RSA)

Since the inception of the ILRS through 2003, the data yield of the network continued to improve (Figure 5) as stations implemented more automated procedures and new satellites are added to the tracking roster. In 2004, the NASA network suffered some severe budget reductions resulting in the loss of two stations and decreased operations in the others. Efforts are underway now to resurrect the closed stations.

Most of the current laser-tracking stations range ten times per second during part or all of the satellite pass, with many stations interleaving passes from different satellites (see Figure 6). An example of a productive day at Yarragadee is shown in Figure 7.

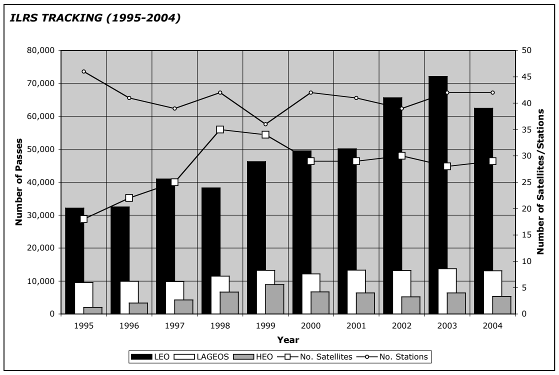

Fig. 5. ILRS Tracking (1995-2004)

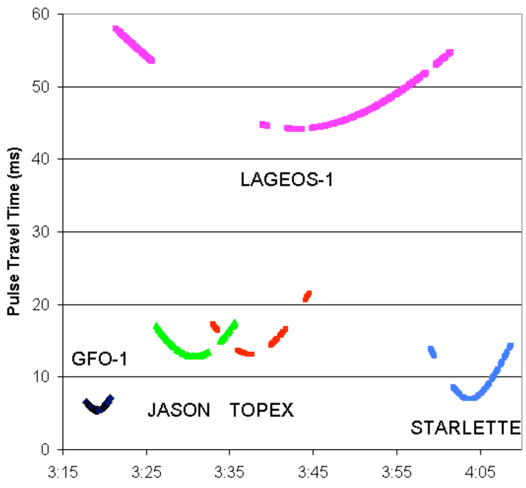

Fig. 6. Interleaved passes from Zimmerwald station

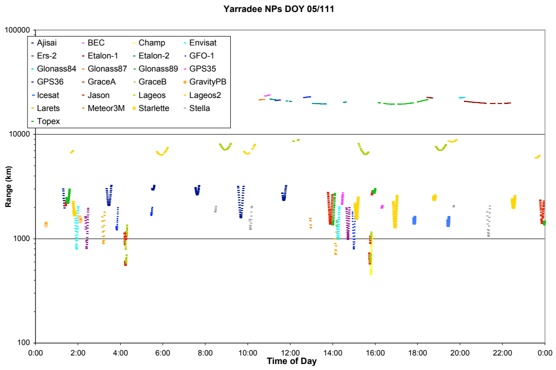

Fig. 7. A productive day of tracking at Yarragadee involves a very busy tracking schedule

5 Data Products

From the beginning, the ILRS has put the generation of official analysis products high on its agenda.

The Analysis Working Group has initiated several pilot projects, to address questions on the official products, to define standards, to reach consensus on product definition and, ultimately, to arrive at a reliable and high-quality operational product.

5.1 Pilot Project "Positioning+EOP"

One Pilot Project focused on the computation of the best-possible ILRS product for station coordinates and Earth Orientation Parameters (EOPs). Various scenarios were defined and tested for establishing the proper satellite mix, means of representing the results, computational strategies, etc.

This resulted in the scheme of processing that is currently operational. At this moment, five different analysis groups (ASI/Italy, DGFI/Germany, GFZ/Germany, JCET/USA and NSGF/UK) deliver weekly solutions on LAGEOS-1 and -2 for global station coordinates and EOPs on Tuesday of each week. These solutions are merged into a combination solution by ASI and DGFI. Based on the contributions that the analysis groups made to the Pilot Project and an evaluation of the quality of their results, the ILRS named ASI as its official Combination Center, with first responsibility for the generation of combination solutions for external customers such as the IERS. DGFI was named the official Backup ILRS Combination Center with the same product generation schedule. Several other institutions such as BKG/Germany, Geosciences Australia, and CSR/USA are also well on their way in the development of their contributions to the official ILRS product.

As an illustration of the quality of the individual solutions as well as that of the official combination product (the quality of the primary and the backup solutions is effectively identical), Table 1 gives a summary of the scatter of weekly solutions for geocenter components and global scale. It is clearly visible that the combination solutions give the best result, and that these products offer the best that ILRS can provide.

The combination solutions are used for a variety of purposes: the IERS Combination Pilot Project, the IERS/NOAA Bulletin A, etc. At the request of IERS, the ILRS AWG has started a back-processing of older SLR data in a similar fashion to serve as input for a successor to ITRF2000 and possible other applications. At this moment, the processing of older data focuses on the 1992-2003 timeframe (i.e., the time period since the launch of LAGEOS-2), but SLR measurements on LAGEOS-1 obtained in the years prior to 1992 will also be processed for input into the subsequent ITRF solutions.

Table 1. Scatter of Helmert parameters w.r.t. ITRF2000 of successive weekly ILRS solutions for 2004 (geocenter in mm, scale in ppb).

		Tx	Ty	Tz	Scale
Individual	ASI	3.6	2.5	6.0	0.3
	DGFI	3.8	3.2	7.9	0.5
	GFZ	3.6	5.0	7.3	0.4
	JCET	3.4	3.2	6.6	0.4
	NSGF	5.1	6.9	11.2	0.6
Combination		2.8	2.6	4.9	0.3

5.2 Pilot Project "Benchmarking"

A Benchmarking Pilot Project has been established to provide internal quality checks and quality control over the analysis process. Initially, this was used to scrutinize individual elements of the SLR observations, measurement corrections and parameter solutions. Having reached a fully operational status, the Benchmarking Pilot Project is now being used to assess the quality of new candidate contributors to the ILRS combination products and to identify possible errors.

Other pilot projects have also been developed to assess candidate products and analysis techniques.

5.3 New Products

In addition to the Station Coordinate and EOP Product, the AWG is studying the production of other official data products including satellite ephemerides and geocenter time history.

6 Modeling

The precision of the travel-time measurement is now of the order of several tens of picoseconds, corresponding to a few millimeters in distance. Ranging accuracy is limited mainly by errors in modeling for refraction propagation and the extrapolation from the reflectors to the satellite center-of-mass.

6.1 Refraction

Since the launch of LAGEOS-1 in 1976, laser ranging stations have used the Marini and Murray model (Marini and Murray, (1973)) for atmospheric propagation correction. The model works well at higher elevations, but degrades substantially below 20 degrees. A new model now available (Mendes and Pavlis (2004)) provides improved refraction correction at lower elevations, a region now of greater importance as we try to expand SLR orbital coverage.

6.2 Retroreflector Array

Early retroreflector designs, even those of the LAGEOS era, relied on multi-cornercube returns to maximize return signal strength. Satellite center-of-mass correction is highly dependent upon return signal strength and detector configuration, neither of which was well considered in the correction models. Errors could be as much as a cm. Models are now being implemented that use ground systems characteristics to improve the modeled correction to the level of a mm.

7 Advances Underway

A number of advances are currently being implemented that will substantially improve data productivity and quality, while at the same time reduce operational costs. Many of these advances that are now working in one or two stations are envisioned as general characteristics of the future SLR network.

7.1 Automation

Stations are implementing increased automation to reduce personnel costs and facilitate data throughput. The new Mount Stromlo station was designed from the beginning with around-the-clock fully automated, unmanned operations. The Zimmerwald laser station operates autonomously for periods of several hours each day. The fully automated NASA SLR2000 is currently under development.

7.2 KHz Ranging

With higher-repetition-rate lasers, faster event timers, and better control software, SLR systems are now able to significantly improve the ranging signal-to-noise conditions. The new Graz SLR station was the first to successfully operate a 2 kHz laser system, increasing the full-rate data volume by up to two orders of magnitude. The SLR2000 prototype is also being developed with this capability, as are upgrades at several other stations.

7.3 New, More Powerful Stations

A number of new systems with large meter-sized telescopes and state-of-the-art optical and mechanical performance are now operational. This helps to give the tracking network a mix of capabilities to better match the range of targets that now appear on the ILRS roster. The Matera station in southern Italy and the remotely controlled Tanegashima station in Japan both use powerful lasers and large optics to achieve single-shot range precision of a few millimeters.

7.4 Two-Color Ranging

Several groups are using two-wavelength ranging which provides a promising technique for developing better models for the refraction delay imposed by the atmosphere. Two-color ranging at 423 nm and 846 nm has been underway at Concepcíón for the past two years. The Zimmerwald station has recently begun routine operations at the same wavelengths. Other stations (including GSFC and Matera) have also demonstrated dual-wavelength capability, some of them with superior accuracy using streak cameras. As this technique matures, it is anticipated that the data will help in the improvement of the refraction models, and hence also the ILRS science products.

7.5 Improved Satellite Retroreflector Array Design

Early retroreflectors were designed to provide multi-cornercube returns to maximize return signal strength. Even with LAGEOS, the return signal is smeared over several centimeters, making measurements highly dependent upon signal strength and ground system properties. Efforts are underway to parameterize the ground stations and standardize models. Retroreflector array designs are also improving. Most of the recently launched satellites are using standardized arrays with restricted cornercube view. The spherical satellite GFZ-1, Westpac, and LARETS experimented with special reflector geometries to limit access to a very few (or single) cubes. Using another approach, the Russian Space Agency has provided the ILRS with a space borne test Luneburg Sphere that gives the same array correction for a wide variety of aspect angles (Meyer-Arendt, (1995)).

7.6 Transponders

Optical transponders for extraterrestrial ranging are currently under early development by several research teams. An optical transponder is a combination of a laser-ranging receiver and a separate laser pulse transmitter. As opposed to two-way ranging with retroreflector targets, one-way ranging with a transponder would offer the exciting opportunity of ranging to Mars, planetary moons or orbiters, and deep space missions (Degnan, (2002)). These transponders will also help to connect the terrestrial reference frame with reference systems used for planetary missions.

8 Conclusions

Laser ranging has proven to be a fundamental component of the space-geodetic complex, offering a straightforward, conceptually simple and highly accurate observable. It provides essential contributions to geosciences, space sciences and fundamental physics. It will play an important role in the GGOS project.

Current and future challenges lie in the improvement of the accuracy, reliability and availability of the data and in the long-term support of the network. Many of the technological building blocks for the next generation of laser ranging have already been demonstrated. Their comprehensive implementation will bring dramatic improvements to the capability of the technique.

Acknowledgements

The authors would like to acknowledge the support of the International Laser Ranging Service and its contributing organizations.

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