Presentation of Position Papers
Session Summaries
&
The Position Papers

Edited by

Erricos C. Pavlis

Goddard Earth Sciences and Technology Center

University of Maryland, Baltimore County

International Laser Ranging Service - 2009

Dedicated to Prof. Emeritus George Veis

A visionary and a teacher

On the occasion of his 80th birthday and the 50th anniversary of his Doctoral thesis on

"The Geodetic Uses of Artificial Satellites"

ILRS Workshop on SLR Tracking of GNSS Constellations

50 years of Satellite Geodesy & Geodynamics

Foreword

The Workshop Program

Part I – Executive Summary

Part II – The Session Summaries

Part III – The Eight Position Papers

1 - Impact of SLR Tracking of GNSS Constellations on GPS

2 - Impact of SLR Tracking of GNSS Constellations on GLONASS

3 - Impact of SLR Tracking of GNSS Constellations on Galileo

4 - Impact of SLR Tracking of GNSS Constellations on COMPASS

5 - Impact of SLR Tracking of GNSS Constellations on QZSS

6 - Impact of SLR Tracking of GNSS Constellations on Science

7 - Technological Challenges of SLR Tracking of GNSS Constellations

8 - Operational Challenges of SLR Tracking of GNSS Constellations

International Laser Ranging Service - 2009

Foreword

The 2009 International Laser Ranging Service (ILRS) Technical Workshop addressed a very timely issue: the tracking of current and future Global Navigation Satellite Systems (GNSS) constellations with Satellite Laser Ranging (SLR). The idea behind this workshop was to bring together experts from the SLR and GNSS communities providing them with a forum to discuss all aspects of the theme, focusing primarily on the science benefits, while tackling also problems arising from the large number of GNSS clients and the finite resources available to ILRS. In the opening lecture of the workshop, Professor Emeritus of the National Technical University of Athens, George Veis, the person to whom the workshop was dedicated on the occasion of his 80th birthday and who is by most considered the father of satellite geodesy, offered an excellent historical review of space geodesy, from its inception to present, including all modern space techniques with many examples and some rare photographic records.

The workshop intended to survey the two communities on the likely gains in Global Geodetic Observing System (GGOS) science from SLR tracking of GNSS constellations. Amongst the objectives of the workshop were to present an overview of the two techniques with emphasis on their synergism, a review of GNSS and SLR constellations and their networks, and the current state of the art. Additionally, presentations demonstrated how the two space geodetic techniques are applied in geodynamics, POD, positioning, gravity mapping, etc. One of the most central objectives was to examine approaches to help accomplish the goals set by GGOS, investigating the various options available (e.g. higher repetition rates, optimal normal point formulation, interleaving tracking of targets, better sampling of orbits, allocating targets to sub-networks, etc.). One of the goals of the workshop was to select the appropriate information for the optimization of the network design and deployment of the appropriate space segment to meet the GGOS requirements. A significant part of the deliberations was devoted to the fundamental differences between geodetic cannonball type targets (LAGEOS) and the complicated GNSS spacecraft. The material presented at the workshop indicated that applications specifically enabled through the synergism of the two techniques would likely benefit the most, however, additional studies taking into account the discussed mode of operations are required in order to define this qualitatively.

The success of the workshop is the result of the hard work of those who assembled and presented the various position papers, as well as those who contributed with supporting presentations and discussions. This workshop is only a first attempt to bring closer two of the IAG Services, ILRS and IGS, and it is hoped that it will be followed by similar events which will result in even closer collaboration between the two in the realm of GGOS. Finally, the overall success of the event is the result of the hard work of the local organizing committee and the support that we received from our sponsors. The workshop adopted unanimously a resolution thanking each and everyone who contributed to the success of the workshop.

Program: ILRS Workshop on SLR Tracking of GNSS Constellations 50 years of Satellite Geodesy & Geodynamics

Sept. 13, Sunday afternoon: Registration, icebreaker (offered by the Mayor of Metsovo) and program committee meeting

Sept. 14, Monday:

08:30 - 12:30 Registration and opening ceremonies
K. Tzafeas, Mayor of Metsovo
Prof. K. Moutzouris, Rector, National Technical University of Athens
Prof. R. Korakitis, Vice President, School of Rural and Surveying Engineering
Dr. Mike Pearlman, Director, International Laser Ranging Service
I. Kolovos, Director, Hellenic Army Mapping Service
Prof. (Emeritus) D. Balodimos, National Technical University of Athens
Prof. (Emeritus) A. M. Balodimou, National Technical University of Athens
Prof. (Emeritus) G. Veis, National Technical University of Athens

Chair: A.M.Balodimou, H.Billiris, K.Papazissi

12:30 - 14:00 Lunch Break

14:00 - 15:30 Impact of SLR Tracking on GNSS Constellations (Position papers)
PP 01:GPS, T. Springer

PP02: GLONASS, V. Vasiliev, V. Glotov

PP03: GALILEO, T. Springer

Chair: Mike Pearlman

15:30 - 16:00 Coffee Break

16:00 - 17:30 Impact of SLR Tracking on GNSS Constellations (Position papers)
PP04: COMPASS, X. Wang

PP05: QZSS, S. Nakamura, M. Sawabe

Status of SLR and the ILRS, M. Pearlman

Chair: E.C.Pavlis

19:45 Meeting at Diaselo
20:00 Dinner

Sept. 15, Tuesday:

09:30 - 10:30 Science from SLR and GNSS – A
Processing large volume GPS data via Bernese V4.2 software
C. Mitsakaki, A. Marinou, X. Papanikolaou, K. Papazissi

InSAR mapping of surface deformation on Lefkada island during 1992-2006 and its relation to seismic activity
A. Ganas, V. Korakas

Crustal Deformation from GPS measurements at the Ionian Sea: Preliminary Results
D. Anastasiou, D. Paradissis, A. Ganas, A. Marinou, K. Papazissi, G. Drakatos, K. Makropoulos

Chair: D. Paradissis
10:30 - 11:00 Coffee Break

11:00 - 12:30 Science from SLR and GNSS – B
Accurate Geoid Undulation Determination along a 120 km Long Railway Traverse in Central Greece: Preliminary Results and Validation
V. Gikas, A. Androulaki, A. Bimis, V. Zacharis, K. Fragos

The Eastern Mediterranean Altimeter Calibration Network – eMACnet
E. C. Pavlis, K. Evans, P. Milas, B. A. Massinas, D. Paradissis

The ASI/CGS contribution to the ITRF maintenance: the ILRSA solution
C. Sciarretta, V. Luceri, G. Bianco

Contribution of Future SLR Networks to the Development of ITRF
E. C. Pavlis, M. Kuzmicz-Cieslak, P. Hinkey

The GPS-SLR bias: dynamics, attitude and current experiments
M. Ziebart, T. Springer

Chair: A. Ganas

12:30 - 14:00 Lunch break

14:00 - 15:45 Science from SLR and GNSS – C
Apparent Geocenter Oscillations in GNSS Solutions Caused by the Ionospheric Effect of Second Order
K. Palamartchuk

Adaptive Likehood Estimator for Forecasting Ionospheric Component on Synthetic Aperture Radar Interferometry (InSAR) Technique
B. A. Massinas, N. Doulamis, D. Paradissis

A Tapped Delay Line Neural Network for Modeling Ionospheric Disturbances Behavior
A. Doulamis, B. A. Massinas, D. Paradissis

Advanced Signal Processing Techiques for Inverse Synthetic Aperture Radar (ISAR) Imaging
A. Karakassiliotis, G. Boultadakis, G. Kalognomos, B. A. Massinas, P. Frangos

Summary of recent and current research on ISAR Signal Processing at the NTUA, Greece
P. Frangos

Deformation of the southern Aegean from continuous Global Positioning System measurements
K. Palamartchuk, M. A. Floyd, P. England, B. Parsons, J.-M. Nocquet, C. Raptakis, D. Paradissis, H. Billiris, J. Galanis

A relation between actual and normal Ricci curvature of the equipotential surfaces of the Earth's gravity field along GOCE track
G. Manoussakis and D. Paradissis

Chair: K. Katsampalos

15:45 - 16:15 Coffee Break

16:15 - 18:00 Science from SLR and GNSS – D
Hellenic Terrestrial Reference System 2007 (HTRS07): A regional realization of ETRS89 over Greece in support of HEPOS
K. Katsampalos, C. Kotsakis, M. Gianniou

Discussion (Datums)

Chair: V. Gikas

19:00 - 20:00 ILRS Data Formats & Procedures WG

Sept. 16, Wednesday:

Daily Excursion

09:30 Departure from Metsovo

10:30 – 12:00 Visit at Archeological Site of Dodoni

13:00 – 16:00 Visit at the Lake of Ioannina

16:30 – 18:30 Visit at the Town of Ioannina

19:00 Arrival at Metsovo

20:00 Gala dinner and live concert music at Diasselo (offered by the Organizing Committee)

Sept. 17, Thursday:

Position paper presentation and discussion

08:30 - 12:30 PP 06: Scientific impact of SLR tracking of GNSS Constellations
E. C. Pavlis

What is the benefit of tracking GNSS satellites with SLR?
D. Thaller, R. Dach, G. Beutler, M. Mareyen, B. Richter

An assessment of the value of SLR observations to GNSS
R. Govind

Collection and processing in TSNIMASH of GLONASS spacecraft ranging data obtained by Russian and global SLR network stations
V. D. Glotov, N. N. Parkhomenko

SLR Observations of COMPASS – G2
Y. Fumin, Z. Zhongping, C. Juping, C. Wanzhen, Z. Haifeng, W. Zhibo, M. Wendong

ESOC SLR Activities
T. A. Springer, C. Flohrer, M. Otten, D. Svehla, J. Dow

Two approaches to build time series of EOP from SLR data
F. Deleflie, D. Coulot, B. de Saint Jean, J.-M. Lemoine, P. Exertier, O. Laurain

(**10:15 - 10:45 Coffee Break**)

Chair: J. Ries

12:30 - 14:00 Lunch break

12:30 – 13:30 ILRS Missions WG meeting (working lunch)
14:00 - 18:00 PP 08: Operational issues
G. Appleby

Scheduling lessons learned from Lunar Laser Ranging
R Ricklefs

Operational 'Best Practices' for the NASA laser systems
H Donovan

Possible strategy for laser tracking the future GPS constellation
S Wetzel

Potential Scheduling Applications to the Tracking of the GNSS Constellations
C Clarke

GOCE orbit predictions for SLR tracking
A. Jäggi, H. Bock, W. Gurtner, R. Floberghagen

Towards 2kHz new SLR system in Metsähovi
K. Arsov, A. Raja-Halli, J. Näränen, M.Poutanen

Routine kHz tracking at Changchun and Shanghai
Z Zhongping, Y Fumin, *et al*

Navigation of the RadioAstron Mission
R. M. Bebenin, Y. N. Ponomarev, V. A. Stepanyants

(**15:45 - 16:15 Coffee Break**)

Chair: M. Pearlman

Sept. 18, Friday: **Position paper presentation and discussion**

08:30 - 12:30 PP 07: Technology Challenges
M. Pearlman

Uncoated Cubes for GNSS Satellites
D. Arnold

Proposed Single Open Reflector for the GALILEO Mission
R. Neubert, J.Neubert, J. Munder, L. Grunwaldt

Target signature effects on laser ranging accuracy for the GIOVE satellites
T. Otsubo, P. Gibbs, G. M. Appleby

Relative signal strengths from SLR tracking of the different retroreflector targets onboard HEO satellites using the fullrate data set
M. Wilkinson, G. Appleby

Creation of the new industry-standard space test of laser Retroreflectors for GNSS constellations
S. Dell'Agnello, G. O. Delle Monache, D. G. Currie, R. Vittori, C. Cantone, M. Garattini, A. Boni, M. Martini, C. Lops, N. Intaglietta, R. Tauraso, D. A. Arnold, G. Bianco, M. R. Pearlman, S. Zerbini, M. Maiello, S. Berardi, L. Porcelli

Some conditions necessary to achieve submillimiter accuracy in SLR
M. A. Sadovnikov
HEO and Moon tracking at Grasse (MeO).
JM Torre, M Aimar, D Féraudy, M Furia, H Mariey.

First T2L2 results and time transfers
P Exertier, E Samain

(**10:15 - 10:45 Coffee Break**)

Chair: G. Appleby

12:30 - 14:00 Lunch break

14:00 - 16:30 Panel discussion with all the PP leaders and a summary and action item identification - Closing remarks

Chair: E. C. Pavlis

Sept. 19, Saturday: **09:00 - 12:00 ILRS Analysis Working Group meeting**

PART I

Executive Summary

Executive Summary

The 2009 International Laser Ranging Service (ILRS) Technical Workshop addressed a very timely issue: the tracking of current and future Global Navigation Satellite Systems (GNSS) constellations with Satellite Laser Ranging (SLR). The workshop brought together experts from the SLR and GNSS communities to discuss all aspects of the theme, focusing primarily on the science benefits, while also tackling problems arising from the large number of GNSS clients and the finite resources available to the ILRS. We summarize herein the most important findings, conclusions and recommendations.

The meeting stressed that there is great synergism between the two techniques and that these synergies should be fully exploited to the benefit of the larger community, in particular the communities of space geodesy and Earth science. What is now required is to understand the requirements of each of the GNSS constellations and then to optimize SLR and GNSS resources to maximize the benefit to all.

The combined list of benefits to both techniques, space geodesy, and to the broader community of users in general, can be summarized in the following:

- SLR tracking of the GNSS satellites allows to connect the ILRS/SLR and IGS/GNSS reference frames in space (using "space ties");
- Validation and calibration of the GNSS orbit quality, passing SLR tracking through GNSS-based orbits and by comparison of GNSS orbits to independently determined orbits from SLR tracking;
- Improvement of GNSS-based results by combining SLR and GNSS data at the observation level;
- Improvement in the determination of the SLR contribution to the terrestrial reference frame by including laser ranging to GNSS satellites along with that to lower satellites (e.g. LAGEOS);
- Improved scale contribution to International Terrestrial Reference Frame (ITRF) from improved GM estimates based on SLR tracking of GNSS satellites (and indirect improvement of lower orbits as well, e.g. for LAGEOS);
- Improving the orbits of LEO satellites with onboard sensors like radar and laser altimeters, sounders, SAR, InSAR, etc.

The presentations of the GNSS operators indicated that there is already a great effort on interoperability of these constellations for the benefit of society. It remains to be seen if these operators will rise to the occasion and we will see an equally enthusiastic harmonization of their relationship to the SLR community, signing up to the requirements and ensuring a uniform treatment for all GNSS constellations. This can only increase the benefits to all parties and keep the cost and effort of the SLR community as low as possible.

From the GNSS point of view, the most important requirements on SLR are:

- Continuous SLR tracking of all GNSS targets, or as network capacity permits, using optimized scenarios that ultimately rely on the combined use of the two techniques;
- GNSS operators should follow strictly the ILRS recommendations for laser reflector array (LRA) designs to meet network requirements for best data yield;
- The SLR community should document unambiguously and maintain a publicly accessible data base of all known system biases for the ILRS network, past and future, with clear documentation even for non-SLR users;
- Extensive and timely (even near real-time) support of GNSS constellations, especially during the initial deployment phase and their "in-orbit validation" phases for models, hardware, software, operations, etc.

From the ILRS point of view, important requirements are:

- All of the GNSS operators should adhere to the adopted ILRS standard for the laser reflector arrays (LRA), so that ILRS can assure uniform tracking capability throughout its network and at all times and conditions;
- An accurate calibration of all LRA designs prior to launch with a goal of a measurement of the vector to the center of gravity of the spacecraft to within a few millimeters (1-3 mm) and continuous monitoring of any changes while in orbit, due to fuel expenditure, attitude changes, etc. ;
- A precise description of the spacecraft attitude routine while in orbit and during periods of SLR tracking in particular;
- The ILRS must work with the separate GNSS constellation communities to develop a practical strategy to satisfy both the tracking requirements of the constellations and those for the development of the terrestrial reference frame;
- The ILRS should continue the simulation activity on GNSS satellites in order to quantify trade-offs among competing options

An overarching requirement is that the GNSS and SLR communities work together to facilitate communications so that planning can be done well in advance of any new GNSS deployments to exploit best the combination of techniques.

PART II

The Session Summaries

Impact of SLR Tracking on GNSS Constellations (GPS, GLONASS, Galileo, COMPASS/Beidou, and QZSS)

Summary of the Session to Present and Discuss Position Papers 1 through 5

The first scientific session of the workshop comprised five position papers, each one presenting the view of each of the GNSS constellations on the impact they expect from tracking them with SLR. A sixth presentation discussed the status of the SLR technique today and the International Laser Ranging Service (ILRS).

The presentations in this session focused on what SLR tracking would add to their operations at all stages, from the early stages of deployment of their spacecraft to the fully operational stage and beyond. Clearly, due to the fact that each of the represented constellations is in a different stage of maturity, the emphasis of the impact of SLR tracking was quite different too. A survey of the different views though shows that all parties recognize some cross-cutting areas that apply to all: (a) the validation and calibration of GNSS orbit quality, (b) improvement of the GNSS-based products through the combination of radiometric and SLR range data at the observation level, and (3) an improved contribution in the development of the reference frame by including laser ranging to GNSS satellites along with the currently used SLR targets (LAGEOS).

Tim Springer presented the GPS Position Paper (PP), after discussions with its primary authors, since none of them could be present at the meeting. The PP focused on material that the GPS community used to back the presented positions and recommendations, most of which are already published in reviewed literature and accepted broadly by the community. Their main points were:

a) With only two GPS satellites equipped with CCR arrays and a very sparse tracking SLR data set mostly due to poor SLR network geometry and inability to track the specific arrays, it is very difficult to understand the contribution of SLR data towards an improved GPS product. The panel recognized past and recent efforts to evaluate the contribution of SLR data and suggested that more studies are required to further clarify this and to decide the optimal operational mode.

b) A key recommendation is that the consensus of the inter-agency working group and the position advocated to the U.S. Air Force and the IFOR is for every GPS III satellite to carry a retro-reflector. The reasons behind this request are the ease of swapping targets during normal operations (all s/c will have the same CCR array), uniformity in the design, development and testing of the GPS III s/c, and given the identical target design, etc., the ability to perform sensitivity analyses of the CoM offsets and other systematic differences among satellites in the same orbit plane or other studies of interest operationally and scientifically.

c) Finally, a very important request from the GPS community is the maintenance of very accurate CoM offsets for the GPS satellites in the future, before launch and during operations.
The position paper was supported by various presentations during the science sessions and the sessions that dealt with the operational and technological challenges of SLR tracking GNSS.

The second PP was devoted to GLONASS, the only operational GNSS with CCR arrays on all past and current spacecraft. Vladimir Vasiliev and Vladimir Glotov presented the PP in two parts: a review of the history and future of GLONASS and SLR tracking with a focus on the network segment (Vasiliev) and the current state and future plans for the space segment with an emphasis on the use of SLR technology (Glotov).

The first part stressed the continued importance of SLR within the GLONASS community, the strong support of past campaigns involving both techniques (e.g. IGEX98) and the benefits from it, and the recent efforts to further extend the use of SLR technology on the future GLONASS spacecraft. The current plans call for an upgrade or new development of ground stations that will bring the total number of stations on Russian territory capable to track GLONASS (and other GNSS s/c) to more than twenty. Some of these sites will have capabilities to range well beyond near Earth, to support astronomical missions (e.g. RADIOASTRON) and missions near the Lagrange points. SLR is also implemented on future GLONASS s/c for inter-satellite communication and ranging purposes, as well as time transfer. The ground network is also being adapted to support one-way and two-way ranging for orbit determination and time synchronization experiments. The future GLONASS arrays will be smaller, rounder and more efficient for better performance.

The second presentation focused on the GLONASS future and the Russian commitment to interoperability with other GNSS and the continued support of operations as they have done in the past. This includes the use SLR as a tracking tool and as it was mentioned in the first presentation, with an expanded role in the future GLONASS. A plan of future launches indicated that by the end of this year there will be six more s/c launched, so that by the end of 2010 the constellation will be fully operational providing global services 99.9% of the time. It is interesting to note that a new s/c design was also presented, the GLONASS-K bus, which will be tested next year and which will gradually replace the current GLONASS-M design under the new plan for GLONASS modernization (2012-2020). The new bus will ensure continued free access to all users, the interoperability with all other GNSS systems and improved GLONASS operations, relying heavily on laser technology.

A third position paper described the impact of SLR tracking of Galileo spacecraft, something that is considered as standard mode of operation for this constellation. The PP was presented by Tim Springer one of the main authors of the document. After a brief review of the Galileo system, the current status and the plan for the deployment of the operational segment, the focus was placed on the use of SLR during all these phases and the high degree of importance that Galileo grants to this tool. Using examples from SLR-enabled improvements from the GPS community as well as the use of SLR tracking during the Initial Orbit Validation phase of Galileo, Springer made a strong case for including as standard the appropriately designed CCR arrays on all Galileo spacecraft and how these will address areas of concern in operating and maintaining an accurate and robust navigational constellation. The Laser Ranging Array (LRA) provides access to many potential advantages coming from SLR, none of which are strictly necessary for meeting the Galileo system requirements, but which give access to potential operational benefits, enforce Galileo's place in space geodesy, and play their role in the evolution of Galileo.

In summary SLR tracking on Galileo may deliver the following contributions:

• Support for satellite fine positioning and operational POD, especially for IOV and early FOC because of sparse Galileo tracking station network.
• Provide a completely independent validation of the Galileo orbits.
• Enable calibration and validation of the spacecraft dynamics.
• Ensure a close alignment of the Galileo TRF and ITRF reference frames.
• Maintain and improve the ITRF.
• Ensure the position for Galileo in the scientific community in general, and GGOS and GMES in particular.
• Position Galileo as the "best" GNSS system

The next PP was devoted to another upcoming navigation system, the Chinese COMPASS/Beidou constellation, and it was presented by Xiaoya Wang. Despite the fact that COMPASS is one of the more recent systems to enter the international navigation community, they have by design assigned a major role to SLR tracking of their spacecraft, very similar to GLONASS operations. One of the added complication in the case of COMPASS is the fact that the constellation comprises of two different segments, one in near-earth orbits similar to the other systems, and a second group that are placed in geostationary orbits. With only one spacecraft of each type in orbit at the moment, COMPASS is in a very similar development state as Galileo. The very sparse ground network of radiometric data receivers and the early stage of these receivers' design forces them to rely very heavily on SLR tracking for POD and for the calibration of their microwave-data-based orbits. With a very well designed CCR LRA, for COMPASS the answer to the question about the impact of SLR tracking is crystal clear: indispensable. Examples of POD with both techniques and relative and absolute accuracy assessment showed that SLR tracking, even at the low level that is currently available for COMPASS, can easily validate the radiometric orbits' quality (meter level) and point out deficiencies in the dynamical modeling of the spacecraft due to the superior quality of the SLR-data-based orbits (decimeter level).

In addition to the general points and recommendations from all systems, COMPASS put forward some very real issues that require the immediate attention from ILRS. The future application of SLR tracking on COMPASS would basically aid in the following:

1) Continue to provide independent SLR-based COMPASS orbits and validate the COMPASS microwave orbits.
2) Evaluate the COMPASS microwave orbits with SLR data and determine what kind of processing strategy is better. This is very important especially now before the whole navigation system has been completed (a few satellites only in orbit) and there are many unstable error sources that make orbit determination difficult and complicated.
3) Check system errors using differences between COMPASS SLR orbits and microwave orbits, orbit evaluation residuals and dynamical model parameter values.
4) Perform additional studies to establish better methods and models to compute improved orbits, including combination orbit determination using SLR data and microwave data together.

However, none of the above can be applied today until we greatly improve the present status with regard to SLR tracking support of COMPASS. Items for urgent attention according to this system's operators include the following:

• Continuous SLR observations are important and necessary for COMPASS POD. When there are large data gaps over several days the adopted validation methods fail.
• The cooperation of more of the ILRS sites is needed, with better global distribution; this is necessary in order to improve COMPASS SLR-based POD.
• A need for SLR data being available in near real time (less than 6 hours). Current experience shows that in some cases no new SLR data for COMPASS exist even within 2-3 days from the date when they are needed.
• A need for studies to quantify and balance the requirement for 'continuous SLR observations' according to the specific needs of each particular investigation using SLR tracking of COMPASS.

In one word, SLR can provide 5 cm level or so orbit determination (it is often 1 m or so from microwave measurements), so high precision SLR data are very useful to improve COMPASS orbits, validate COMPASS microwave orbits, look for system errors and improve adopted models and methods. This is especially true during Phase 1 of the COMPASS development, since SLR observations are most important due to their potentially global coverage (as opposed to the limited and regional character of the available microwave data).

The fifth and final PP for a navigation system was addressed to the Japanese QZS system developed by JAXA. The PP was presented by M. Sawabe and S. Nakamura. The Quasi-Zenith Satellite System (QZSS) is a regional space-based positioning system that uses a constellation of satellites placed in multiple orbital planes with a similar purpose to that of the European EGNOS. The satellites have the same orbital period of a traditional equatorial geostationary orbit, however, they are elliptical and they have a large orbital inclination both of which result in a dynamical ground-track on Earth. The system covers regions in East Asia and Oceania centering on

Japan and is designed to enable users in the coverage area to receive QZS signals from a high elevation angle at any time.

The presentations highlighted the purpose, design and operation of QZSS when fully deployed, several years from now. They also stressed the high dependence of the system on accurate and timely SLR data for its success. The proposed CCR LRA was described and discussed and it was compared to the one (similar) that was launched on the ETS-8 spacecraft of JAXA, which was successfully tracked by many ILRS stations. Based on that proven design and following a very careful "scaling" process, the design was adapted for use on the future QZS spacecraft. In addition to this detailed discussion, the proposed SLR tracking for the various stages of deployment of QZSS were also presented.

The conclusions reached during this phase of the project are that SLR will be an integral part of QZSS at all stages. In order to distribute reliable QZS final orbit/clock data, it is better to add the SLR data on QZS navigation data when developing the final products. During this process, SLR data plays an important role: its absolute nature and high accuracy can decouple the ambiguity between range bias and time bias, thus leading to significantly improved products. JAXA expects to make full use of the ILRS data acquired under a very precisely prescribed plan:

1) 1st stage (campaign):
Sufficient SLR data needed to perform POD only by SLR data.
Core Time Tracking: 0:00-0:15, 4:00-4:15, 8:00-8:15, 12:00-12:15, 16:00-16:15, 20:00-20:15 (UT).
Candidate SLR stations: ILRS western Pacific area

2) 2nd stage (nominal operation):
It is not necessary to get SLR data on all occasions during the operational phase.
Core Time Tracking: For Example, 9:00-9:15, 12:00-12:15, 15:00-15:15 (UT)
Candidate SLR stations: ILRS western Pacific area.

JAXA has committed to support these operations from their own SLR station as well as the other Japanese sites.

The final presentation of the session was not a position paper but rather a status report on the present state of the SLR technique and the plans for the future. This by and large represented the description of the ILRS present and future, as the highest international authority coordinating the application of laser technology for precision orbit determination and other geodetic applications. Michael Pearlman, Director of the Central Bureau of the ILRS, made the presentation.

After a brief introduction of the technique and its contributions to science, the presentation focused on demonstrating the long history of SLR support for many diverse missions and with a multitude of requirements. The significance of SLR in the development of universally used products such as the ITRF was stressed, as well as the many times that SLR supported tracking of GNSS for various campaigns. The plans for the improvement of the ground segment of the ILRS network as well as the design of optimal LRA targets were also presented, to allay any fears of substandard support in the future, as it was expressed earlier for the past and present situation by most of the GNSS position papers. The presentation conclude by offering a possible plan for multiple GNSS tracking:

• Assumptions:

– Satellites carry the enhanced array (factor of 5 increase in effective cross section);
– Precise Center of Mass information including the change with fuel consumption required for all spacecraft;
– Many network stations will be using enhanced systems (e.g. kHz ranging, improved detection, etc.) in the 2013 timeframe for improved performance on weak targets;
– Increased automation and data interleaving procedures at the field stations will increase ranging efficiency;

• Concepts for an Operational HEO Plan:

– Support GPS, Galileo, GLONASS, COMPASS, QZSS and possibly others;
– Pointing predictions based on on-board GNSS data and SLR data for improved pointing particularly in daylight using real-time communications;
– Decrease Normal Point intervals (from the nominal 5 minutes) as data volume increases, thereby increasing tracking capacity;
– Three segments per pass (ascending, middle, descending);
– Data available for analysis immediately after each pass;
– Network tracking roster organized for at least 16 GNSS satellites at a time (at least one satellite per orbital plane per system);
– Tracking cycles set for 30 – 60 days (to cover all satellites within a 12 month period);
– Greater stress on daylight tracking;
– Flexible tracking strategies; organized in cooperation with the agencies involved and the requirements for the ITRF.

This presentation set the stage for the remaining three position papers that are devoted to (a) the impact that SLR tracking of GNSS constellations will have on science, (b) the technological challenges that SLR must meet in view of this effort and (c) the operational challenges that were set forth by the requirements established by each of the presented GNSS position papers.

Impact of SLR Tracking of GNSS Constellations on Science

Summary of Session to Discuss Position Paper 6

The presentations in this session demonstrated a number of ways that SLR tracking to GNSS can significantly impact science results. These can be partitioned into three broad areas; (1) validation and calibration of the GNSS orbit quality, either through passing GNSS-based orbits through the SLR tracking or by comparison with orbits determined independently from the SLR tracking, and (2) improvement of the GNSS-based results through direct ingestion of the SLR data at the observation level, and (3) improvement in the determination of the SLR reference frame by including laser ranging to GNSS satellites with the lower LAGEOS satellites.

The independent SLR tracking provides the opportunity to validate various aspects of the GNSS modeling. In some cases, such as the GPS and COMPASS satellites, the SLR tracking is rather sparse, and accurate independent orbits are more difficult to determine. However, even in the case of sparse tracking, the microwave-based orbits can be passed through the SLR data to distinguish modeling improvements at the cm level. For example, it was shown that when the GNSS modeling was improved to include Earth radiation pressure and the transmit power recoil, the residual bias of ~4 cm in the SLR tracking was reduced to ~2 cm. In another presentation, larger SLR residuals were observed during shadowing, indicating that there may be significant mismodeling of the satellite yaw during these periods. If the yaw modeling is modified, it should be clear in the SLR residuals whether the model is an improvement. When independent orbits can be accurately determined from the SLR tracking, it was shown that such orbits could reveal systematic orbit errors, such as cross-track orbit errors that may be correlated with clock errors, that cannot be resolved using the microwave data alone. Finally, the GNSS spacecraft center of mass (CoM) models can be validated with the SLR tracking to the few mm level. This has already been demonstrated for the Jason-1 altimeter satellite, where a 13±1 mm offset in the X-axis was confirmed with the SLR data, while the ~40 mm offset seen only in the GPS data could be shown to be incorrect (now known to be due to the incorrect, at the time, modeling of the GPS transmit antenna phase center).

The second contribution of the SLR tracking would be to incorporate the absolute range information with the GNSS data at the observation level. This allows the estimation of some of the GNSS biases that cannot be separated using GNSS data only. This approach was demonstrated to significantly improve the overall quality of the GNSS-based reference frame, particularly in sorting out biases that can affect the scale of the GNSS-based terrestrial reference frame (TRF). While SLR uniquely provides the origin of the TRF, and SLR/VLBI provide the scale, it is essential that this origin and scale be accurately transferred to the GNSS frame. This is especially important since GNSS is generally the only disseminator of the TRF to the users; there will typically be no SLR or VLBI site next to a tide gauge, for example. The combination of laser ranging and microwave tracking to the same target was demonstrated to provide a stronger link between the SLR and GNSS-based frames. This can help compensate for the lack of precise local ties at some ground stations or provide an independent assessment of the accuracy of existing survey ties. All this should lead to more accurate and internally consistent determinations of the TRF based on the various contributions of SLR, VLBI, GNSS and DORIS.

The third impact of SLR tracking of GNSS satellites would be the improvement of the SLR contribution to the terrestrial reference frame, especially in terms of scale. Because SLR tracking provides a measurement of the absolute distance to the satellite, it is able to simultaneously determine the satellite orbit, the reference frame scale, the Earth's mass (GM) and even the ranging biases; biased range measurements such as GNSS and DORIS cannot. Consequently, the GNSS analysis 'inherits' the scale of the geocentric frame from SLR. However, absolute knowledge of the satellite's center of mass must be known, and the current uncertainty in determining GM is limited at the few mm level by possible systematic errors in the LAGEOS CoM model. Because of the effect of scale on estimating GM, the SLR tracking of GNSS satellites, if the CoM is known to a few mm, may be able to improve the estimate of GM by perhaps a factor of two or more. The SLR tracking of the lower satellites would benefit from this improved estimate of GM, helping to sort out the CoM issues for the lower satellites and improve the TRF scale as determined by SLR.

In addition to improving the estimation of GM, simulations were presented that demonstrated the direct improvement in determining the terrestrial reference frame when laser ranging to a constellation of GNSS satellites was included in the SLR-based solution. While the error models for this initial simulation were relatively simple, the results demonstrate the potential for SLR to GNSS satellites to help achieve the part in 10^{10} level that is the current goal for the terrestrial reference frame for precise geodetic applications.

Technological Challenges of SLR Tracking of GNSS Constellations

Summary of Session to Discuss Position Paper 7

Mike Pearlman summarised his Position Paper on Technological Challenges for SLR tracking of GNSS constellations. The main points raised are summarised below.

- The current diverse ILRS network technology was discussed and it was noted that the lack of an ideal geographic distribution is less of an issue for GNSS tracking
- Only a relatively few of the most capable stations currently make a significant contribution to GNSS tracking
- Several stations are being upgraded with event timers, high-rep lasers, photon-counting detectors, etc., that will significantly improve performance for the low-signal, high-altitude GNSS satellites
- The NASA Next Generation SLR is an example of this type of system
- Short-pulse, high-repetition systems probe the target arrays at high resolution, leading to clear single-cube signatures and the need for more complex data analyses
- Increased detector noise at high-repetition rates can be circumvented using very small range-gates, and work is being done to investigate potential small range bias effects in single-photon avalanche diodes (SPADs) when small (few ns) gates are used
- Array design issues were discussed; the efficiency of the retro-arrays is of paramount importance for high-orbiting satellites because poor return signals will rapidly dissuade stations from attempting tracking as well as providing too little data for serious analysis.
- Of particular interest is the material of the cubes, the size of the array and of the individual cubes, whether or not they are coated or uncoated, the 'spoiling' angle at the vertices and the likely thermal conditions once in orbit.
- The ILRS has developed standards for retro design that mission engineers should adhere to in order to provide sufficient return signal for day and night-time tracking, as well as to ensure the provision of very accurate metric data on the location both of the arrays and the satellites' centres of mass. The arrays are to provide a cross-section of at least 100 million square metres at GPS heights, suitably R^4 scaled for other heights.

Following the presentation of the Position Paper a number of related presentations were given, summaries of which follow here.

- David Arnold presented the theoretical basis for preferring uncoated, zero-dihedral-angle cubes for GNSS-height satellites. The diffraction pattern from a cluster of such cubes, properly oriented, is close to circular and thus ideal at all positions of a tracking station in the far-field. The lack of coatings is also likely to reduce thermal distortion effects.

- Reinhardt Neubert *et al* presented a design study for a proposal for a single, open, cube for the GALILEO satellites. The advantage of low-mass and small size did not appear to compromise their efficiency.

- A presentation of work by Toshi Otsubo looked at the potential for range bias from the extended, flat arrays on GNSS satellites. He compared a model of the expected signature effect from the arrays on the GIOVE satellites with that actually seen in residuals from kHz ranging at Herstmonceux, noting that careful treatment will be required to maintain mm-level range measurements to the satellites' centres of mass.

- A detailed study into the efficiency of the in-flight arrays on GPS, GLONASS, COMPASS-M1, GIOVE and ETALON was carried out and presented by Matt Wilkinson. His analysis used as a proxy for array efficiency the range-corrected return rates derived from archived full-rate data from a number of stations from 2007 to date. A further normalisation by number and geometric size of cubes in each array showed that per unit area the ETALON, GPS and GIOVE satellites give comparable responses. The COMPASS-M1 target is significantly better and the GLONASS targets are notably less responsive.

- Simone Dell'Agnello *et al* presented the latest status of the tests on existing arrays that are being carried out in the space-environment facility at INFN-LNF in Frascati, Italy. Such tests will be used on proposed designs, especially to test their thermal stability that is crucial for maintaining return signals at their theoretical levels.

- J-M Torre gave an update on the important upgrades to the MEO LLR/SLR system at OCA Grasse. The system is tracking the GNSS satellites to low elevations and hopes to begin operational LLR soon. The stumbling block here seems to be the performance of the telescope, which will require significant additional cost to improve, and additional down time.

- J-M Torre presented an update on T2L2 tracking and time-transfer results from colleagues at OCA. A good number of sites are now routinely tracking and delivering full-rate data in CRD format. More work will be done to monitor using the data from the maser-driven sites the stability of the on-board DORIS oscillator. The FTLRS system will shortly go to the Paris observatory to take part in a time-transfer experiment.

- Mikhail Sadovnikov finally presented some ambitious plans for new Russian laser systems that will attempt to reach sub-mm precision and accuracy. The plans include ranging at MHz rates with short-pulse lasers, and it is expected that preliminary results will be available in a year or so.

Overall, there are a number of technological studies, simulations and tests ongoing both at the station and LRA levels that will put the Network into a better position to contribute strongly to the increasing demand from the GNSS community.

Operational Challenges of SLR Tracking of GNSS Constellations

Summary of Session to Discuss Position Paper 8

Graham Appleby summarized his Position Paper on Operational Challenges for SLR tracking of GNSS constellations. The main points raised are summarised below.

- The populating of the GNSS constellations with satellites with retroreflector arrays will pose a challenge for the ILRS network. However, with operational and technical improvements, coupled with carefully planned tracking strategies, the network and the ILRS infrastructure can meet the challenge.
- Pass interleaving has become routine for some stations, permitting satellites simultaneously in view to be tracked. In particular, short segments of a GNSS satellite passes can be interleaved with satellites at all altitudes.
- The present network has considerable unused capacity in terms of time when tracking is not underway. Even the Yarragadee station with nearly continuous coverage and nearly perfect weather only tracks about 1/3 time. As autonomous operations become more common, we anticipate that stations will be tracking many more passes.
- The network productivity on the GNSS satellites has steadily increased due in part to improved technology and additional satellites, but dedicated campaigns have shown that improved tracking techniques, better predictions, and more experience have all played an important role. Currently 12 – 15 stations provide nearly all of the GNSS SLR data. As more stations go through upgrading and as new stations become operational, production will improve.
- Aircraft safety has been a historical issue with SLR. The introduction of radars and new optical and infrared sensors have made this routine at most stations; some groups are also working on eye safe laser systems that operate at emitted energy densities below the eye safety threshold.
- Through the years the ILRS data flow has been streamlined, to the point now where most normal point data is available to the users within 1 - 2 hours of acquisition, making near real-time applications practical.
- Recently, the ILRS has been tasked to track satellites with optically vulnerable payload under some orientations. The ILRS has introduced a hierarchy of restricted tracking constraints, including a web-based go-nogo key with which satellites missions can command the SLR stations to cease operations on their satellite.
- Many stations are undergoing hardware and software upgrades that will improve ranging capability, including increased daylight ranging, a critical aspect of accurate orbit determination.
- An ever present issue with the ILRS network is funding; operations and upgrades can only continue if adequate funding is available. The ILRS and its parent organizations such as the IAG must continue to stress the importance of SLR to the science community and to insist that its data users give proper recognition and credit for ILRS support. It would also seem reasonable that the benefit to the GNSS

Missions of laser tracking should be recognized by some funding mechanism especially if that benefit falls outside the purely scientific.

Following the presentation of the Position Paper a number of related presentations were given, summaries of which follow here.

- Randy Ricklefs described some of the operational issues with lunar ranging and lessons learned;

- Buddy Donovan gave a review of best practices used in the NASA Network and the benefit that can be derived from careful maintenance and calibration; he used the example of the improvement in performance at the Yarragadee station after recent maintenance procedures; he stressed the importance of simple, but carefully implemented procedures.

- Scott Wetzel discussed some ideas for an operational plan for GNSS tracking, recognizing that the number of targets will increase dramatically as the GNSS complexes become populated; strategies need to be implemented that will sample all of the array-carrying satellites while at the same time provide continuity on at least some satellites to support the ITRF development and maintenance.

- Chris Clark described a system being developed by NASA for complex scheduling for multi-target, multi-constraint conditions that might be applicable for GNSS tracking; with many satellites being tracked and interleaving of passes of several satellites at one time, the bookkeeping will become quite complicated.

- Adrian Jaggi described the new IAUB daily predictions that have dramatically improved SLR data acquisition on GOCE. While the predictions were scheduled to stress the European stations, all regions have benefited. Plans are underway to further enhance the service by adding a second prediction cycle each day focused on the other areas.

- Kirco Artov described the progress being made at the Metsahovi site on a new SLR system based on a 2 kHz laser and novel application of commercially available hardware. As an interim measure, they are presently rebuilding their old mount with new mechanical and electrical components. They are also using inexpensive but powerful computer components from commercially available computer games in their command and control systems.

- Zhongping Zhang reported on the progress made with the new kHz laser at the Changchun station with great improvements in data volume and daylight ranging. This is very significant since all of the Chinese stations are going this route with the expectation that the whole networks will see dramatic improvement.

- Roman Bebenin described the RadioAstron VLBI mission which could fly in late 2009 or early 2010 into a highly eccentric orbit from a few hundred kilometers altitude out to near lunar distance. This terminal, coupled with a terminal on the Earth will provide a variable VLBI baseline out to a distance of about 300,000 km. The retroreflector array has been positioned and optimized for ranges in the neighborhood of 150,000 – 180,000 kilometers. The spacecraft will be visible at 12 – 14 magnitude, so visual acquisition will be quite practical with a modest CCD and telescope, and all the LLR-capable stations are to be invited to contribute to the ranging effort.

PART III

The Eight Position Papers

Impact of SLR tracking on GPS

Position Paper presented at the
ILRS Workshop on SLR Tracking of GNSS Constellations
September 14–19, 2009
Metsovo, Greece

Y. Bar-Sever,[1] J. L. Davis,[2] R. Dach,[3] C. Flohrer,[4] T. Herring,[5] J. Ray,[6]
J. A. Slater,[7] and D. Thaller[3]

1. Current status

Throughout the history of the Global Positioning System, laser retro-reflector arrays have been installed on only two GPS satellites, both members of Block IIA: SVN 35 (PRN 05, launched 1993 August, deactivated April 2009) and SVN 36 (PRN 06, launched March 1994). The purpose of this deployment is as a test of the ability of SLR to enhance precise orbit determination. Only SVN 36 is still in service as of this writing. Also as of this date, no future GPS retro-reflectors are planned until after Block IIIA (perhaps the late 2010s). Although spacecraft (s/c) belonging to other GNSSs may carry laser retro-reflectors, they are not considered here.

1.1 *Laser retro-reflector array for GPS*

The laser retro-reflector array used on SVN 35 and 36 (Figure 1) consists of 32 fused-quartz corner cubes in alternating rows of four and five, for a total dimension of 239 mm × 194 mm × 37 mm, and a mass 1.27 kg. Built by the Russian Institute for Space Device Engineering, the design is similar to that for GLONASS satellites, but with a smaller total reflecting area. (See *Degnan and Pavlis* [1994].)

[1] Jet Propulsion Laboratory, Mail Stop 238-600, Pasadena, Calif. 91101, USA.
[2] Harvard-Smithsonian Center for Astrophysics, Cambridge, Mass. 02138, USA.
[3] Astronomical Institute, University of Bern, Sidlerstrasse 5, CH-3012 Bern, Switzerland.
[4] Navigation Support Office, OPS-GN, European Space Operations Centre ESOC, Robert-Bosch-Str. 5, 64293 Darmstadt, Germany.
[5] Department of Earth, Atmosphere, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, Mass., USA.
[6] NOAA/NGS, N/NGS6, SSMC3/8117, 1315 East-West Highway, Silver Spring, Md. 20910-3282, USA.
[7] National Geospatial-Intelligence Agency, Basic and Applied Research Office (IB), 12310 Sunrise Valley Drive, MS P-126, Reston, Va. 20191-3449.

Figure 1. Laser retroreflector array used on GPS satellites SVN 35 and 36. From http://ilrs.gsfc.nasa.gov/satellite_missions/list_of_satellites/gp35_reflector.html.

In any analysis, the offset between the center of mass (CoM) of the GPS s/c and the reflection center for the laser retro-reflector array must be accurately known (Figure 2). In fact, this quantity must be carefully monitored because the s/c CoM will move as fuel is expended. Over the lifetime of the satellite, this movement is expected to be -4.6 mm in the Z direction (s/c frame). As of August, 2007, the retro-reflector offsets in the Z direction for the two GPS satellites differ by 2 mm [*Davis and Trask*, 2007], reflecting differences in the CoM in those satellites. (For SVN 35, the CoM Z location reported by *Davis and Trask* [2007] was 1013.6 ± 3 mm and for SVN 36 it was 1011.3 ± 3 mm.) The CoM/laser retro-reflector array Z offsets were 669.5 mm (SVN 35) and 671.7 (SVN 36).

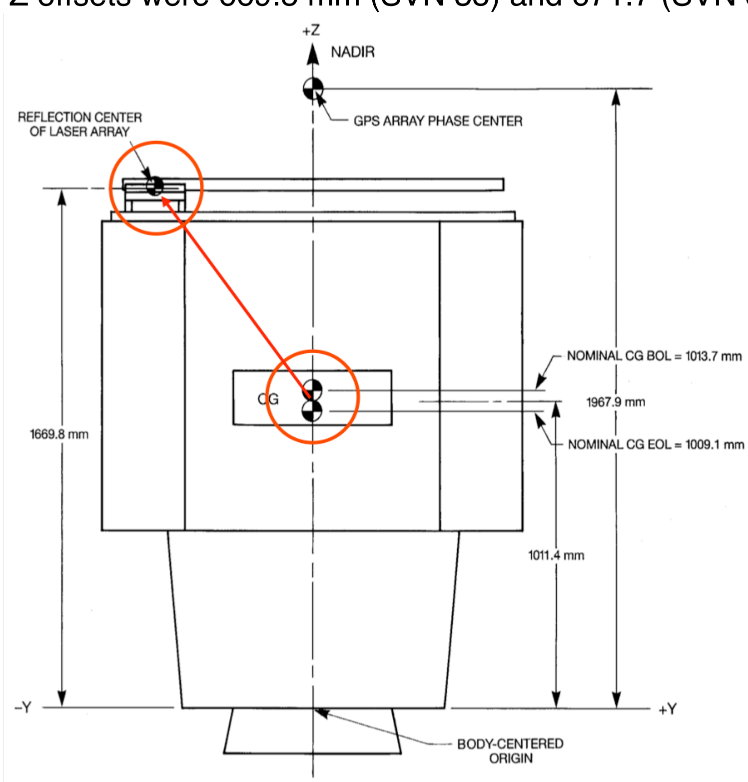


Figure 2. XY-plane view of the GPS s/c illustrating the locations of the GPS satellite center of gravity (CG), the effective laser array center of reflection, and the phase center of the L-band transmitting antenna array. The positive-Z coordinate axis is in the direction of satellite nadir.

1.2 *SLR network for ranging to GPS*

The number of SLR stations that have tracked SVNs 35 and 36 is small (~20), and of these only a handful have acquired more than 1000 observations (Figure 3). The ILRS tracking schedule for the GPS s/c utilizes night tracking only, further reducing the number of observations. *Urschl et al.* [2005] shows a similar distribution for January 2001–April 2004.

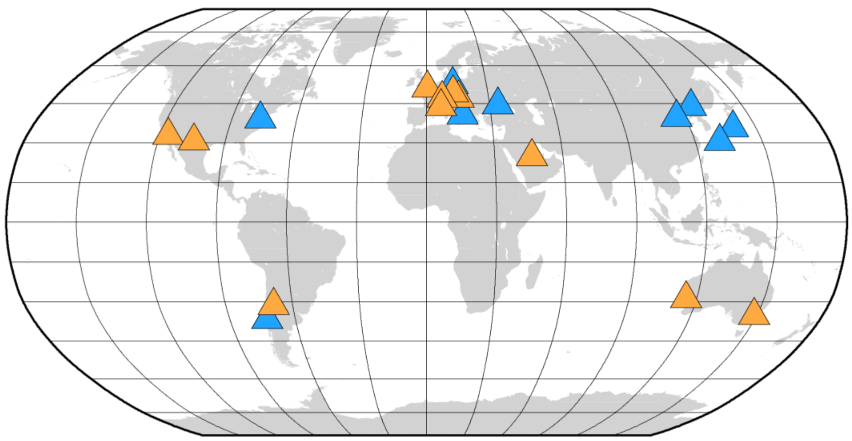


Figure 3. The SLR network (2008.0–2009.5) used for GPS tracking. Sites with fewer than 1000 observations over the period 1995.0–2009.0 are shown in blue, and those with 1000 observations or more over this time are shown in orange.

1.3 *SLR bias corrections*

Unlike “standard” analyses of SLR observations, GPS analysts using SLR for validation or combination do generally not apply SLR bias corrections. This situation seems to be because for “non-ILRS” analysts it is difficult to find out which biases should be applied in SLR data analysis.

For example, the information provided on the ILRS web site provides a data correction Sinex file, but it was last updated in 2003. This Sinex file should include range, time, pressure, and Stanford counter biases, but the latter are not included. These and other issues can create confusion for the GPS analyst who attempts to utilize ILRS data, and indicates one area where improvement in documentation may assist the joint analysis of GPS and SLR data.

2. Review of analyses to date

Analyses of SLR tracking of GPS have so far been used in two types of studies: (1) Independent validation of GPS orbits, which provides important information about radial orbit accuracy, inter-system biases, and orbit modeling problems [e.g., *Pavlis*, 1995; *O'Toole*, 1998; *Urschl et al.*, 2007]; and (2) Combination studies, in which GPS orbits are estimated based on GPS and SLR observations [e.g., *Zhu et al.*, 2007; *Urschl et al.*, 2007]. As of this writing, SLR data have not been used for routine GPS orbit improvement, due to limited amount and poor distribution (temporally and geographically) of SLR data. However the studies that have been performed indicate that the potential exists for GPS orbit improvement. Here, we provide a brief review of the results to date.

Springer et al. [2008] used data from 2007 to show that typical SLR range residuals for IGS analysis centers (ACs) GPS orbits and the IGS final GPS orbits

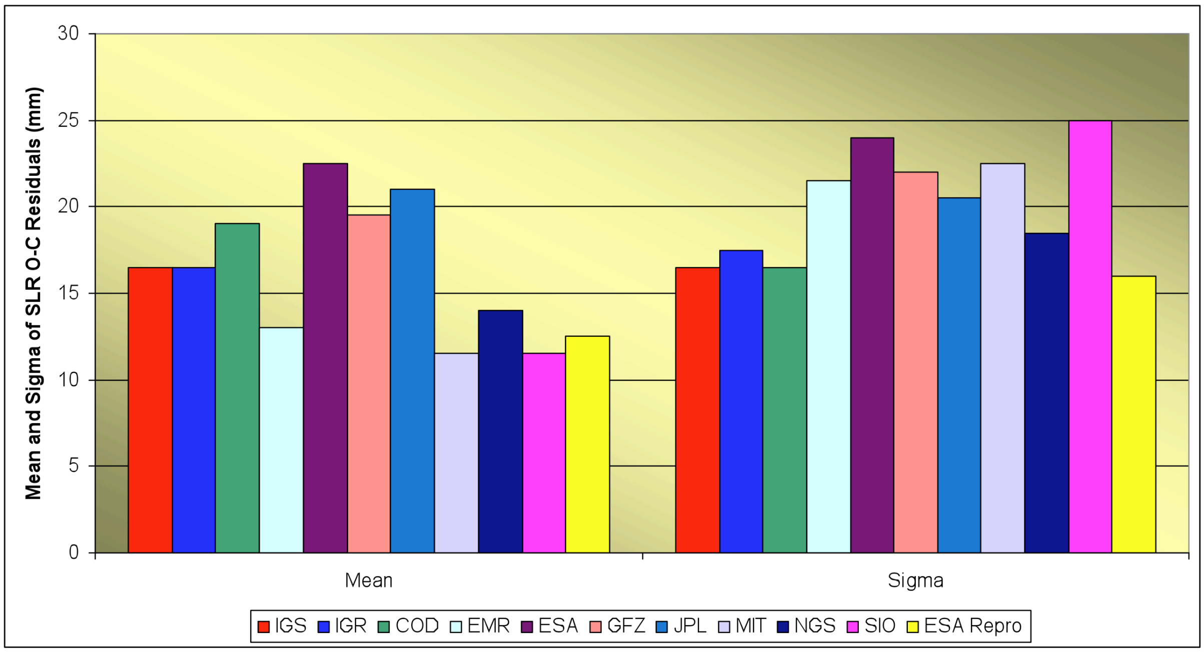


Figure 4. Mean and standard deviation of SLR range residuals to GPS satellites for the various IGS Analysis Centers final orbits. After *Springer et al.* [2008].

are in the range 1–2 cm (Figure 4). This value compares well with the ~1 cm RMS for SLR long-arc tracking of Lageos. These residuals have improved over time due to GPS orbit improvement.

The results in Figure 4 indicate a 1.5–2.5 cm range *bias*, possibly reflecting: AC orbital scale analysis difference (range of ±1.3 cm); possible albedo mismodeling; possible CoM offset mismodeling; or a combination of these effects. In fact, *Urschl et al.* [2007] found deficiencies in the priori solar radiation pressure model for the GPS s/c. They found that the ROCK solar radiation pressure (SRP) model [*Fliegel et al*., 1992] commonly used for GPS analysis caused large systematic residuals close to eclipse seasons (Figure 5). Use of the CODE SRP model [*Springer et al*., 1999] reduces this systematic behavior significantly (Figure 6). Using ESOC reprocessing of IGS data (1995.0–2009.0) one finds a very good agreement between GPS and SLR, with only a small bias (~1.8 cm) and small eclipse effects remaining.

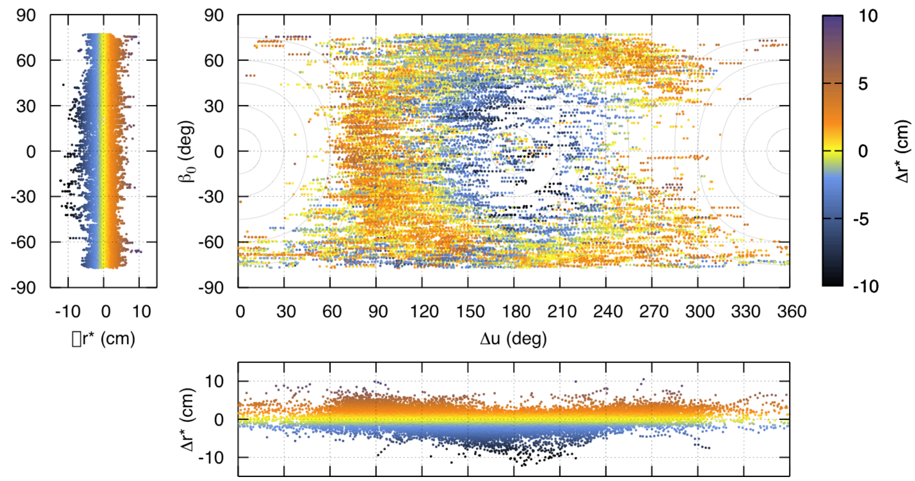


Figure 5. Color-coded de-meaned SLR range residuals determined using the ROCK SRP model [*Fliegel et al.*, 1992]. The residuals are projected into a coordinate system where β is the elevation above Sun above the satellite's orbital plane and *u* is the argument of latitude of the satellite relative to that of the Sun. After *Flohrer* [2008].

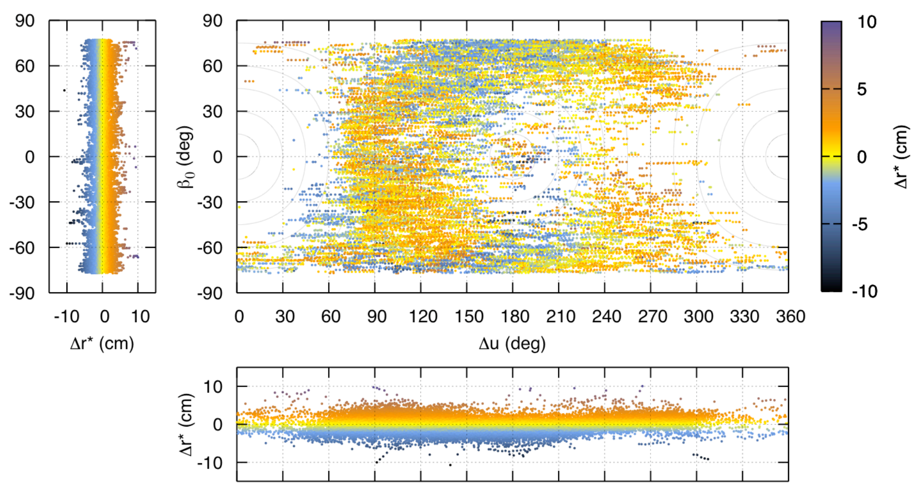


Figure 6. Same as Figure 5, except the CODE SRP model [*Springer et al.*, 1999] was used. After *Flohrer* [2008].

In summary, SLR has been demonstrated to be a viable, valuable and unique technique for independent analysis of GPS orbits through evaluation of the GPS error budget, by providing estimates of the radial orbit accuracy and for detection of systematic errors such as inter-system biases. The technique has enabled a verification of orbit accuracy, such as solar radiation pressure, albedo, and attitude. However, SLR has had very limited impact on GPS orbit improvement in combined data analyses due to current sparseness of observations. There have been only two (now one) GPS s/c with retro-reflectors. In addition, the SLR network tracking GPS has been insufficient, and there has been only sparse data acquisition.

3. The future of SLR tracking of GPS

3.1 *Potential benefits*

As we have discussed, there is great potential for **GPS orbit improvement** by tracking GPS s/c with SLR. For this technique to be effective, however, a number of factors require additional work and improvement; inter-system biases have to be well understood and modeled; orbit-model deficiencies have to be resolved; and SLR tracking data has to be able to cover most of the GPS orbital arc. This last requirement in particular will require an upgrade of the SLR tracking network to fill in the large "blank" areas in the southern hemisphere.

Assuming that these and other factors are implemented, the routine analysis of GPS data by the IGS Analysis Centers would then have to include on a routine basis SLR data or data products. Much work needs to be done to determine the best approach for SLR data to be integrated into GPS analysis, including, as discussed above, the documentation required to simplify use of these data.

In addition to GPS orbit improvement, SLR tracking can provide basis for a **common observing system** for nearly *all* satellites because laser retro-reflectors can be put on nearly *any* satellite. A major contribution of the SLR observations of GPS satellites will therefore be the ability to tie together two of the major geodetic measurement techniques that **define the ITRF**. They will help define the geocenter and enable the quantification of scale differences between SLR and GPS.

SLR tracking will provide an independent means of **quality assurance** for GPS that does not currently exist. The SLR data can be used as a metric reference for the radiometric measurements made from the satellite's L-band signals and for the broadcast and precise orbits. A time history of SLR-GPS range differences may be useful in detecting behavioral differences between individual GPS satellites or between groups of satellites (e.g., blocks, orbit planes) and could be useful in diagnosing unexplained perturbations in satellite orbits, center of mass issues and other performance-related phenomena. The time series will also provide a means of monitoring sudden changes and long-term trends in individual satellites, since the SLR measurements have sub-centimeter precision and centimeter-level accuracy.

A key application of the SLR observations will be in **orbit and clock modeling.** Since the SLR measurement is independent of the GPS station and satellite clocks, the effects of the GPS clock modeling can be separated from the orbit modeling and potentially lead to better understanding of modeling errors. A major asset of SLR is its independence from ionospheric effects in contrast to the microwave measurements. SLR data will help refine existing orbit modeling and help to identify unmodeled systematic effects. This may also aid in the reduction of low earth orbiting (LEO) satellite data in cases where the LEO satellites have both GPS receivers and SLR retro-reflectors.

Linkage of GPS and SLR observations will help improve the **long term stability, accuracy and precision of the ITRF and WGS 84**. This will, in turn, enable new scientific applications of GPS and enhance the capabilities of the operational system. Both U.S. Department of Defense (DoD) and civilian users of GPS are currently modeling and correcting GPS measurements for effects at the decimeter and centimeter level. As measurement and modeling capabilities improve, the ability to see changes in the environment improves. Station positions can be monitored for millimeter changes on a daily basis. Such monitoring has applications for monitoring land subsidence, volcanoes, earthquakes, polar ice sheets, sea-level change, climate change, and for weather forecasting and high resolution aerial and satellite imagery. Real-time applications at the 1–10 centimeter level require reference frame stability at the 1–10 mm level. SLR tracking could help make this possible.

3.2 *Future prospects*

In 2007, a working group comprised of representatives from multiple U.S. government agencies developed a set of geodetic requirements for the future GPS III constellation. These requirements were based on the historical record of continuous improvements in GPS performance and the accuracy, precision and response time of GPS applications. The four basic geodetic requirements are to

1. Achieve a stable geodetic reference frame with an accuracy of at least ten times better than the anticipated user requirements for positioning, navigation, and timing.
2. Maintain a close alignment of WGS-84 with ITRF.
3. Provide a quality assessment capability independent of current radiometric measurements used to determine GPS orbits and clock performance.

4. Ensure interoperability of GPS with other GNSSs through a common, independent measurement technique.

[Source: *GPS III Geodetic Requirements, submitted to IFOR, 13 April 2007* (for Official Use only)]

After reviewing a number of possible alternatives for meeting these requirements, the working group decided that satellite laser ranging (SLR) was the most practical, cost-beneficial and effective means of meeting the geodetic requirements as well as the long-term goals for GPS III.

3.3 *Operations*

The U.S. government inter-agency working group in consultation with the ILRS developed a proposed concept of operations that defines how the ILRS stations would control and schedule laser ranging to GPS satellites. The need is to ensure the integrity and safety of the on-board systems on the satellites and to be able to explicitly identify legitimate, authorized laser-ranging operations and distinguish these from unauthorized activities and other phenomena that may be confused with laser ranging effects.

The ILRS proposes a set of Standards for Participation in the international SLR program as follows:

- Station will only illuminate satellites which are on the ILRS permission list, or for which the station has separate permission
- Adhere to go/no-go lasing windows for missions that have requested this
- Maintain a record of station configuration and upgrades
- Maintain a record of station location relationship with respect to IGS/GNSS receivers
- Tracking schedule established and agreed by mission participants
- Coordination with Air Force Laser Clearinghouse for GPS
- One strategy to be established for all GNSS satellites
- Observation Spans fixed to Engineering Goals and ITRF requirements
- Measurements driven by the ability to achieve Normal Points
- SLR sites encouraged to include local ties to GNSS geodetic observing sites
- Precise Center of Mass should be specified and maintained with an accuracy of 1 mm throughout satellite mission life.

Two primary modes of SLR operations are envisioned: (a) routine scheduled laser ranging by the ILRS stations to a subset of GPS satellites and (b) campaigns of more intensive data collection. The routine schedule would be strictly adhered to and publicly available. This has worked for many years with

GLONASS. Despite having GPS satellites routinely tracked by the ILRS, the data collected will be sparse. Therefore, it will be useful to organize short focused campaigns that collected a lot more data than the routine tracking can provide. These campaigns should be designed for specific objectives. As with the routine scheduled SLR operations, these campaigns must be coordinated with the GPS OCS so that there are no surprises to the system operators or users, and to make sure that the campaign does not interfere with other critical system operations or testing.

It is expected that the ILRS will process the raw SLR data, generate standard normal points and perform analyses of these data. Under the proposed concept of operations, the ILRS will transmit the normal point data, metadata, weekly and monthly tracking reports, and analysis results to NGA in St. Louis, Missouri. It is assumed that the CDDIS at NASA GSFC will archive the GPS SLR data. All of these data will be in the public domain.

4. Position and Recommendations

Based on analyses people have been able to do to date on two GPS satellites, GLONASS and LEO satellites, there are significant potential benefits to SLR on GPS. However, a number of technical issued need to be resolved and/or investigated in order to take advantage of these benefits. Among these are:

1) Studies are required to demonstrate and quantify the potential benefits that have been discussed in Section 3.
2) Studies are required to develop optimal coordinated observing strategy encompassing all satellites to be observed.
3) The state of the ILRS network must be improved. The network requires more sites, a better geometry, better tracking capabilities, and enhanced data acquisition capabilities.
4) Accurate CoM offsets for the GPS satellites need to be maintained.
5) Recent work by one of us (Thaller) indicates that combining normal equations from SLR and GPS solution may enable accurate SLR-GPS “space ties” to be obtained, which may alleviate the need for accuracy in local ground ties. More research on this issue is required (see #1 and #2), however, including studies of the number of SLR observations of GPS s/c needed in order to have good “space ties.”
6) Accurate local ties for collocated ground stations may or may not be required.
7) A greater number of GPS s/c with retro-reflectors is required, and the SLR network needs to be able to acquire a large number of observations on these satellites. The number of GPS s/c with laser retro-reflectors required for scientific applications has not yet been determined. The con-

sensus of the inter-agency working group and the position advocated to the U.S. Air Force and the IFOR is for *every* GPS III satellite to carry a retro-reflector. This plan has the following operational advantages: (1) any satellite may be substituted for another in the routine ILRS tracking schedule in cases of satellite failure or other problems; (2) uniformity of design, installation and testing for all GPS III satellites; and (3) ability to perform sensitivity analyses of the CoM offsets and other systematic differences among satellites in the same orbit plane or other studies of interest operationally and scientifically.

5. References

Davis, M. A. and A. J. Trask (2007) Insight into the GPS navigation product accuracy using the SLR measurements, available at http://ilrs.gsfc.nasa.gov/docs/davisgpstray.pdf.

Degnan, J. J., and E. C. Pavlis (1994), Laser ranging to GPS satellites with centimeter accuracy, *GPS World*, *5*(9), 62–70.

Fliegel, H., T. Gallini, and E. Swift (1992), Global Positioning System Radiation Force Model for Geodetic Applications, *J. Geophys. Res.*, *97*(B1), 559–568.

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

O'Toole, J. W. (1998), Evaluation of NIMA and Air Force GPS satellite ephemerides using NASA laser ranging data, *Proceedings, ION 54th Annual Meeting*, Denver, Colo., June 1–3.

Pavlis, E. C. (1995), Comparison of GPS s/c orbits determined from GPS and SLR tracking data, *Adv. Space Res.*, *16*(12), 1255–1258.

Springer, T. A., G. Beutler, and M. Rothacher (1999), improving the orbit estimated of GPS satellites, *J. Geodesy*, 73(3), 147-157.

T.A. Springer, F. Dilssner, E. Schoenemann, I. Romero, J. Tegedor, F. Pereira, and J. Dow (2008), ESOC IGS reprocessing, Poster, 2008 IGS Analysis Center Workshop 2008, Miami. Available at http://www.ngs.noaa.gov/IGSWorkshop2008/docs/ESOC_IGS_Reprocessing.ppt.

Urschl C., W. Gurtner, U. Hugentobler, S. Schaer, and G. Beutler (2005), Validation of GNSS orbits using SLR observations, *Adv. Space Res.*, 36, 412–417.

Urschl C., G. Beutler, W. Gurtner, U. Hugentobler, and S. Schaer (2007), Contribution of SLR tracking data to GNSS orbit determination, *Adv. Space Res.*, 39(10), 1515–1523.

Zhu, S., Ch. Reigber, F.-H. Massmann, H. Neumayer, H. Meixner, and F. Flechtner (2007), Combination of multi-satellite techniques at the observation level, *IERS Technical Note*, 30, 84–86.

Impact of SLR tracking on GLONASS

V. Vasiliev[1], N. Parkhomenko[1] and V. Glotov[2]
(1) Science Research Institute for Precision Instrument Engineering (IPIE)
(2) Information-Analytical Centre (IAC) TSNIMASH

I. 1-st position – Past

In the Soviet Union, substantial progress in laser systems development has been made during the late sixties and the following decade. In particular, before the end of seventies several SLR sites were constructed and put into operation. Therefore, at the start of GLONASS development there was some experience in satellite laser ranging, as well as clear understanding of its importance for navigation/geodesy satellite systems. It has been also confirmed that SLR systems of that time may be used for accurate and regular ranging of retroreflector-equipped spacecraft at various orbits from very low ones to geostationary.

Just after the start of GLONASS development, it was decided to install retroreflector arrays on board of every GLONASS spacecraft, as well as to launch two passive spherical satellites with retroreflrctors (ETALON-1 and ETALON-2) into the GLONASS orbit for investigation of orbit evolutions. Thus, during the first phase of GLONASS deployment (starting 1986) much useful information has been obtained and examined. One of the first practical results of SLR application to GLONASS was discovery of a large (more ten m) error in RF measurements caused by an erroneous phase correction.

In the late nineties, it was decided to take part in the International GLONASS Experiment IGEX-98, which started on October 19, 1998 and was planned to last till April 19, 1999, but has been later prolonged till 2003. The experiment was conducted following the initiative of five international organizations in science and technology. The primary purpose of the experiment was to investigate the possibility of GLONASS application for solving of scientific and practical problems in geodesy, geodynamics, and positional navigation timing. It should be noted that Russian stations in Mendeleevo, Irkutsk, and Khabarovsk (belonging to the Rosstandart network) as well as MCC-M as the official Analysis Center for GLONASS actively participated in the experiment.

On September 1999 the organizers of the experiment met in Nashville (USA) and decided to extend the use of GLONASS for basic and applied research in geodesy, geodynamics, and positional navigation timing during the next four years (2000 – 2003). Thereby, the newly created IGLOS – PP Service (International GLONASS Service – Pilot Project) should operate similarly to the IGS (International GPS Service), which operated successfully since 1994. Currently, the IGLOS-PP is based on the same principles as IGS and on the same software.

As indicated in the IGLOSS – PP initial documents prepared by its Executive Committee Chairman J. Slater, the main purposes of the Service are:

1. Provision of the global GLONASS navigation receiver network operation in accordance with the international standards, including calibration with the existing GPS receiver network nodes.
2. Calculation of precise ($1\sigma = 10$ cm) orbits, estimation of on-board clock accuracy and station coordinates based on individual solutions of the Data Analysis Centers obtained from laser and RF measurements with a time lag less than 3 weeks from the moment of measurement.
3. Monitoring and estimation of the GLONASS system operation quality.
4. Estimation of possibility of GLONASS data use for improvement of the Earth rotation data accuracy.

5. Improvement of the atmosphere/ionosphere investigation results.
6. Total integration of GLONASS and GPS navigation measurement data collection, storage, and processing systems to provide better accuracy of results obtained by the Service by solution of various problems in Earth Sciences.

Basic results of IGEX-98

The precision orbit determination of GLONASS spacecraft was fulfilled during the IGEX 98 experiment in 11 data analysis centers, based on laser and RF measurements, with final orbit accuracy of 20…50 cm; thereby, in 5 centers, including the only Russian center MCC-M, the results were obtained during the full time of the experiment. The final ephemeris of all GLONASS spacecraft were obtained with an accuracy of 10…20 cm (1σ) from regular individual solutions of different analysis centers. All precise orbits are stored in the above databases and are available for everyone.

Two-frequency GLONASS receivers have been developed and tested during the experiment, produced by three companies (GG-24 и Z-18 Ashtech, 3S-Navigation, “Legacy” Javad Positioning System), as well as by one university. Up to now, no Russian company has produced a two-frequency, double system (GLONASS/GPS) receiver with a quality better than the above receivers. Software packages have been improved (e.g. BAHN, Bernese, GIPSY,) to provide combined processing of GPS and GLONASS measurement data. International data exchange formats have been extended to include GLONASS data. Several research groups have obtained matrices for transfer between the Russian П390 (GLONASS) and WGS84 (GPS) reference systems. Using the high-accuracy GLONASS ephemeris, the accuracy of international time transfer and synchronization has been improved.

MCC-M was the only Russian experiment participant as data analysis center. It has obtained the following primary results:

- GLONASS spacecraft ephemeris have been calculated during the total 6-month period of the experiment, with a precision of 10…20 cm (1σ), using the processing results of 6500 laser measurement sessions made by the global SLR network.
- The П390 (GLONASS)/WGS84 (GPS) transfer matrix has been obtained, as well as estimation of its variations.
- Methods, algorithms and software for high-accuracy GLONASS spacecraft ephemeris calculation has been created .
- Quick interaction via Internet with the international data collection and analysis centers has been established.

In accordance with the experiment technology, the MCC-M data analysis results have been provided to the data analysis storage centers and were appreciated as part of primary results of the IGEX98 experiment.

Finally, the following was fulfilled during the IGEX98 main period and its extension:

- two-frequency double-system multichannel navigation receivers have been developed and tested
- a global network currently including more than 50 stations was created
- international formats have been developed for measurement, processing and exchange of GLONASS data to provide high-accuracy ephemeris and time values
- software for combined high-accuracy GLONASS measurement data processing was created

- high-accuracy ephemeris/time data have been obtained and verified using the results of GLONASS measurements by the global network; the final ephemeris accuracy was thereby estimated as 10…20 cm (1σ)
- the transfer matrix between П390 (GLONASS) and WGS84 (GPS) reference systems has been obtained, as well as estimation of its variations.

The experiment results were discussed in details during the ION-99 meeting in Nashville.

International collaboration in SLR

Before the use of global SLR network measurement data which started 1995, for GLONASS spacecraft ephemeris determination, RF measurement were used with systems deployed within the Russian territory. The nominal accuracy of the RF measurements was several meters and the accuracy of constants and models used for the П390 reference system was also within several meters. Thus, the GLONASS spacecraft orbit determination accuracy was then at the several meter level, and could not compete with the GPS measurement accuracy.

The use of centimeter - level accuracy SLR data allowed to support the high-accuracy ITRF system with its coordinated system of constants, Earth, Moon, Sun and planet gravitation models, transfer parameters between various reference systems, etc.

Based on the above data and experience in SLR measurement processing, the MCC-M was able to solve the following problems:

- to build a precise adaptation model of the GLONASS spacecraft motion, taking into account the light pressure at sun- illuminated and shadow parts of orbit the spacecraft thermoregulation system activity, etc.;

- to examine the connectivity between the П390 (GLONASS) and WGS84 (GPS) reference systems to obtain the transfer matrix, and to provide recommendations for reduction of intersystem coordination errors from meter to decimeter level;
- using the results of processing of more than 20 thousand measurement sessions obtained by 40 SLR stations of the ILRS network during a 7-year-long period, to provide accurate ephemeris of GLONASS spacecraft;
- within the IGEX 98 framework, to confirm the mean orbit determination accuracy by comparison of laser measurements and RF measurement results obtained from 5 data processing centers; the confirmed orbit determination accuracy from laser measurements is 18 cm to 30 cm (1σ);
- to confirm the capability to provide precise ephemeris for the future GLONASS-K program.

The high-level processing of SLR measurement data is also made in the Ministry of Defense analysis center for testing of related software and measurement means and for investigation of new laser and RF measurement methods.

During this 1-st phase of SLR development in Russia, a number of SLR sites and three types of SLR equipment have been developed, built, and put into operation:

- A unique site on top of Maidanak mountain in Uzbekistan, equipped with two telescopes 1.1 m in diameter, and two completely separate laser/ receiver/tracking equipment sets (see slide 1). The station is still in operation, in accordance with an Agreement between the Russian Federation and the Uzbekistan Republic.

- A station equipped with a 70-cm-diameter telescope in Crimea, Ukraine (no more in operation).
- A station of Sazhen-S type in Komsomolsk-on-Amur, equipped with two 50-cm-diameter telescope (one for SLR, the other for photometry and angular measurements). The station is still active (slide 2).

Besides this, a number of small SLR- stations of the Sazhen-2 type providing ranging at distances up to 3000 km were build, and operated successfully till late eighties; the stations (one of them was located in Mendeleevo near Moscow) have been used, in particular, for ranging to GEOIK spacecraft (several satellites of this type were used for geodesy during the last period of Soviet Union existence). The compact Sazhen-2 station design included four 30-cm-diameter telescopes (see slide 3). All the Sazhen-2 stations are out of operation.

II. 2-nd position – Current

During the first decade of XXI century, to meet the new requirements for measurement accuracy and to compensate for lost stations of the previous generations, two completely new SLR sites have been established: the Shelkovo station of Sazhen-T type near Moscow (in operation since 1999 (see slide 4) and the Altay optical / laser center (the 1-st phase SLR station, similar to the one in Shelkovo, is in operation since 2004 (slide 5).

Additionally, a transportable SLR station has been installed in the Baikonur region (slide 6). All three stations are equipped with 60-cm-diameter telescopes. The Shelkovo and Altay stations have been recently upgraded: they use short-pulse (150ps) high-repetition-rate (300 Hz) lasers and modern electronics for time interval measurements

Besides this, production has started of a multitude of compact mobile SLR-stations of Sazhen-TM type with two 25-cm-diameter telescopes and a 300-Hz, 150 ps laser (slide 7).

All stations (including the compact one) demonstrated the capability for SLR-tracking at distances up to 25,000km with an accuracy of 1-2 cm, as well as photometry and angle measurements

Regular GLONASS SLR- tracking is made during the last period: data are provided to the Ministry of Defense analysis center and to the MCC-M analysis center.

An improvement has been recently made in the GLONASS retroreflector arrays: the GLONASS – 115 array provides approximately 1.5 times more returns per normal point as compared with previous arrays (see Table 1).

III. 3-rd position – Future

A 2-nd phase installation is under construction at the Altay optical and laser center. It will be equiped with a 3.12 m-diameter telescope; start of operation is planned for late 2011.

A new fixed SLR station is under construction in the Northern Caucasus region. Some early SLR experiments measurements there may start in 2010.

The number of compact Sazhen-TM stations will increase year by years (22 such installations have been already ordered by several Institutions in Russia (see slide 8), and there is a preliminary agreement to install a station of this type in Israel). Thus, a far better coverage of wide Russian territory will be provided, and a contribution to global coverage improvement will be also made.

Some important research has been made in preparation for development of a new-type SLR station providing a better power budget while being still more compact than Sazhen-TM and capable to provide very high accuracy ranging.

Further improvements are planned in reduction of the target error of GLONASS retroreflector arrays.

An experimental spacecraft-to-spacecraft laser ranging and data exchange link is under development and first testing on two GLONASS-M satellites. If successful, the link may provide range and time data exchange with a final goal of interconnecting all the spacecraft in the future GLONASS constellation to provide better timing and thus improvement of the GLONASS system positioning and timing accuracy (see figure 9).

Development has also started of a one-way laser link for GLONASS spacecraft ranging and timing improvement. It could be also used for scientific missions requiring high-accuracy orbit determination, but having very high orbits (such as astronomical missions planned for operation at the Lagrange L2 point).

Impact of SLR Tracking on Galileo

T.A. Springer, D. Navarro-Reyes*, D. Escobar, R. Zandbergen
ESA/ESOC Robert-Bosch-str. 5, Darmstadt, 64289, Germany
*ESA/ESTEC Keplerlaan 1, Noordwijk, the Netherlands
Tim.Springer@esa.int

Galileo Overview

The Galileo Programme is being implemented in three phases:

- Definition phase
- Development and In-Orbit Validation phase
- Full Deployment and Operations phase

The Definition phase was completed in 2003 resulting in the basic specifications for the system. The Development and In-Orbit Validation phase was initiated in late 2003. This phase aims to perform an in-orbit validation of the system using a reduced constellation of four satellites (which is the minimum number to guarantee the provision of exact positioning and time at test locations) along with a number of associated ground stations.

Early in this phase, an experimental satellite was launched, to secure the Galileo frequency filings, to characterize the orbits to be used by the in-orbit validation satellites and to test some of the critical technologies, such as the atomic clocks. GIOVE-A, which was launched on 28 December 2005, transmitted the first Galileo signals in space on 12 January 2006. A further experimental satellite, GIOVE-B, has been launched on 27 April 2008. Its main purpose is to ensure continuity of the Galileo signals in space and to space qualify the H-maser onboard clock, a really exciting new piece of equipment for satellite navigation.

The four satellites that will be used for the primary In-Orbit Validation and that will be part of the 30-satellite constellation have been ordered and are being built for launch in 2010/2011. The ground stations needed for this phase are also being prepared. There will be a partial constellation and a partial ground system, allowing a real-world check of the transformation from theory to practice with the basic infrastructure of Galileo.

Once the In-Orbit Validation is complete, the lessons learned will be used as the programme enters its Full Deployment phase. This will cover construction of the full ground infrastructure and the launch of the remaining 26 satellites to complete the constellation.

Once all the satellites have been deployed, service will commence with the complete constellation of 27 operational satellites and three spares, all stationed on three Medium Earth Orbits (MEOs) at an orbital radius of 29 600 km and with an inclination of 56º to the equator. To support this there will be an extensive network of ground stations and local and regional service centres. Galileo is set to become the global standard for civil navigation by satellite. There will be total interoperability between the European and US navigation systems (an agreement between the European Union and the United States was signed in June 2004 at the EU-US summit in Dublin) and the Russian system GLONASS. Cooperation agreements with other countries are being negotiated by the European Commission giving a truly global dimension to Galileo, the first civil complete navigation satellite system.

The Galileo System

The Galileo System will comprise global, regional and local components. The global component is the core of the system, comprising the satellites and the required ground segment. The Galileo global component will provide the constellation of Galileo satellites, each of which will broadcast navigation timing signals together with navigation data signals which will contain not only the clock and ephemeris correction data essential for navigation but also integrity signals which provide a global space-based augmentation service. The space segment will be complemented by the Galileo ground segment, which will consist out of a few control centres and a global network of transmitting and receiving stations.

The regional component of Galileo may comprise a number of External Region Integrity Systems (ERIS), implemented and operated by organisations, countries or groups of countries outside Europe to obtain integrity services independent of the Galileo System, in order, for example, to satisfy legal constraints relating to system guarantees.

Local components may be deployed for enhancing the performance of Galileo locally. These will enable higher performance such as the delivery of navigation signal in areas where the satellite signals cannot be received. Value-added service providers will deploy local components.

Space segment

The Galileo space segment will comprise 30 satellites in a Walker constellation with three orbital planes at 56° nominal inclination. Each plane will contain nine operational satellites, equally spaced, 40° apart, plus one spare satellite to replace any of the operational satellites in case of failures. The orbit radius of 29 600 km results in a repeat cycle of approximately ten sidereal days during which each satellite has completed seventeen revolutions. An artist impression of the Galileo orbit constellation is shown in Figure 1.

The Galileo satellite constellation has been optimised to the following nominal constellation specifications:

- almost circular orbits (satellite orbit radius of 29 600 km)
- orbital inclination of 56°
- three equally spaced orbital planes
- nine operational satellites, equally spaced in each plane, one spare satellite (also transmitting) in each plane

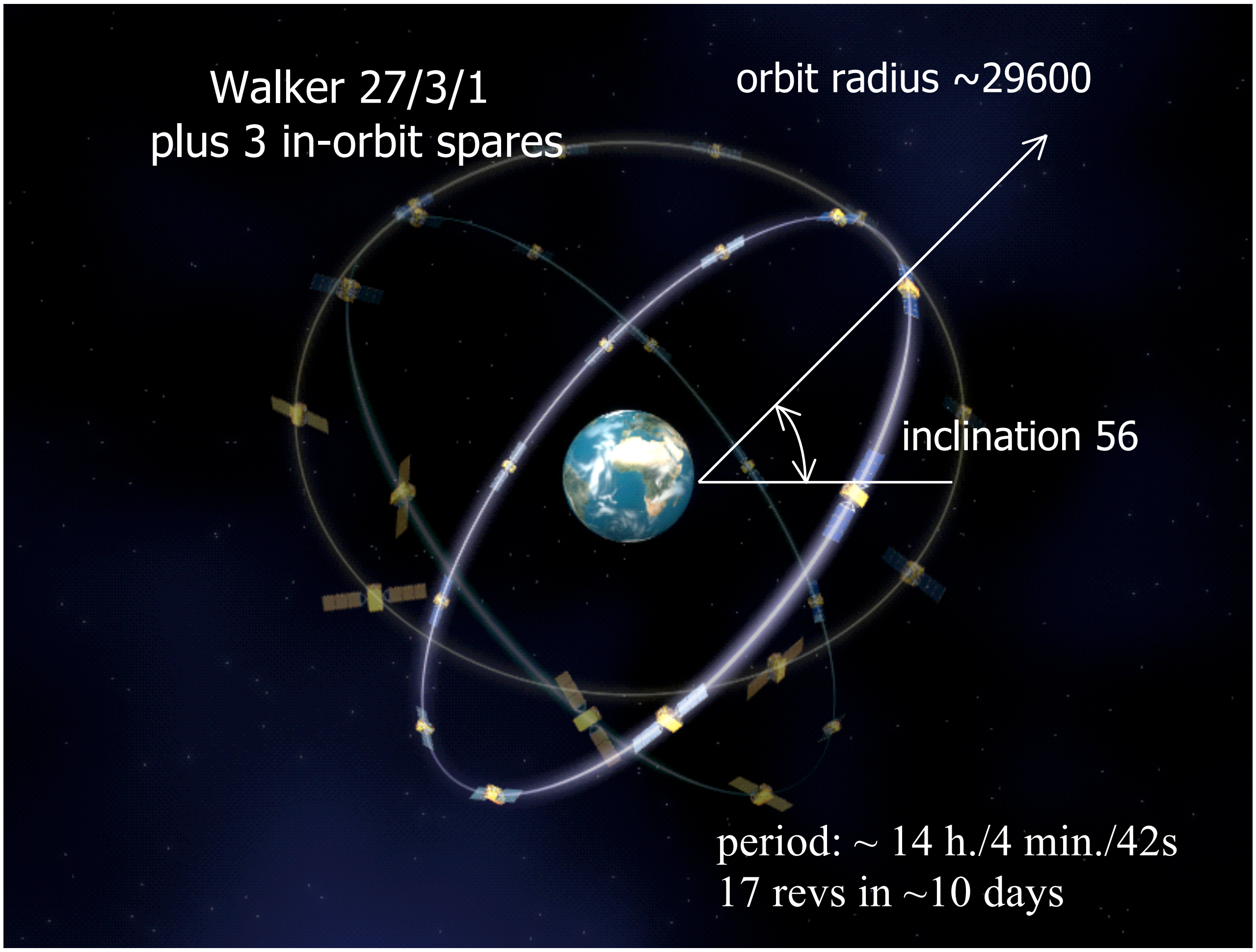


Figure 1: Artist Impression of the Galileo Orbit Constellation

Constellation features

The altitude of the satellites has been chosen to avoid gravitational resonances so that, after initial orbit optimisation, only one station-keeping manoeuvre will be needed during the 12-year lifetime of a satellite. The altitude chosen also ensures a high visibility of the satellites.

The position constraints for individual satellites are set by the need to maintain a uniform constellation, for which it is specified that each satellite should be within +/- 3° of its nominal position relative to the adjacent satellites in the same orbit plane and should be within 3° of the orbit plane.

The in-plane accuracy is equivalent to a relative tolerance of over 1000 km but requires very careful adjustment of the satellite velocity to ensure that the orbit period of all the satellites is kept precisely the same. The across-track tolerance allows the inclination and RAAN of each satellite to be biased after launch so that natural drifts remain within the tolerance without the need for orbit plane changes requiring major expense of fuel.

The spare satellite in each orbit plane ensures that in case of failure the constellation can be repaired quickly by moving the spare to replace the failed satellite. This could be done in a matter of days, rather than waiting for a new launch to be arranged which could take many months.

The satellites are designed to be compatible with a range of launchers providing multiple and dual launch capabilities.

Ground segment

The core of the Galileo ground segment will be the control centres. Each control centre will manage 'control' functions supported by a dedicated Ground Control Segment (GCS) and 'mission' functions, supported by a dedicated Ground Mission Segment (GMS). The GCS will handle spacecraft housekeeping and constellation maintenance while the GMS will handle navigation system control.

Ground control segment

The GCS will use a global network of nominally five TTC stations to communicate with each satellite on a scheme combining regular, scheduled contacts, long-term test campaigns and contingency contacts.

The TTC Stations will have large, 13-metre, antennas operating in the 2 GHz Space Operations frequency bands. During normal operations, spread-spectrum modulation (similar to that used for TDRSS and ARTEMIS data relay applications) will be used, to provide robust, interference free operation. However, when the navigation system of a satellite is not in operation (during launch and early orbit operations or during a contingency) use of the common standard TTC modulation will allow non-ESA TTC stations to be used.

Mission control segment

The Galileo Mission Segment (GMS) will use a global network of nominally thirty Galileo Sensor Stations (GSS) to monitor the navigation signals of all satellites on a continuous basis, through a comprehensive communications network using commercial satellites as well as cable connections in which each link will be duplicated for redundancy. The prime element of the GSS is the Reference Receiver.

The GMS communicates with the Galileo satellites through a global network of Mission Up-Link Stations (ULS), installed at five sites, each of which will host a number of 3-metre antennas. ULSs will operate in the 5 GHz Radio-navigation Satellite (Earth-to-space) band.

The GMS will use the GSS network in two independent ways. The first is the Orbit Determination and Time Synchronisation (OD&TS) function, which will provide batch processing every ten minutes of all the observations of all satellites over an extended period and calculates the precise orbit and clock offset of each satellite, including a forecast of predicted variations (SISA - Signal-in-Space Accuracy) valid for the next hours. The results of these computations for each satellite will be up-loaded into that satellite nominally every 100 minutes using a scheduled contact via a Mission Up-link Station.

The second use of the GSS network is for the Integrity Processing function (IPF), which will provide instantaneous observation by all GSSs of each satellite to verify the integrity of its signal. The results of these computations, for the complete constellation, will be up-loaded into selected satellites and broadcast such that any user will always be able to receive at least two integrity messages.

The integrity messages will comprise two elements. The first element is an "integrity flag", which warns that a satellite signal appears to exceed its tolerance threshold. This flag will be generated, disseminated and broadcast with the utmost urgency, so that the Time-to-Alert, being the period between a fault condition appearing at a user's receiver input and the integrity flag appearing there will be no more than six seconds, and will be re-broadcast a number of times. The second element of the integrity message comprises integrity tables, which will be broadcast regularly to ensure that new users or users who have missed recent signal (for example when travelling through a tunnel) will be able to reconstitute the system status correctly.

The OD&TS operation thus monitors the long-term parameters due to gravitational, thermal, ageing and other degradations, while the IPF monitors short-term effects, due to sudden failure or change.

The Galileo Global Component will also include a set of test user receivers.

The Galileo Satellites

Figure 2 shows an artist's impression of a Galileo spacecraft in orbit with solar arrays deployed. The spacecraft rotates about its Earth-pointing axis so that the flat surface of the solar arrays always faces the Sun to collect maximum solar energy. The Galileo satellite design is a 700 kg/1500 W class satellite. The antennas, shown on the upper side of the body in the picture, always point towards the Earth. The spacecraft body measures 2.5 x 1.2 x 1.1 metres and the deployed span, including the solar arrays, is 19 metres. Each Galileo satellite will broadcast precise time signals, ephemeris and other data.

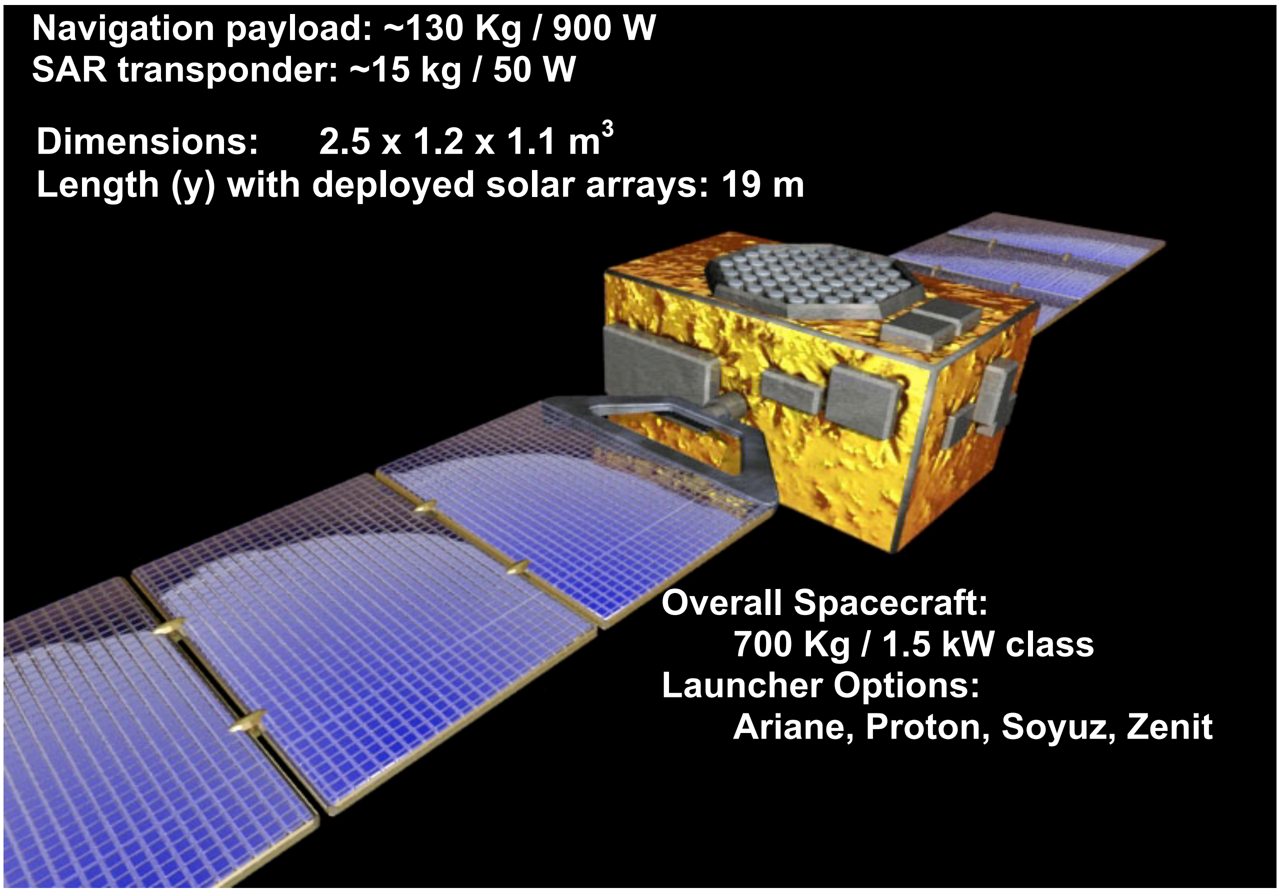


Figure 2: Artist Impression of a Galileo Satellite

Satellite components

The L-band antenna transmits the navigation signals in the 1200-1600 MHz frequency range.

The SAR (Search and Rescue) antenna picks up distress signals from beacons on Earth and transmits them to a ground station for forwarding to local rescue services.

The C-band antenna receives signals containing mission data from Galileo Uplink Stations. This includes data to synchronise the on-board clocks with a ground-based reference clock and integrity data which contains information about how well each satellite is functioning. The integrity information is incorporated into the navigation signal for transmission to users.

Two S-band antennas are part of the telemetry, tracking and command subsystem. They transmit housekeeping data about the payload and spacecraft to ground control and, in turn, receive commands to control the spacecraft and operate the payload. The S-band antennas also receive, process and transmit ranging signals that measure the satellite's altitude to within a few metres.

The infrared Earth sensors and the Sun sensors both help to keep the spacecraft in the correct attitude, i.e., its Z-axis pointing at the Earth and the solar panels facing the Sun. The infrared Earth sensors do this by detecting the contrast between the cold of deep space and the heat of the Earth's atmosphere. The Sun sensors are visible light detectors which measure angles between their mounting base and incident sunlight.

The laser retro-reflector array allows measurement of the satellite's altitude to within a few centimetres by reflecting laser pulses transmitted by the ground stations of the International Laser Ranging Service (ILRS).

The space radiators are heat exchangers that radiate waste heat, produced by the units inside the spacecraft, to deep space and thus help to keep the units within their operational temperature range.

Interior: payload

A passive hydrogen maser clock is the master clock on board the spacecraft. It is an atomic clock which uses the ultra stable 1.4 GHz transition in a hydrogen atom to measure time to within 0.45 ns over 12 hours. A rubidium clock will be used in case the maser clock fails. It is accurate to within 1.8 ns over 12 hours.

The clock monitoring and control unit (CMCU) provides the interface between the four clocks and the navigation signal generator unit (NSGU). It passes the signal from the active master clock to the NSGU and also ensures that the frequencies produced by the master clock and the active spare are in phase, so that the spare can take over instantly should the master clock fail.

The navigation signal generator, frequency generator and up-conversion units (FGUU) are in charge of generating the navigation signals using input from the clock monitoring unit and the up-linked navigation and integrity data from the C-band antenna. The navigation signals are converted to L-band for broadcast to users.

The remote terminal unit is the interface between all the payload units and the on-board computer.

Interior: service module

The Solar Array Drive Mechanism (SADM) connects the solar arrays to the spacecraft and rotates them slowly so that the surface of the arrays can remain perpendicular to the Sun's rays at all times.

The gyroscopes measure the rotation of the spacecraft, whereas the reaction wheels control the rotation of the spacecraft. The satellite rotates twice per orbit around its Z-axis to allow the solar arrays to remain parallel to the Sun's rays. The magneto bar modifies the speed of rotation of the reaction wheels by introducing a torque (turning force) in the opposite direction.

The power conditioning and distribution unit regulates and controls power from the solar arrays and batteries and distributes it to all the spacecraft's subsystems and payloads.

The on-board computer controls all aspects of spacecraft and payload functioning.

Impact of SLR tracking on Galileo

SLR is the only observation technique that provides measurement accuracies better than the GNSS microwave signals. In particular the SLR measurements do not have any ambiguities, do not suffer from signal perturbations in the ionosphere and have no clock biases. Furthermore, the SLR measurements are completely independent of the GNSS measurements. As such it is, in principle, an extremely valuable validation and calibration technique. The laser reflector array (LRA) is a relatively light piece of equipment (~5 kg), fully passive with only a mechanical interface to the satellite, and thus it presents no risk at all of interfering with any satellite function.

For LEO satellites the usefulness of SLR is demonstrated routinely, where SLR-based orbit solutions belong to the state of the art. For MEO satellites this capability has not been fully exploited in the past, because routine ranging to MEO satellites has been scarce, which makes SLR-based orbit determination less accurate than microwave-based orbit determination. However, combined with the GNSS observations they lead to better results [2] and [3] for the GIOVE satellite orbits. With the increased capability of modern and future SLR systems, and a suitable LRA design [4], campaign-based SLR orbit determination of Galileo satellites will be of similar accuracy as the microwave orbit determination, and, to stress it again, fully independent of it.

All 4 IOV satellites are equipped with laser reflector arrays whereas GIOVE-A and GIOVE-B, also equipped with LRA, are already successfully tracked by the ILRS stations; see [2], [3], [6]. It is planned that all Galileo satellites will be equipped with satellite laser reflector arrays.

Galileo SLR Scenarios

The Galileo system has been designed to be operable and certifiable without relying on SLR. On the other hand, while not relying on SLR, Galileo may be supported by this technique in several valuable operational areas. In this section we look at three different scenarios which are:

1. Support to Galileo early phases
2. Calibration of spacecraft dynamics
3. Alignment of GTRF to ITRF

The results shown in this memo are based on the current state-of-the-art SLR techniques and operations [5] and are based on the following assumptions for SLR operations:

- Satellites priorities set according to satellite altitude (the lower the satellite, the shorter the pass, so less time is available for tracking)
- Five minute Normal Point (i.e. one condensed measurement), with accuracy of 1 cm.
- Three Normal Points per segment.
- Three segments per pass: ascending, middle, and descending.
- SLR sites include local ties to GNSS (mostly GPS; Galileo and/or GNSS in the future)
- The data are available in public website within two hours.
- Knowledge of relevant S/C characteristic (LRA centre of phase, Centre of mass) in the order of 10 millimetre accuracy.

In any case, improvements are expected in both night time and day time ranging, with increased ranging efficiency, thanks to updates in equipment and procedures planned for 2009-2011 [5] like:

- KHz ranging
- Improved detectors
- Increased automation/autonomous tracking

Scenario 1: Support to Galileo Early Phases.

For the early phases of the System, when the number and distribution of deployed GSS is still below nominal, SLR can provide additional data that allow a more robust orbit determination, as was already demonstrated for the GIOVE Mission [6]. Theoretical analysis showed that an improvement of 60% was possible by combining L-band measurements from a limited number of GSS (13 GESS, in the case of GIOVE) with the sparse SLR measurements obtained for GIOVE-A [3]. A posteriori analysis based on real data has shown that the improvement is actually in the order of 40% [7], being still remarkable. Possible Galileo infrastructures able to perform this analysis are the GMS MSF, the GPC E-OPSF, and the GALSEE IOCE. In addition, the GRSP is also able to process both SLR and L-Band observations and provide reference orbits. SLR as a complement to GSS L-band and TTCF S-band ranging will have a relevant effect at the beginning of the FOC phase, when the GSS and TTCF are not yet fully deployed. It is therefore recommended to equip all the Galileo FOC satellites in the first batch, i.e. the first 16, with LRA.

Scenario 2: S/C Dynamics calibration

For establishing a good dynamic modelling for the Galileo satellites, where in particular the radiation pressure model is of key importance and was subject for many analysis in the past [8], SLR data will be a valuable addition to the microwave data. SLR data, unlike microwave data, is not dependent on a great number of potential instrument issues like antenna patterns, carrier-code-coherency, temperature dependence, etc.

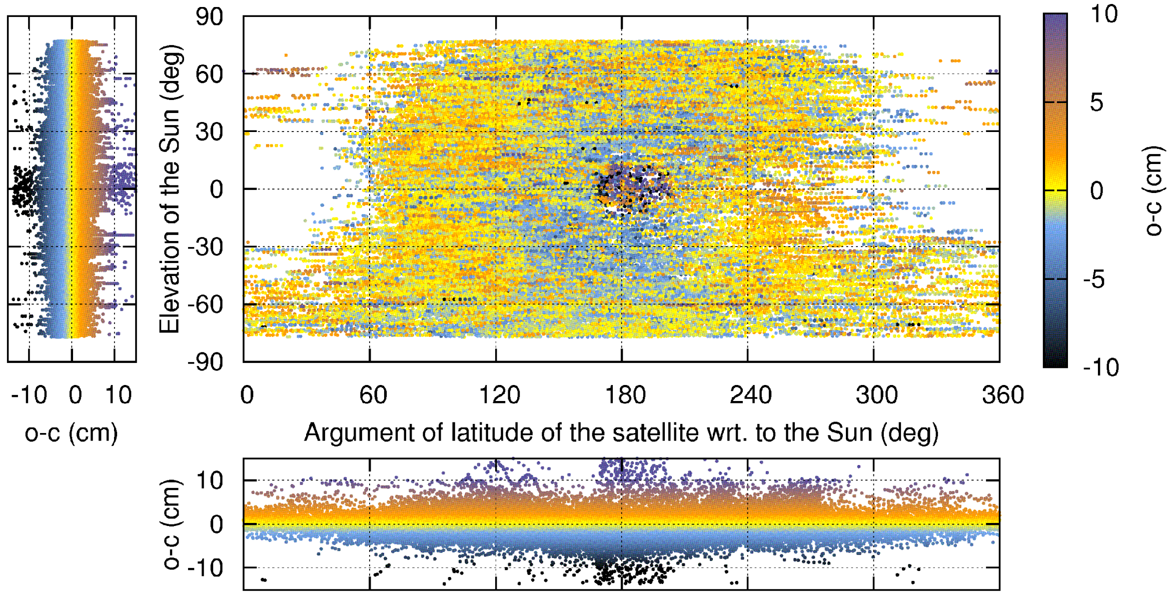


Figure 3: SLR residuals vs. Microwave-based orbits, as a function of Sun projection in orbit plane (u) and Sun angle with orbit plane (β). β<14 and u=[170,190] corresponds to eclipse. The lack of data in the regions u~0 and u~360 indicates no daylight tracking. The plot is based on the residuals of the SLR observations from the GPS satellites over the time frame of 1995 to 2008 using the ESOC reprocessed orbits.

As an example, the international GNSS community has been using SLR data from the two GPS satellites carrying LRA in order to study some S/C dynamics effects due to Earth radiation that had not been properly modelled. These unmodelled effects degrade the accuracy of GPS orbits, in particular during eclipses. This effect is most likely to be present in Galileo satellites as well, and the lack of LRA will impede proper calibration of this dynamic effect. Another earlier example, during the 1996 GPS laser ranging campaign, a number of interesting conclusions could be drawn, in particular with respect to eclipse modelling, as a GPS satellite was tracked during an eclipse pass. At this event, modelling errors of up to 10 cm could be measured, and in particular it was possible to measure the spacecraft attitude deviation (rotation) during the eclipse [9].

The Galileo LRA requirements for these studies, to be carried out by GRSP, would be met with the current GPS/GIOVE-A LRA design. In spite of the lack of day-light tracking (as it can bee seen in Figure 3), enough information has been extracted [8]. However, a more even distribution of SLR data (allowed by day-light tracking) will definitely improve these results.

If the satellite manoeuvres are coordinated properly with the ILRS community SLR could also contribute to observing the satellite manoeuvres by taking measurements during such an (once in a lifetime) event.

Scenario 3: Alignment of GTRF to ITRF

For the establishment of the Galileo Terrestrial Reference Frame (GTRF) and alignment to ITRF as required by GSRD-907 [10], SLR data provides an important additional data source that will allow linking the Galileo GSS coordinates to the ITRF more accurately, and improving the determination of the origin of the reference frame. In addition, SLR data will allow the independence of GTRF from GPS.

This link, based on the concept of "space ties", is only valid if the SLR data are well spread geographically and time-wise. The current GIOVE and GPS LRA designs are difficult to track during day-light, and the number of SLR station able to track them is limited. According to the ILRS, the amount of data gathered for GLONASS is enough for establishing robust space-ties. It is difficult to confirm this assumption with real data; GLONASS SLR data, even though abundant, has degraded range accuracy because the fact that the reflective area is built out of many split LRA's spread all over the Earth facing side of the satellites, which increases the range error. This was, in fact, the reason for the GIOVE-A final compact design of one LRA instead of the original design of one split in-two LRA [11].

Following the ILRS recommendations, the Galileo LRA shall have an effective cross section (measure for 532 nanometre wavelength) of 180 million square metres in order to provide enough day-light data. The current IOV LRA design meets this requirement (assuming that thermo-optical behaviour shows to perform as designed). Preliminary qualitative analysis shows that three satellites with LRA per plane, with maximum in-plane separation (e.g. A1, A4 and A7; being A, B, C the three Galileo planes), would be enough to provide a good spatial distribution. Less than two satellites per plane will leave holes in the spatial distributions. More than three satellites will over-load the SLR network; three satellites per plane means that any SLR station, at a particular time, will only see one high elevation target per plane, therefore, having to track no more than 3 Galileo satellites at any time.

Please note that the IOV satellites will be in consecutive positions (A1, A2; B9, B1) and from this point of view they would count as only one satellite per plane, one in plane A, and one in plane B. Further optimizations as to which constellation slots to fill with LRA carrying satellites will have to be done as part of Mission Analysis. At least *7* ***FOC*** satellites with LRA would be needed (two in plane A, two in plane B, and three in plane C).

Galileo and Geodesy, Galileo evolution

It is beyond any doubt, that having LRA equipment on Galileo satellites is of significant benefit to the scientific and geodetic communities [1], [12]. Does this by itself warrant the cost and effort of installing this equipment on all Galileo satellites?

While space geodesy is more concerned with issues that do not directly affect the system requirements placed on Galileo it would be short-sighted to detach Galileo from the geodetic world. Both the definition and implementation of the Galileo system and the space and ground segments have benefited, and still are benefiting, directly and in a very significant manner from the geodetic community, through work done by communities like the IERS, IGS and ILRS. Should the Galileo constellation, one of Europe's flagships in space in the coming decades, be of limited use to initiatives like the IAG's Global Geodetic Observing System (GGOS), and the common definition of the Earth's reference frame based on all space techniques?

Even if initially it might appear that the geodetic community will derive more benefit from LRA on Galileo than the system itself, the advantages it brings will certainly flow back to Galileo, in terms of improved standards, reference systems and models both of physics and of properties of the satellites. This should also be seen in the light of Galileo evolution activities. Current performance targets for Galileo can probably be met without the use of SLR, but SLR will play a role in targeting, analysing and achieving future performance values. Specific examples of areas for application of Galileo SLR data are:

- The reference frame 'scale' issue in GTRF/ITRF. The terrestrial reference frame definition depends on the measurement technique used. Even if the discrepancy is only of the order of up to 1 cm, Galileo, combining two of the prime techniques: L-band and SLR ranging, may be a key element in resolving this discrepancy, benefiting from the operational scenarios described above.
- Dynamic modelling errors can be diagnosed, as shown in Figure 1 above. A consistent modelling error of up to 10 cm in GPS orbit determination is made clearly visible by this analysis as per scenario 2.

Galileo will always be in competition with other non-European navigation systems and will need to be able to draw the maximum benefit from available techniques and expertise in Europe. Satellite laser ranging squarely belongs in that category. The "competition" is keeping a keen eye on what Europe decides on this topic.

Summary

The LRA provides access to many potential advantages coming from satellite laser ranging, none of which are strictly necessary for meeting the Galileo system requirements, but which give access to potential operational benefits, enforce Galileo's place in space geodesy, and play their role in the Galileo evolution.

In summary SLR tracking on Galileo may deliver the following contributions.

- Support for satellite fine positioning, especially for IOV and early FOC because of sparse Galileo tracking station network.
- Support for Galileo operational POD, especially for IOV and early FOC because of sparse Galileo tracking station network.
- Provide a completely independent validation of the Galileo orbits.
- Enable calibration and validation of the spacecraft dynamics.
- Ensure a close alignment of the GTRF and ITRF reference frames.
- Maintain and improve the ITRF.
- Ensure the position for Galileo in the scientific community in general, and GGOS and GMES in particular.
- Position Galileo as the "best" GNSS system
    - no SLR LRA's on GPS in the near future and
    - "split" LRA's on GLONASS giving rise to significant residuals.

- Ensure interoperability of Galileo with other GNSS systems through a common, independent measurement technique.

References

[1] J.M. Dow et al., Galileo and the IGS: Taking advantage of multiple GNSS constellations, Advance in Space Research 39 (2007)
[2] E. Schoeneman et.al., GIOVE-A Precise Orbit Determination from Microwave and Satellite Laser Ranging Data – first Perspectives for the Galileo Constellation and its Scientific Use", 1st Colloquium on the Scientific and Fundamental Aspects of the Galileo Program.
[3] C. Urschl et al., Orbit determination for GIOVE-A using SLR tracking data, ILRS Workshop, Canberra 2006.
[4] ILRS Meeting on Retroreflectors Arrays (Vienna, April 2006)
[5] M. Pearlman, ILRS Standard for Retroreflector Arrays at GNSS Altitudes, Third Meeting of the ICG, Pasadena December 2008.
[6] M. Falcone et al., Satellite Laser Campaigns: GIOVE's Track, GPS World, November 2006
[7] I. Hidalgo, Use of SLR Observations to Improve Galileo GIOVE-B Orbit and Clock Determination, ILRS workshop, Poznan 2008.
[8] C. Urschl et al., Assessing the quality of GNSS orbit models using SLR, EGU General Assembly 2007.
[9] P. Steigenberger, Reprocessing of a Global GPS Network, PhD Thesis, DGK Reihe C, Nr 640, ISBN 978-3-7696-5052-5
[10] System Requirements Document ESA-APPNS-REQ-00011 4.2 27 July 2004
[11] GSTB-V2/A - Space Segment Design Description and Justification File (SSTL Doc No: GDHB-56257 5.0 28/01/05)
[12] Galileo Mission Support Request Form, August 2004):
http://ilrs.gsfc.nasa.gov/satellite_missions/list_of_satellites/gioa_support.html

Impact of SLR Tracking on COMPASS/Beidou

Xiaoya Wang, Bin Wu, Xiaogong Hu, Yuanlan Zhu, Weijing Qu, Fumin Yang
Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai, China.

Graham Appleby
NERC Space Geodesy Facility, Herstmonceux, Hailsham, UK
E-mail: wxy@shao.ac.cn.

1. COMPASS overview

COMPASS/Beidou is the Chinese satellite navigation system and each satellite will be equipped with Laser Retro-reflector Arrays (LRA) to support orbit determination and perform orbit accuracy evaluation. It is planed to deploy the system in two phases. Phase I is required in order to set up a regional satellite navigation system. It includes 12 satellites (5 GEOs, 3 IGSOs and 4 MEOs). Its constellation in detail was given in our presentation "**Impact of SLR Tracking on COMPASS/Beidou**". To date two experimental satellites named COMPASS-M1 and COMPASS-G2 have been launched, on 14 April 2007 and 15 April 2009, respectively. They are being used to test the performance of all instruments including onboard and ground-based equipment as well as some software. Ten or more satellites will be launched in the next two years and the whole system will be completed by 2011 as scheduled. Phase II is now in the planning phase and, once implemented, COMPASS will become a true global satellite navigation system. There will be 30 (24 MEOs, 3GEOs and 3IGSOs) COMPASS navigation satellites at that time. The system will be initiated in 2015 and completed in 2020.

2. Current status

2.1 Laser retro-reflector array for COMPASS

The laser retro-reflector array used on COMPASS satellites includes two types. One consists of 42 fused-silica corner cubes, with an effective reflective area of 360cm^2 and a mass of 2.45kg. This type is made for the MEO satellites of the COMPASS system. Another type consists of 90 fused-silica corner cubes, with an effective reflective area of 770cm^2 and a mass of 5.00kg. It is made for the COMPASS GEO/IGSO. The diameter of the corner cubes is 33mm (1.3 inches). Each corner cube is uncoated both on the front and back faces. We choose the hexagon array for COMPASS in order to reduce the returned pulse spread and thus to achieve better ranging precision. The performance of LRAs on COMPASS has been proved very efficient by ILRS ranging to COMPASS-M1 and COMPASS-G2.

2.2 Orbit determination of COMPASS by SLR

As we know SLR has some specific and unique strengths due to its absolute, unbiased character and high precision range measurements. SLR measurement precision is of the order of 8 to 16mm for most of the stations of the ILRS Network. This precision is far higher than that of microwave pseudo-range measurements. In addition, COMPASS in phase I is a regional satellite navigation system and has only a few COMPASS tracking sites distributed in mainland China, further limiting the microwave orbit precision of

COMPASS MEO. Since December 2008, the ILRS began tracking COMPASS-M1. But there are still too few sites tracking COMPASS-M1 (often only 5 sites or so for 7-day arcs, only 10 sites at best) and even on some days there is no SLR data at all. This lack of SLR data makes daily parameter estimates very uncertain and difficult to perform. The gaps of course make daily parameter estimation impossible or even make the solution worse. The mean daily NP (Normal Point) observation number is 14 and its standard error is 11.7, leading to a mean number of SLR NPs in each 7-day arc of 61.7 with a standard error of 21.0. From these results it is clear that the observation numbers in daily and in each 7-day arc are both very poor and certainly much less than the situation with GPS and GLONASS. So we hope there will be a big improvement in SLR tracking for future COMPASS MEO satellites.

The existing SLR data was processed both in Shanghai and in Herstmonceux to produce the SHAO and NERC SLR solutions, using two different software packages (for the details see our presentation). The post-fit residuals for the 7-day orbital arcs in the period from December 2008 to June 2009 typically have residual RMS values of between 2-5cm for the NERC and between 1-6cm for the SHAO solutions. The RMS values don't always show the same behaviour, meaning that the two different methods and models most likely are absorbing different errors. Better agreement could no doubt be obtained by a careful comparison of models and estimated parameters and other factors in the treatment of the SLR data.

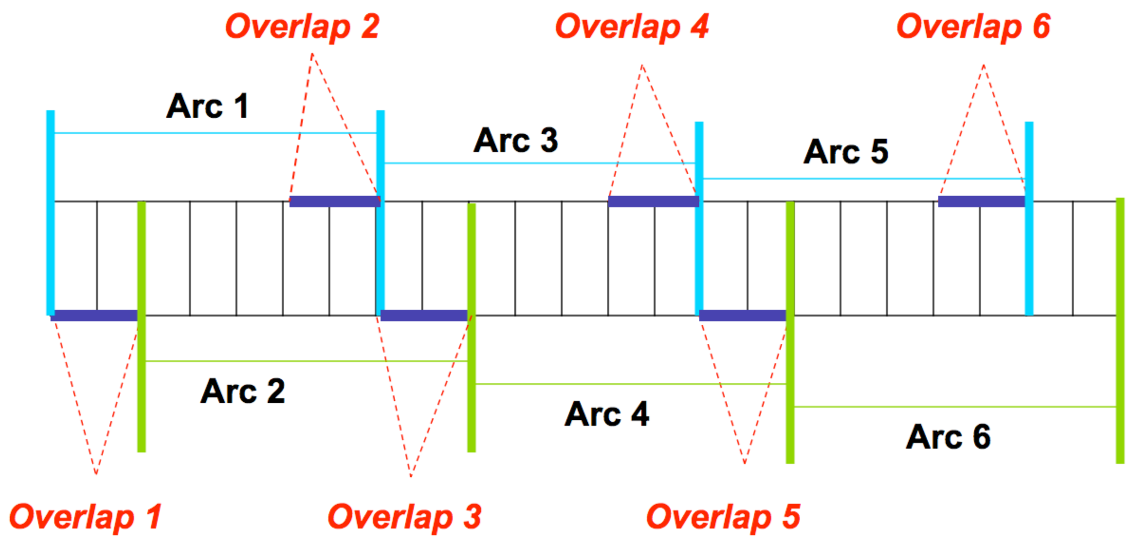


Figure 1. Definition of the adopted 7-day arcs, with a sliding 2-day offset.

In order to evaluate SLR-based orbit accuracy, we adopted a two-day sliding window which means that arc number 2 covers the data span from day#3 of the first arc and runs for seven days (Figure 1). The orbit overlap errors are computed by differencing the geocentric coordinates of the fitted orbits over the two-day common arc. Based on the RMS of the resulting orbit overlap differences from all the 7-day sliding orbital arcs during the period from 08 December 2008 to 17 August 2009, we find that the orbit overlap errors are about 1-3m in radial, 5-15m in transverse, 10-20m in normal direction and 20-40m in 3-D position. The best orbit overlap agreement is 0.18m in radial, 0.88m in transverse, 1.70m in normal direction and 1.92m in 3-D position (for MJD54895). There are some abnormal orbit overlap errors suggesting poor orbits, even though the orbits show small post-fit residual RMS; i.e., spuriously high precision caused by too few observations with respect to the number of estimated parameters or very high correlations among them. Sometimes, although the post-fit residual is large, the orbit overlap error is small (e.g. the 20090803 solution and the 20090805 solution show that). This demonstrates that a poorer post-fit residual precision doesn't necessarily mean a low-accuracy orbit.

2.3 Orbit accuracy evaluation by SLR

Besides SLR providing independent COMPASS orbits, it is also a unique tool to validate and assess the accuracy of COMPASS orbits based upon microwave data alone.

The microwave pseudo-range measurements likely contain large errors due to biases from the satellites' and the users' clock errors besides observation noise. So, we adopted three methods to deal with those clock errors. Method 1 is a pass-by-pass clock bias estimate (one constant bias plus one linear drift bias) for every site; Method 2 is a constant clock bias plus one linear and one quadratic bias estimate within the 3-day arc length for every site; Method 3 is only one constant clock bias estimate for every site and one common linear and one common quadratic estimate for all sites within the 3-day arc length.

The adopted models and estimated parameters are as detailed in our presentation. The results of the microwave-data orbit determination using the three methods above on different days all show that the methods give different post-fit residual and orbit overlap errors. The post-fit residuals of the microwave orbits is often about 1m or so (0.5m-3.0m). The orbit overlap error is often about 10m or so (5m-60m), where the largest overlap errors result from an explicit lack of microwave data. Method 1, estimating pass-by-pass clock bias for each site, has the smallest post-fit residual and better orbit overlap agreement. An orbit difference comparison of all three methods shows that Method 1 differs most from other two Methods, the biggest difference being about 40m. So, it is important to attempt to carry out an independent assessment of the accuracy of those orbits in order to discriminate between our methods. SLR provides such a useful, independent and reliable tool to do this work. Using the available SLR data, we find that Method 1 produces the poorest (lowest accuracy) orbits during these two periods. The comparison does show that the microwave orbits determined from all three methods are of meter order for COMPASS-M1, and that the residuals for COMPASS-G2 are better than those for COMPASS-M1.

2.4 Solution quality check and system error check

During the seven-day SLR-only orbital solutions, a single solar radiation multiplicative coefficient was solve-for. The behaviour of the resulting series of solar radiation coefficient values can act as a quality check on the solutions and also can potentially be a test of the stability of the vehicle. Each value is sensitive to the mean attitude of the spacecraft relative to the direction to the Sun over each orbital arc.

The NERC solution shows a periodic (~140-day) variation in the solar radiation coefficient values of amplitude some 2%. The presence of the smooth variation probably reflects the lack of a suitably complex radiation pressure model that should for example take into account the effect on the irregular-shape of the satellite of the varying direction of the Sun relative to the precessing orbital plane of COMPASS-M1. The 'spike' in the values at around day 135 (mid April 2009) is again most probably caused by the same deficient model and occurs at a time when the Sun is normal to the orbital plane. Similar behavior has been seen during POD of the GLONASS vehicles. It is likely that a more complex solar radiation model would account properly for these changes in radiation pressure, and hence 'flatten' the empirical coefficients.

The SHAO solution shows that the solar radiation coefficient values change between 1.1 and 1.4. There are three abnormal changes. The first one is for the 090202 solution, which only has 16 NP data. The other two anomalous solutions (090720 and 090603) become normal after we change the estimated parameters from the normal acceleration estimation to a drag acceleration estimation and also add site range-bias estimation. The derived solar radiation coefficients from 3-day microwave NAV orbits are different from those from 7-day SLR orbits (0.94 versus 1.3) although the radiation pressure model is the same and the software used is basically the same.

We still need to do more investigations, for instance to study how different data or different methods can result in such differences. Furthermore, our results for NAV orbits show 3% or so change within 7 days. So, for example, is our solar radiation pressure model accurate enough for COMPASS-M1? We are not sure.

3. The future application and needs of SLR tracking on COMPASS

The future application of SLR tracking on COMPASS would basically include the following aspects:

1) Continue to provide independent SLR-based COMPASS orbits and validate the COMPASS microwave orbits.
2) Evaluate the COMPASS microwave orbits by SLR data and determine what kind of processing strategy is better. This is very important especially now before the whole navigation system has been completed (a few satellites only) and there are many unstable error sources that make orbit determination difficult and complicated.
3) Check system errors using differences between COMPASS SLR orbits and microwave orbits, orbit evaluation residuals and solar radiation coefficient values.
4) Do more study to establish better methods and models to compute improved orbits, including combination orbit determination using SLR data and microwave data together.

However, in order to better complete these key points, we need to greatly improve the present status with regard to SLR tracking support. Items for urgent attention include the following:

- Continuous SLR observations are important and necessary for COMPASS POD. When there are data gaps for some days the adopted methods have to be modified.

The choice of estimated parameters is important for SLR data processing especially for sparse data. Moreover, continuous observations can of course make for SLR-based orbits of higher precision and accuracy.

- The cooperation of more of the ILRS sites, better globally-distributed, is necessary in order to improve COMPASS SLR-based POD.
- Could SLR data be available in near real time (less than 6 hours)? Looking through the ILRS data archives, we often find no new data for COMPASS even within 2-3 days from the date when we need to predict the orbit. If it is possible it could be used to evaluate and validate the COMPASS microwave orbits in real time and rapidly find any systematic errors and perhaps aid other real time applications.
- We need to quantify and balance ‘continuous observations’ according to the specific needs of the particular investigation being undertaken into the value of SLR tracking on COMPASS.

In one word, SLR can provide 5cm-level or so orbit determination residuals (it is often 1m or so from microwave measurements). So high precision SLR data is very useful to improve COMPASS orbits, validate COMPASS microwave orbits, look for system errors and improve adopted models and methods. Especially during Phase 1 of the COMPASS development, SLR observations are most important due to their global coverage.

様式2

正式配布

Impact of SLR tracking on QZSS

概要

国際レーザレンジジング機構(ILRS)2009 年秋の Workshop が「SLR と測位衛星」をテーマとして開催される。JAXA も、かねてより ILRS の枠組みの中で準天頂衛星(QZS)への SLR 実施を依頼してきたため、この Workshop に対して資料を作成し、説明する義務が生じた。このたび、QZS の概要、SLR の必要性、搭載反射器の概要、SLR 運用の在り方等を整理した、ILRS 向けの資料を作成したので文書として制定するものである。

キーワード	SLR, QZS, ILRS, LRA
情報の区分	■一般　□取扱指定　□社外開示制限　□部外開示制限　□秘　□極秘　□特殊 (TSS SSS SS) 開示制限解除年月：　　年　　月

配付先	ILRS	統合追跡NW技術部	準天頂プロジェクト
配付種類	正	正	参
部数	1	1	1

宇宙航空研究開発機構 '09.8.17 発行

関連 QZSプロ	承認	点検	作成	技術資料番号	改訂符号
寺田 沢辺 野田 岸本(鋭)	成田 H21・8・17	加 中村(崇) 井上	中村信一 H21・8・11	QNX-090036	
				統合追跡NW技術部	

Impact of SLR tracking on QZSS

Japan Aerospace Exploration Agency (JAXA)

Flight Dynamics Division

QZSS Project

August/2009

1 What is QZS (Quasi-Zenith Satellites)

1.1 Background

Recently, services using GPS, such as car navigation, mobile navigation, etc. have become essential for our life. Since Japanese geographical feature (mountains and tall buildings in urban areas) causes the interruption of satellite positioning or degradation of positioning accuracy, GPS is not useful in mountainous and urban areas, in which there is a strong requirement for using GPS. We suppose that there are many solutions to solve above-mentioned issues. One choice of the solutions is the QZSS (Quasi-Zenith Satellite System). At concept of the QZSS, there are more navigation satellites with high elevation angle.

1.2 Overview of QZSS

The Quasi-Zenith Satellite System (QZSS) is a regional space-based positioning system that uses a constellation of satellites placed in multiple orbital planes. The satellites have the same orbital period as a traditional equatorial geostationary orbit, however, they have a large orbital inclination and therefore have a dynamical ground track on the earth. The QZS orbits are also elliptical and are sometimes known as "highly-inclined elliptical orbits" or HEO. The system covers regions in East Asia and Oceania centering on Japan and is designed to enable users in the coverage area to receive QZS signals from a high elevation angle at any times.

The QZSS enhances GPS services in the following two ways:

1) Availability enhancement, that is, improving the availability of GPS signals,

and

2) Performance enhancement, that is, increasing the accuracy and reliability of GPS signals.

By broadcasting signals that are similar to and compatible with GPS, the QZSS enhances standalone GPS availability for any user that has visibility to, and can track one or more QZS. This enhancement will be the greatest for users in the region of Japan because the constellation design is optimized for that area. However, users in many other Asia-Pacific will also benefit from the enhanced geometric arrangement made possible by the QZSS. This increases the area and times at which positioning is possible in both urban and mountainous areas where a portion of the sky is often blocked from view.

To ensure interoperability and compatibility with the modernized GPS civil signals, GPS enhancement signals transmitted from QZS use modernized GPS civil signals as a base, transmitting the L1C/A, L1C, L2C and L5 signals. This minimizes changes to specifications and receiver designs.

The QZSS further improves standalone GPS accuracy by means of ranging correction data provided through the transmission of submeter-class performance enhancement signals L1-SAIF and LEX from QZS. It also improves reliability by means of failure monitoring and system health data notifications. The QZSS also provides other support data to users to improve GPS satellite acquisition. (see Appendix A)

The JAXA QZSS project will be implemented incrementally in accord with the official policy of the Government of Japan released on March 31, 2006 as follows.

- Phase One: The first QZSS satellite will be launched to conduct the technical validation and application demonstration:
- Phase Two: Following the successful completion of Phase One, the 2nd and 3rd QZSS satellites will be launched. Full system operation will be demonstrated.

1.3 QZSS System

The QZSS consists of

(a) the QZSS Space Segment (SS) comprised of a constellation of Quasi-Zenith Satellites (QZS) orbiting the Earth,

and

(b) the QZSS Ground Segment (GS) comprised of Monitoring Stations (MS), a Master Control Station (MCS), Tracking Control Stations (TCS) and Time Management Station (TMS). [Fig. 1.3-1]

QZS signals are transmitted from QZS and monitored by the MS. The MCS collects the MS monitoring results and estimates and predicts the QZS time and orbit. The MCS also gathers other data as well and generates navigation messages, and uplinks to QZS via the Tracking Control Station.

The Tracking Control Stations constantly monitor the status of QZS and function in cooperation with the MCS to provide appropriate services as needed. In addition, approximately once per year, the TCS exercise orbital control to ensure that QZS is maintained in the correct orbital position.

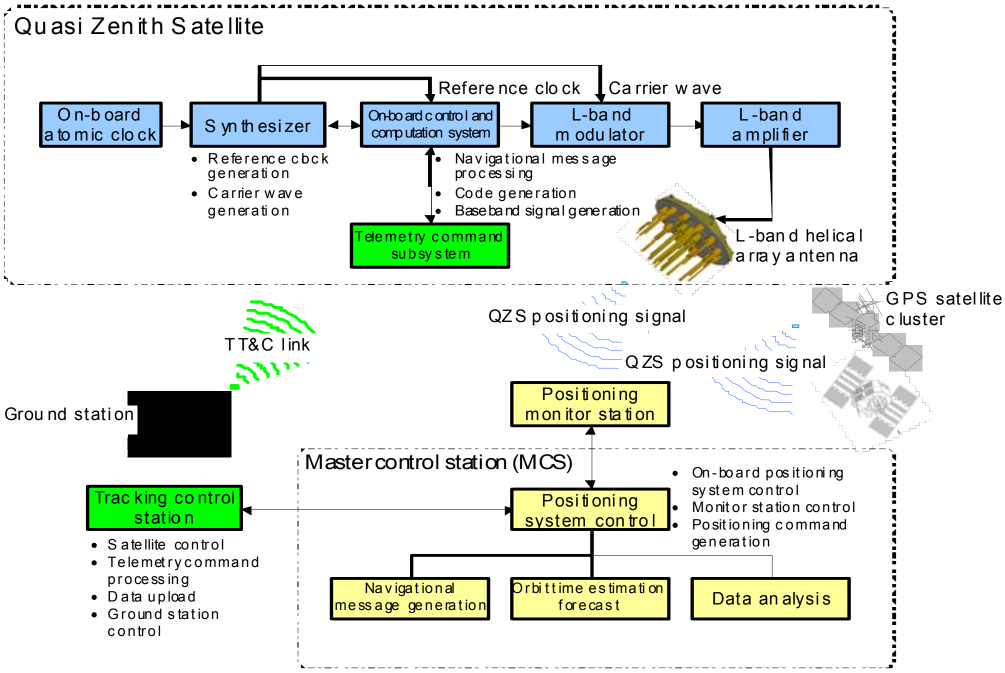


Fig.1.3-1 Configuration of the QZSS system

1.3.1 Space Segment

Space segment means Quasi-Zenith Satellite (QZS).

Three satellites are in elliptical and inclined orbits in different orbital planes to pass over the 8-shaped ground track. The QZSS is designed so that, at least, one satellite out of three satellites exists near zenith over Japan.

Navigation payload of QZS consists of (a) the rubidium Atomic frequency standard (RAFS), (b) the L-band signal transmission subsystem (LTS), (c) the time transfer subsystem (TTS), and (d) the laser reflector array (LRA).

Functions of navigation payload are defined by reception of the navigation message from the satellite, generation and transmission of the navigation signals, generation and transmission of the time comparison signals to ground stations, and laser reflection for laser ranging.

1.3.2 Ground Segment

Ground segment means Master Control Station(MCS), Monitoring Stations (MSs) and satellite tracking and control system.

1.3.2.1 Master Control Stations (MCS)

MCS is developed at Tsukuba Space Center in Japan. The role of MCS is defined by determination and prediction of QZS's orbit and timing, planning of the Navigation experiment and Control of the navigation system, generation and upload of navigation message, judgment and notification of the integrity, evaluation and analysis of navigation data, and data recording and distribution.

1.3.2.2 Monitor Stations (MSs)

Ten MSs are developed at the area according to QZS visibility. [Fig. 1.3-2]

MSs receive signal data from QZS and GPS, and acquire the environmental data like weather data. Observed data is transmitted to the MCS in JAXA Tsukuba Space Center.

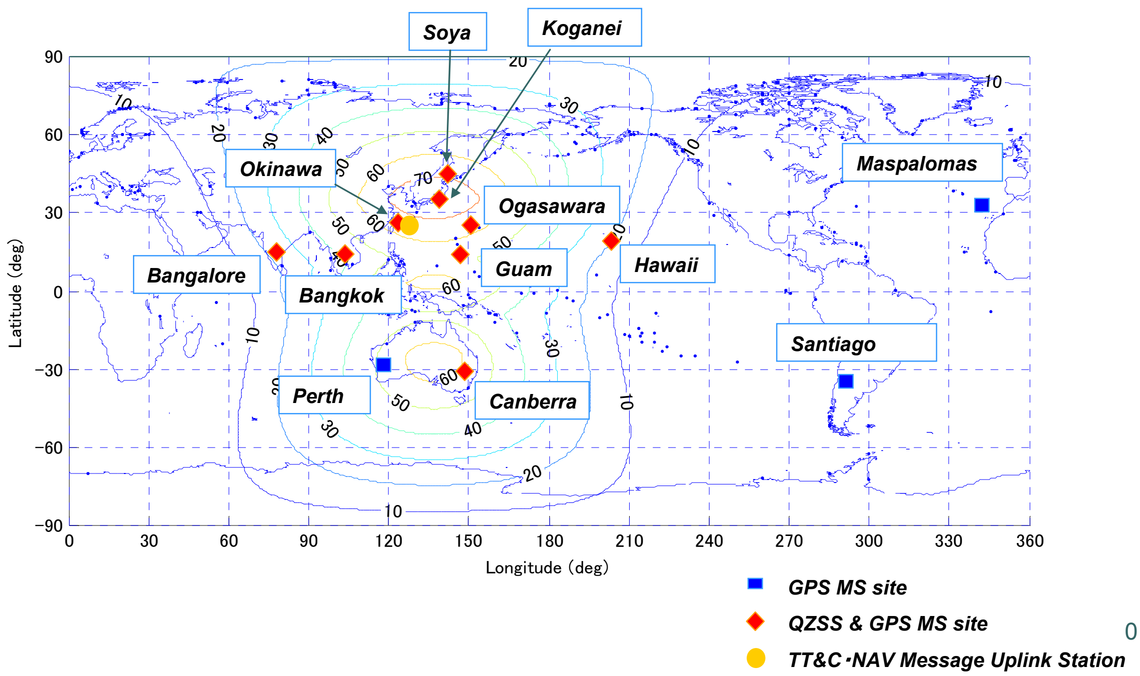


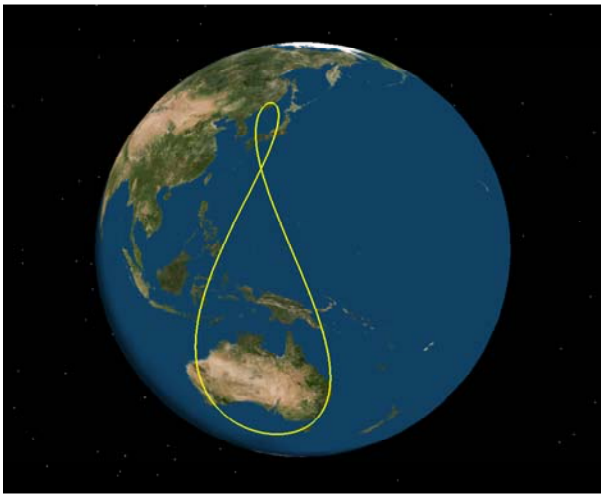
Figure 1.3-2　Location of MSs

1.4 Orbit Information

Typical orbital elements are shown in Table 1.4. Three satellites are in elliptical and inclined orbits in different orbital planes to pass over the same ground track. The QZSS is designed so that at least one satellite out of three satellites exists near zenith over Japan [Fig. 1.4-1].

Table 1.4 Orbit during QZS operation

Semimajor Axis (a)	Eccentricity (e)	Inclination (i)	RAAN (Ω)	Argument of Perigee (ω)	Center Longitude
42164.17km (average)	0.075 +/- 0.015	43 deg +/-4 deg	NA	270 deg +/-2 deg	135 degE +/- 5 deg



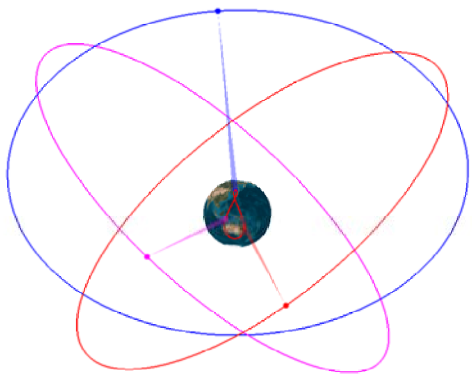


Fig. 1.4-1 Image of ground track (left) and orbital planes (right) of QZS.

1.5 QZSS Service

1.5.1 QZS Service Objectives

Since the QZSS can provide a seamless service from high elevation angle, we expect that the availability of PNT (positioning, navigation and timing) services in urban and mountainous areas will be increased. The QZSS enhances GPS services in the following two ways: 1) Availability enhancement (improving the availability of GPS signals) and 2) Performance enhancement (increasing the accuracy and reliability of GPS signals).

1.5.2 QZSS Service Area

The following figures show the availability (the percentage of time during which the specified minimum elevation angle condition is fulfilled) of a single QZS across the surface of the Earth due to the QZSS constellation. For the 3-satellite QZSS constellation, at least one QZS is available 100% of the time not only in Japan but in almost all parts of Southeast Asia and Oceania at an elevation angle of 10° or more. In Japan, at least one QZS is available 100% of the time at an elevation angle of 60 degrees or more (see Figs. 1.5.2-1 and 1.5.2-2).

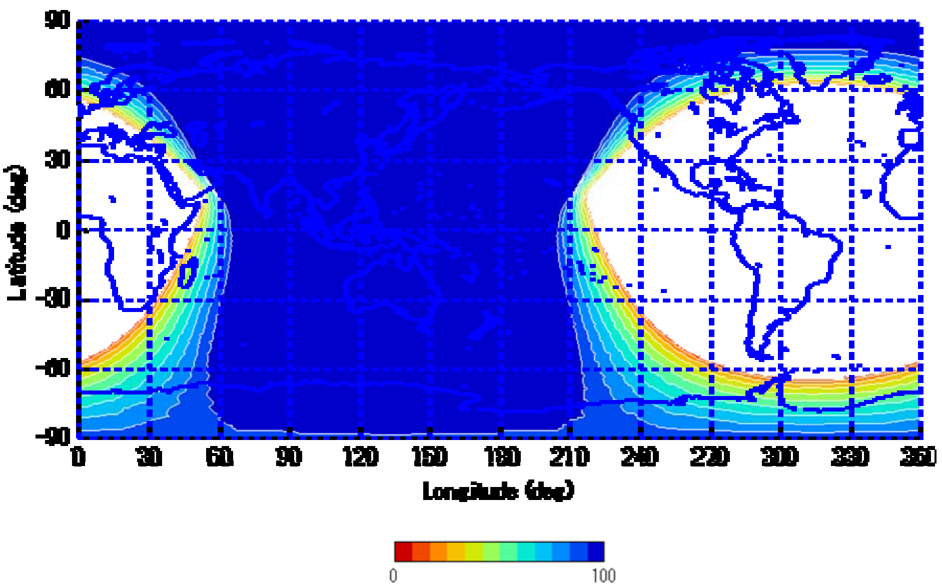


Figure 1.5.2-1: Percentage of time during which at least one QZS in the 3-satellite QZSS constellation can be seen at an elevation angle of 10° or more

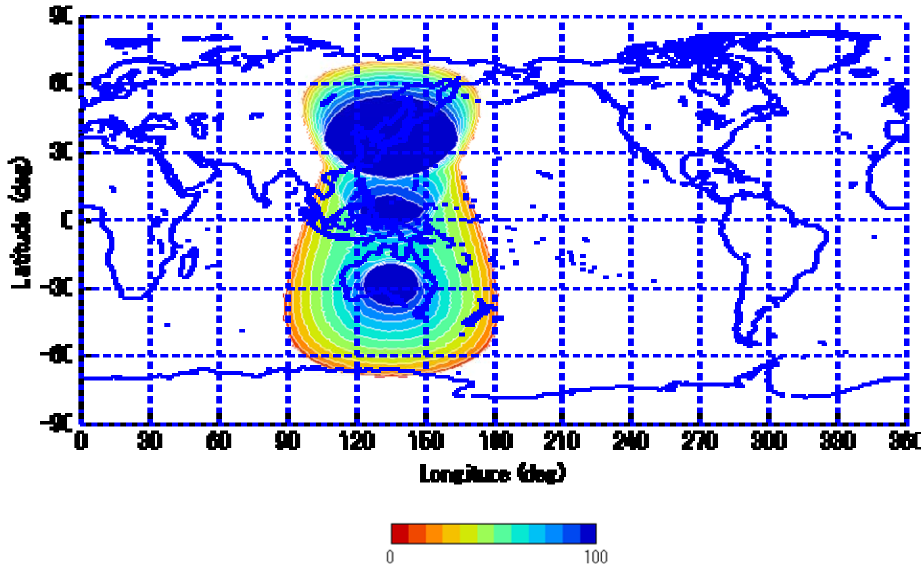
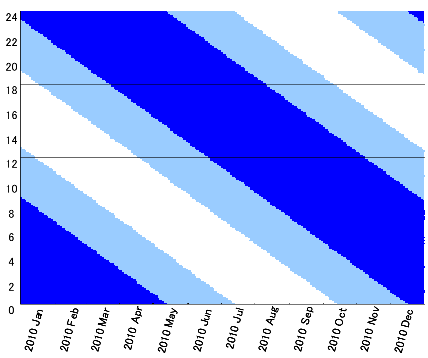


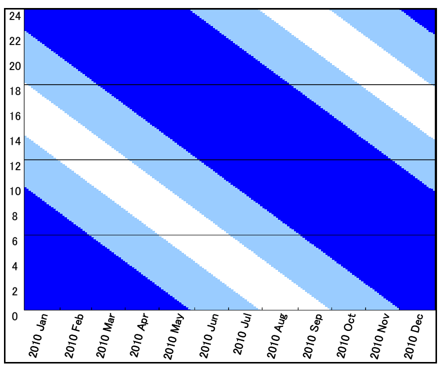
Figure 1.5.2-2: Percentage of time during which at least one QZS in the 3-satellite QZSS constellation can be seen at an elevation angle of 60° or more

1.5.3 Service Time / Interval

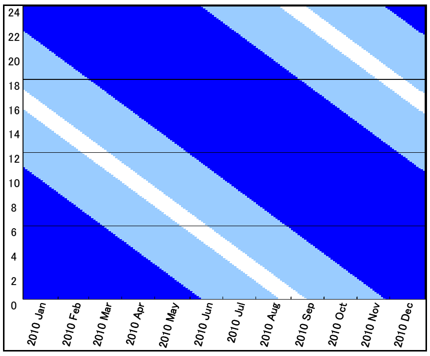
Each QZS transmits positioning signals 24 hours a day, 365 days a year. However, the time of day during which a particular QZS is visible to a given location varies with the date. This can be seen in following figure which shows the QZS visibility time bands for eight reference locations [Fig. 1.5.3].



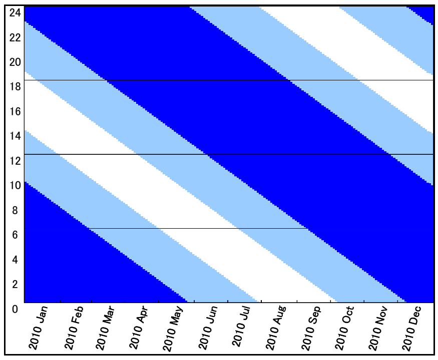
Wakkanai (Hokkaido, Japan)



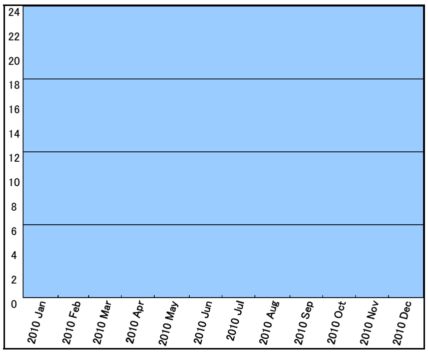
Tokyo



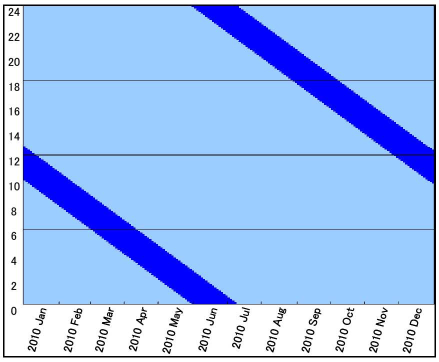
Okinawa



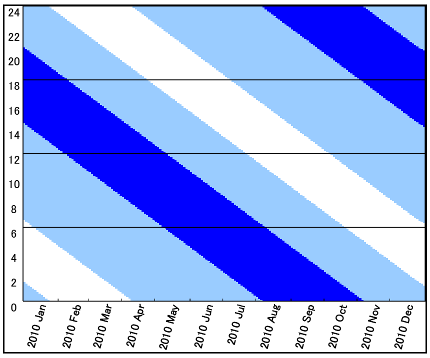
Seoul



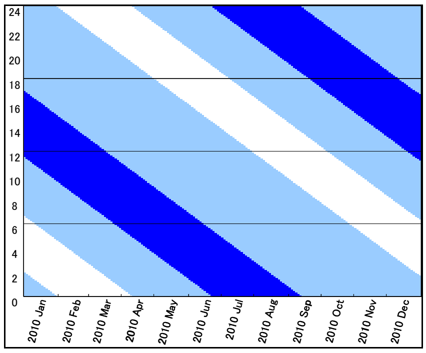
Bangkok



Singapore



Sydney



Perth

Figure 1.5.3: Initial Single-satellite QZSS visibility time for eight reference locations (dark shaded areas represent elevation angles of 60° or more; light blue areas represent elevation angles of 10° to 60°; vertical scale is hours)

1.5.4 Accuracy

The Signal-in-Space (SIS) accuracy is less than 1.6 m (95%) for all GPS interoperable signals. Horizontal positioning accuracy using GPS interoperable signals of QZS and combination with the GPS signals [Table 1.5.4].

Table 1.5.4 List of Accuracy

Positioning accuracy (95%)	Note
Single frequency: 21.9 m	Single frequency (User Ranging Error: 7.3 m)
Dual frequency: 7.5 m	Dual frequency (User Ranging Error: 2.5 m))

1.6 Schedule of QZS

The QZSS will be developed in a step by step manner.

1st step: Launch the 1st QZS and accomplish technical validation and application demonstration. Now, 1st QZS (QZS-1) will be launched in 2010.

2nd step: Launch the 2nd and 3rd QZS several years later and demonstrate system operation.

1.7 Anticipated Launch Date

Summer/2010 (TBD)

1.8 Expected Mission Duration

10 years or more

2 Letro reflector Array (LRA) on QZS s/c

2.1 Detail of Array

Appearance of QZS's LRA is given in Figure 2.1.

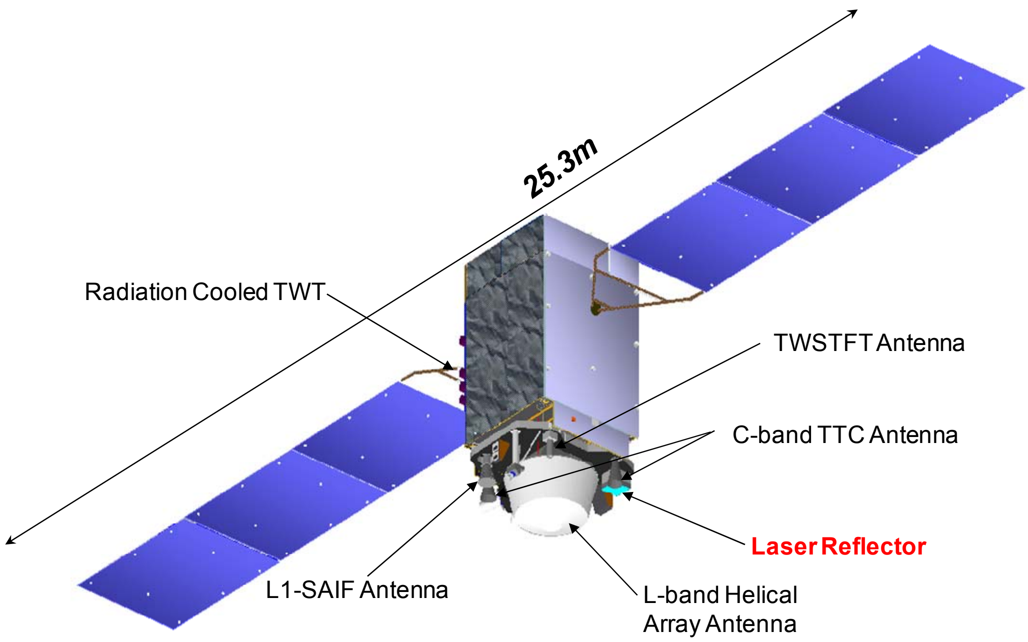
- planar type
- 56 CCRs (7rows * 8 lines)
- Diameter of each cube is 1.6 inch.

2.2 Details of Cube

- Suprasil
- index of refraction 1.46
- Dihedral Angle 0.8 arcsec
- Non coating

Fig. 2.1 Appearance of QZS's LRA

2.3 Location of LRA on QZS s/c



Satellite Configuration on Orbit

LRA is located at the bottom of satellite body. LRA always faces to the earth.

Specific position (x,y,z) relative to center of gravity will be provided.

2.4 Link Analysis

Before considering the link analysis, it is useful to use an analogy of ETS-8 tracking.

At first, we reviewed the ETS-8, which is gestational satellite located at 146 deg longitude, and its LRA. ETS-8 had mounted similar LRA to QZS, however, some properties were different from those of QZS. The following tables (Table 2.4-1 and 2.4-2) summarize the difference and common properties between LRA of ETS-8 and that of QZS.

Table 2.4-1 Difference between QZS LRA and ETS-8 LRA

	Number of CCR	Dihedral Angle
ETS-8	36	0.5 arcsec
QZS	56	0.8 arcsec

Table 2.4-2 Common properties between QZS LRA and ETS-8 LRA

	Shape	Diameter of CCR	Coat/Non Coat	Materials	Ref Index
ETS-8/QZS	Circle	1.6 in	Non coating	Sprasil	1.46

Tanegashima, Koganei, Yaragadee, Changchun, and Mt. Stromlo are success fully tracking for ETS-8. [Note that ETS-8 located 146 deg East longitude]

Tracking results is shown in Table 2.4-3.

Table 2.4-3 Summary of ETS-8 Tracking

Station Name	Return Rate	Note
Tanegashima	5% to 15 %	250mJ laser, 10Hz fire
Koganei	typically 1 %	50mJ laser, 20Hz fire
Yaragadee	1% to 3 %	100mJ laser, 5Hz fire
Changchun	0.1% to 1 %	150mJ laser, 20Hz
Mt. Stromlo	0.1 % to 1%	21mJ laser, 60Hz

Here, we pay attention to the expected return rate from QZS. At tracking QZS, compared to ETS-8, there is a big difference in the range between SLR station and satellite. According to the inverse fourth power of range, it shows a decrease in the number of expected return photoelectron.

Calculation result of the maximum slant range from each SLR station is shown in the following table. Here, JAXA calculated maximum slant range from each SLR stations.

Table 2.4-4 Some properties for ETS-8 tracking

	Maximum Slant Range of QZS	Elv	Slant Range of ETS-8	QZS/ETS8
Yarragadee	41,872.12 km	20	37,804.4 km	1.107
Mt. Stromlo	41,590.77 km	20	37,228.7 km	1.117
Tanegashima	39,146.86 km	75	37,138.6 km	1.054
Koganei	38,906.96 km	80	37,294.8 km	1.043

Slant range is about 10% longer than ETS-8 case at Yarragadee and Mt. Stromlo.

If we need similar return signal photoelectrons from QZS at Yarragadee and Mt. Stromlo during low elevation, we need bigger LRA.

LRA on ETS-8 consists of 36 cubes (6*6 array). Here, JAXA calculated equivalent LR of ETS8 for QZS. At first, I estimated necessary cube number for QZS,

$$N = 36 \times \left(\frac{11}{10}\right)^4 = 52.7\,.$$

On the above calculation, SLR link equation depends on slant range as $1/r^4$ =0.683

During our discussion, JAXA ignores effect of cirrus. This cirrus effects strongly on low elevation. Considering cirrus effect, QZS needs large LRA, which has, at least, 53 cubes

(7*8 array is better).

In order to compensate the decrease by long range, QZS LRA has bigger reflective area than ETS-8, that is, (56/36)=1.56 times.

Comparing with ETS-8 case, expected return photoelectron is changes 0.683*1.56=1.065 times without considering atmospheric absorption.

As a result, apart form decreasing effect by atmosphere absorption, we expect the similar return rate to ETS-8 in spite of longest range (lowest elevation). Even at higher elevation, we expected higher return rate than ETS-8.

Here, expected return rate from QZS is shown in Figs. 2.4-1 and 2.4-2. In both Figures, observed return rate from ETS-8 is shown by arrow.

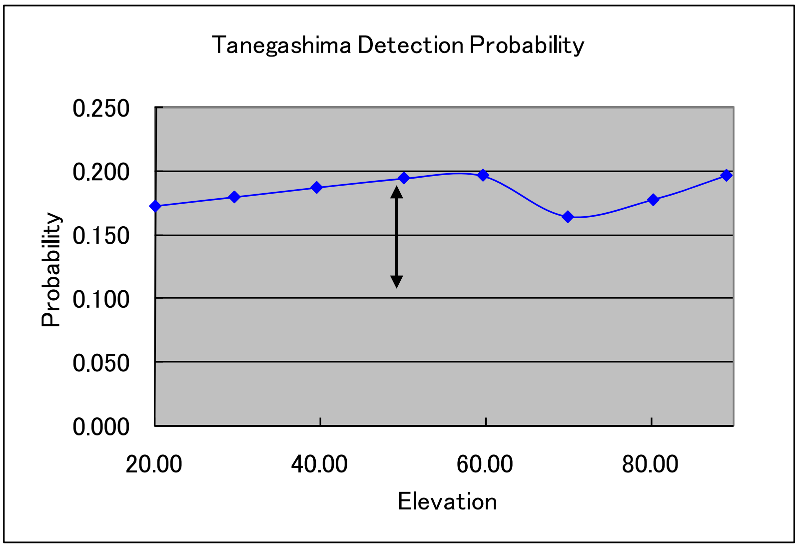


Fig.2.4-1 Expected Return rate at Tanegashima

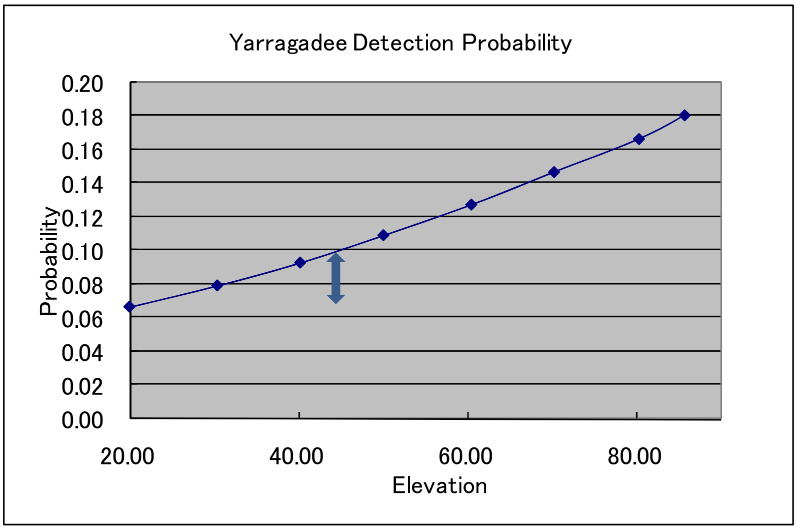


Fig.2.4-2 Expected Return rate at Yaragadee

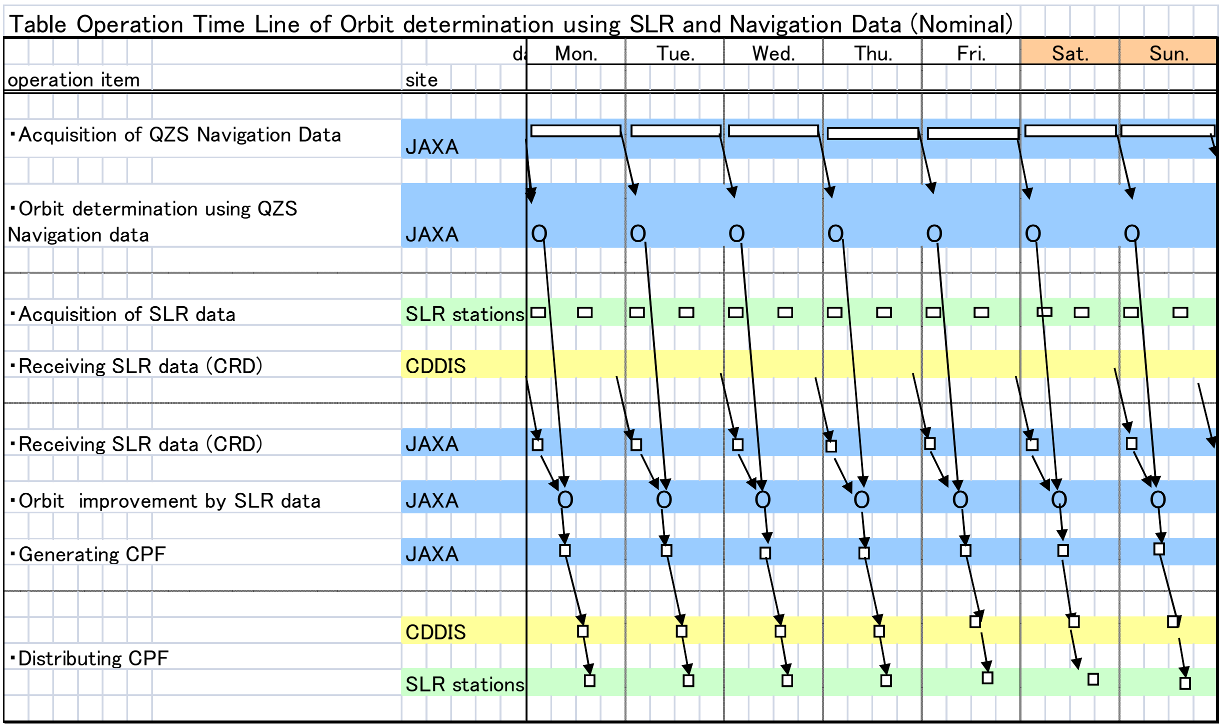
3 SLR Tracking and QZS Operations

3.1 General Information for Precise Orbit Determination of QZS

During QZS operations, JAXA uploads the ephemeris periodically [Table 3.1]. The ephemeris is calculated by real-time QZS navigation data which is observed at 10 monitor stations (see 1.3.2.2).

As for the SLR operations, orbit determination is performed on daily basis. Operational time line is shown in the following table. Using daily QZS navigation data from 10 monitoring stations, orbit determination is performed every morning. Also, JAXA downloads SLR observational data (CRD) from CDDIS on daily basis. At JAXA, orbit improvement is performed by combining SLR data to QZS navigation data. After orbit improvement, JAXA calculates the SLR prediction file (CPF) and distributes it via CDDIS server.

Table 3.1 Timeline of SLR operation



3.2 Satellite Laser Ranging Role of Mission

SLR tracking plays an important role in QZS mission, that is, precise orbit determination for QZS. In order to contribute to geodesy and earth science, JAXA distributes precise orbit of QZS (QZS final orbit), which is similar to the final orbit of GPS. In order to calculate QZS final orbit, JAXA needs to determine QZS clock bias and orbit simultaneously. As well known, since SLR data helps to eliminate the error (bias) from observed data, JAXA estimates QZS final orbit with high accuracy.

3.3 Tracking Schedule

JAXA hopes 2 stages tracking;

- 1st stage (Campaign):

  Purpose : confirmation of precise orbit determination, clock estimation, estimation of bias for each monitor station, QZS checkout

  Priority : High such as GIOVE-A campaign

  Frequency : in-orbit initial phase, checkout phase for satellite performance, ground system performance and every 6 months

  Core Time: For example, 0:00-0:15, 4:00-4:15, 8:00-8:15, 12:00-12:15, 16:00-16:15, 20:00-20:15 (UT).

- 2nd stage (Nominal Operation):

  Purpose : increasing orbit determination accuracy of ordinary operation

  Priority : low such as GPS35,36, Glonass, GIOVE-A

  Frequency : all day, but we hope core time ; For Example, 9:00-9:15, 12:00-12:15, 15:00-15:15 (UT)

Tracking information will be notified to all SLR stations by web and/or SLR-mail. Tracking prediction file (CPF) will be distributed by CDDIS server.

3.4 Success Criteria

- 1st stage (Campaign)

As success criteria, the accuracy of orbit determination, accuracy of clock estimation, and bias for each monitor stations during 1st stage should be preformed only by SLR data.

Precise orbit determination have to be performed only by SLR data for long arc, such as 1 day arc.

- 2nd stage (Nominal Operation)

In order to distribute reliable QZS final orbit/clock, it is better to add SLR data on QZS navigation data.

However, since accuracy validation is performed at 1st stage tracking, it is not always necessary to obtain SLR tracking data from ILRS western pacific ocean network. But, at least, JAXA Tanegashima SLR station always tracks QZSS.

As success criteria, SLR data acquisition is frequently done.

3.5 Spatial Coverage

Only Around Western Pacific Ocean. Visible Area from Tanegashima and Yarragadee SLR stations are shown in Figs. 3.5-1 and 3.5.2, respectively. In this figures, minimum elevation angle is set to 20 degree.

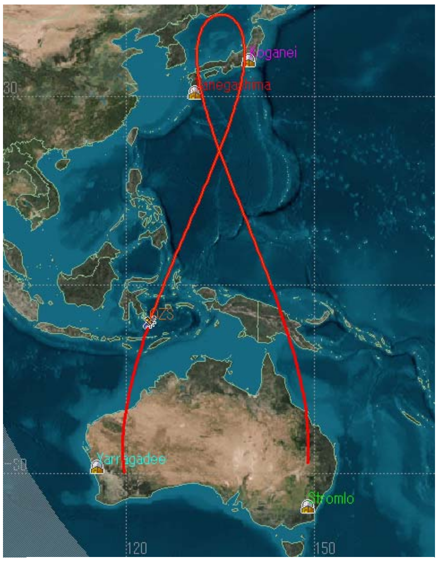


Fig.3.5-1 Visible Area from Tanegashima

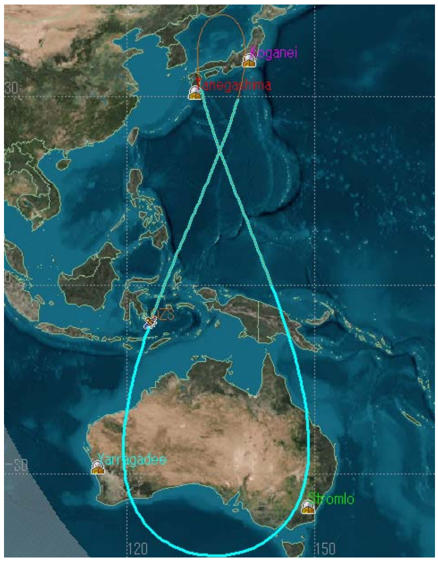


Fig. 3.5-2 Visible Area from Yarragadee

3.6 Temporal Coverage

At any time,

However, in order to grow in efficiency of precise orbit determination process, JAXA hopes to make core time of tracking, for example, 9:00-9:15 (UT), 12:00-12:15(UT), and 15:00-15:15 (UT).

3.7 Data Accuracy

Millimeter to Centimeter ranging accuracy

3.8 Data Delivery Time Requirements

Sub-Daily to CDDIS and/or EDC on Nominal Operation

4 Conclusion

JAXA summarizes the impact of SLR tracking on QZSS, which is the main title of this document.

4.1 For Global Navigation System around Western Pacific Ocean

In order to distribute reliable QZS final orbit/clock, it is better to add SLR data on QZS navigation data. At this process, SLR data plays an important role. Since SLR data is quite high accurate, we can decouple the ambiguity between range bias and time bias. Thus, introducing SLR data, the accuracy of QZS final orbit/clock can be significantly improved.

4.1.1 For SLR stations and ILRS tracking network

JAXA hopes to get support of ILRS western pacific ocean network tracking.

- At 1st stage (campaign)

  Enough SLR data is needed to perform precise orbit determination only by SLR data.

  Core Time Tracking : 0:00-0:15, 4:00-4:15, 8:00-8:15, 12:00-12:15, 16:00-16:15, 20:00-20:15 (UT).

  Candidate SLR stations : ILRS western pacific ocean

- At 2nd stage (nominal operation)

  In order to improve accuracy of final QZS orbit/clock, SLR data is needed. However, it is not always necessary to get SLR data.

  Core Time Tracking : For Example, 9:00-9:15, 12:00-12:15, 15:00-15:15 (UT)

  Candidate SLR stations : ILRS western pacific ocean.

5 Point of Contact

Division	Name	E-mail
Flight Dynamics Team Manager	Mr. Harushige Noguchi	noguchi.harushige@jaxa.jp
Flight Dynamics Team	Mr. Shinichi Nakamura	nakamura.shinichi@jaxa.jp
Flight Dynamics Team	Mr. Ryo Nakamura	nakamura.ryoh@jaxa.jp
Flight Dynamics Team	Mr. Takahiro Inoue	inoue.takahiro@jaxa.jp
QZS project Mission Manager	Mr. Mikio Sawabe	sawabe.mikio@jaxa.jp
QZS Project	Mr. Hiroyuki Noda	noda.hiroyuki@jaxa.jp
QZS Project	Mr. Motohisa Kishimoto	kishimoto.motohisa@jaxa.jp

Appendix A

As references, QZS broadcast some signals as followings;

Signal name	I/Q channel identification	Center frequency	Frequency Bandwidth	Received Minimum Power Level*	
L1C/A	$L1_{CA}$	1575.42 MHz	24 MHz (±12 MHz)	-158.5 dBW	
L1C	$L1_{CD}$		24 MHz (±12 MHz)	-163.0 dBW	-157.0 dBW (Total)
	$L1_{CP}$			-158.25 dBW	
L1-SAIF*	-		24 MHz (±12 MHz)	-161.0 dBW	
L2C	-	1227.60 MHz	24 MHz (±12 MHz)	-160.0 dBW (total)	
L5	$L5_I$	1176.45 MHz	25 MHz (±12.5 MHz)	-157.9 dBW	-154.9 dBW (Total)
	$L5_Q$		25 MHz (±12.5 MHz)	-157.9 dBW	
LEX	-	1278.75 MHz	42 MHz (±21.0 MHz)	-155.7 dBW (total)	

* L1-SAIF: L1-Submeter-class Augmentation with Integrity Function

The Impact of SLR Tracking of GNSS Constellations on Science

Erricos C. Pavlis, GEST/UMBC - NASA Goddard (epavlis@umbc.edu), John LaBrecque (NASA HQ) (John.LaBrecque@nasa.gov), John Ries (CSR, Univ. of Texas), Richard Gross (NASA/JPL).

Introduction:

The numerous applications of the signals from navigational constellations with varying levels of accuracy requirements has rightfully earned GNSS a place amongst the typical utility services that we have come to expect readily available worldwide. From the very early stages of the first such system, the Global Positioning System – GPS, users from very diverse areas attempted to extract highly accurate results, well before the system became fully operational. Scientists very quickly realized the potential of such technology and were some of the first and most demanding users. The need for high accuracy for geodetic applications drove the development of sophisticated receiving equipment at a very rapid pace. Today we have available a multitude of GNSS constellations that are either operational or nearly so, while there are yet more in the process of development. GNSS has evolved as the prime system for a number of geodetic applications, some of which are precise positioning, monitoring of deformation fields, Earth rotation monitoring, Precise Orbit Determination (POD) of LEO missions, the contribution to the development of the International Terrestrial Reference Frame (ITRF), as well as providing access to it for the users, to name a few.

The purpose of this position paper is to focus on the scientific benefits from the tracking of such constellations with SLR. Direct impact of SLR tracking on the GNSS constellations was already presented in the corresponding Position Papers. Herein we will focus on the areas where the improved products will likely have significant implications and the new opportunities presented to the SLR community with the large number of Laser Retro-reflector Arrays (LRA) that will be very soon launched in orbit.

A summary of the direct benefits to GNSS

All of the GNSS operators agree that the tracking of their spacecraft with SLR, an independent technique, insensitive to the ionosphere and with very small dependence on atmospheric water vapor (refraction delay), will aid their calibration and validation of their orbits. Furthermore, SLR observations will aid in modeling the onboard clocks, a key part of GNSS techniques. SLR measurements are independent of the GNSS station positions and onboard clocks, thus the effect of any mis-modeling of the GNSS clocks can be separated from orbit errors, leading to improved understanding of clock behavior in space. This in turn will lead to improved GNSS positioning and navigation for the users. Other areas that will benefit directly are the tracking support in the initial phases of deployment of new constellations, when their own tracking network is still in its infancy, the improvement and validation of spacecraft dynamics, the alignment of the GNSS intrinsic reference frames to ITRF, and enabling the interoperability of these systems through a common, independent measurement technique.

Additional, indirect benefits

Earth science relies heavily on GNSS for positioning and navigating instrumented platforms, whether fixed on the ground, seaborne, airborne, or on spacecraft. For highest accuracy applications such the reference frame and Earth orientation, the results are obtained reducing the data in a grand scheme that estimates all parameters simultaneously. There are a number applications though for which the use of these precise orbits in a second step provides accurate enough results without the need for a global estimation scheme requiring data from around the world and significant computational effort. Precise Point Positioning (PPP) has become a standard for many users who do not demand the highest accuracy and rely on precise orbits available through IGS or other individual institutions and agencies. These users will experience an increase in accuracy and they find that their results will become more consistent with the ITRF. This alone can have major implications for the use of PPP that will probably see an exponential user increase.

Similarly, the many missions that today use GNSS tracking for their POD will see a more accurate orbit and higher consistency with the ITRF, leading to better geolocated products and most likely a quicker turn-around of their products, which sometimes is a critical factor. Oceanographic missions like OST/Jason-2 for example will be able to release sea surface height maps in near real-time with much higher accuracy than it is possible today, leading to various oceanographic applications not possible at present. GRACE products will benefit from the higher quality of the GPS orbits to the extent that they can make better use of that tracking data for the resolution of the very low-degree harmonics that are now typically substituted from SLR-based solutions (Fig. 1).

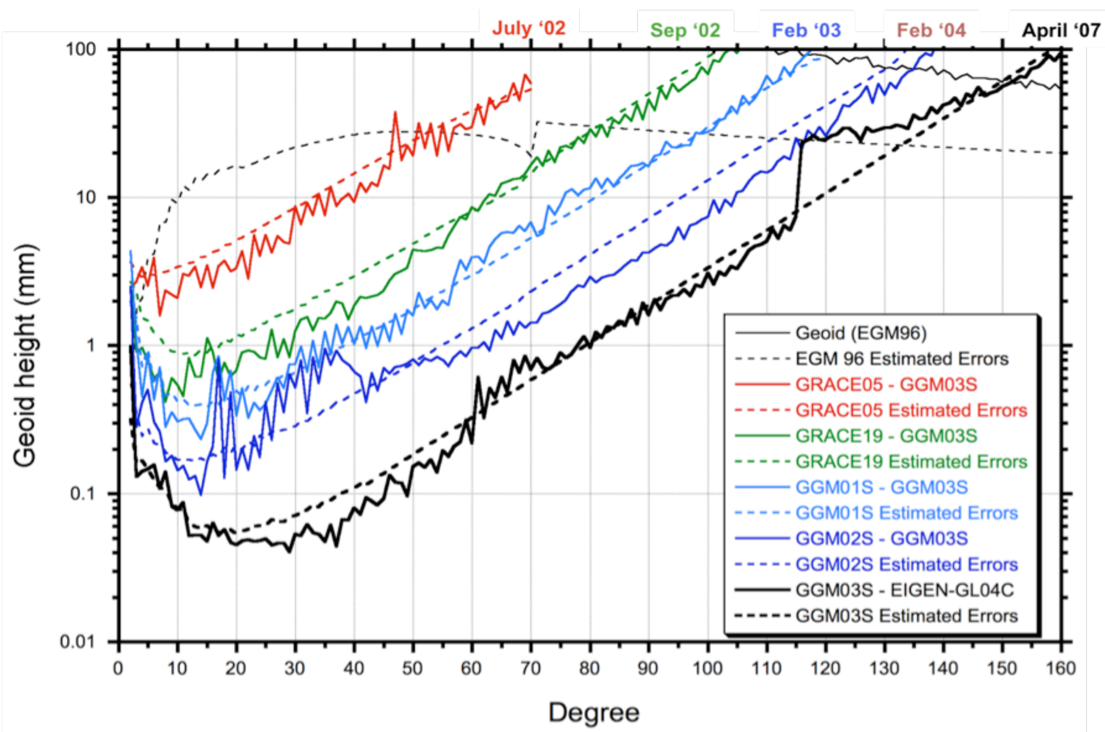


Figure 1. Geoid height error spectrum for GRACE-derived gravitational field models.

It is easily noticed that while GRACE results are by nearly two orders of magnitude more accurate than the previously best estimates for degrees ten and higher, the longest wavelengths are not benefiting as much, and for degrees below three, there is hardly any improvement. The improvement of the fitted GPS orbits and clocks at JPL, and the resulting resolution of a much larger number of ambiguities in tracking Jason-2 resulted in a significant improvement of its orbit, especially in the radial direction (Fig. 2).

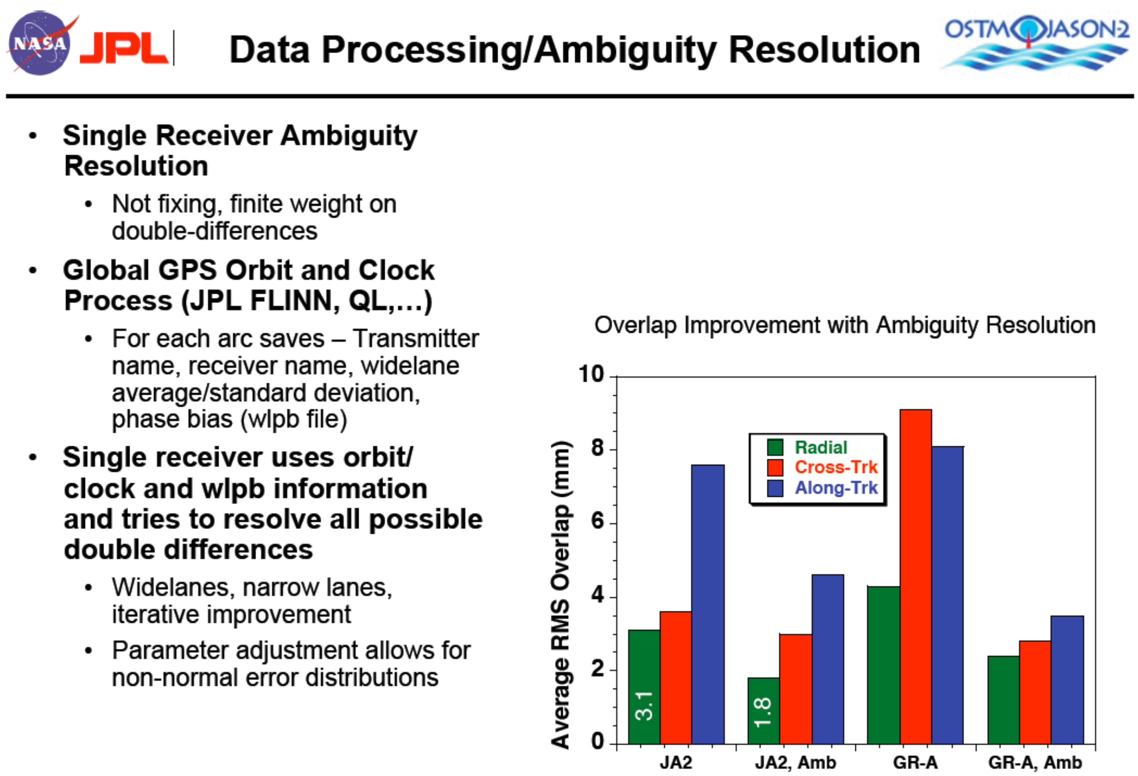


Figure 2. Orbit overlap RMS for Jason-2, based on improved ambiguity resolution [Bertiger et al., 2009].

As of today there are several other Earth-observing missions currently using GNSS as their positioning technique and many more planned for the near future. Table 1, compiled recently for a report to NASA, shows a subset of future missions likely to succeed, along with their main application area, sponsor, and geodetic requirement. Higher accuracy GNSS orbits and clock modeling will certainly have a significant impact on the results, operations and products of these missions. The consistent use of a very well defined and traceable reference frame (ITRF) made widely accessible with high fidelity through the GNSS constellations, will place by default the results and products from all of these missions under the same frame. This common reference for all Earth observations will enable the integration of such results in more complex coupled global models, removing the need for estimation of biases or other transformations between results and making their interpretation simpler and less ambiguous. Improvement of these global models based on current observations will consequently result in improved forecasts, which will lead to a more reliable prediction of natural hazards.

Table 1. Upcoming Missions' Requirements on Space Geodesy

Science Objective	Mission	Category/Sponsor	Geodesy Requirement
Atmospheric Science Climate Change	CLARREO (NASA portion) 2010-2013	Decadal Survey - NASA	precise orbit determination
Atmospheric Science Hydrologic Science	SMAP 2010-2013	Decadal Survey - NASA	geo-referencing
Cryospheric Science Climate Change	ICESat-II 2010-2013	Decadal Survey - NASA	precise orbit determination
Solid Earth Science Cryospheric Science Natural Hazards Climate Change	DESDynI 2010-2013	Decadal Survey - NASA	precise orbit determination
Solid Earth Science	HyspIRI 2013-2016	Decadal Survey - NASA	geo-referencing
Ocean Science Hydrologic Science Natural Hazards	SWOT 2013-2016	Decadal Survey - NASA	precise orbit determination
Solid Earth Science Hydrologic Science	LIST 2016-2020	Decadal Survey - NASA	precise orbit determination
Solid Earth Science Hydrologic Science Ocean Science	GRACE-II 2016-2020	Decadal Survey - NASA	precise orbit determination
Cryospheric Science Hydrologic Science	SCLP 2016-2020	Decadal Survey - NASA	geo-referencing
Atmospheric Science Climate Change	CLARREO (NOAA portion) 2010-2013	Decadal Survey - NOAA	precise orbit determination
Atmospheric Science Climate Change	GPSRO 2010-2013	Decadal Survey - NOAA	precise orbit determination
Ocean Science Natural Hazards	Jason-3 2013 launch	Future ocean altimetry	precise orbit determination
Ocean Science Natural Hazards	Sentinel-3A 2013 launch	Future ocean altimetry	precise orbit determination
Cryospheric Science Ocean Science Natural Hazards	CRYOSAT-2 2009 launch	Future ocean altimetry	precise orbit determination
Ocean Science Natural Hazards	SARAL 2010 launch	Future ocean altimetry	precise orbit determination
Ocean Science Natural Hazards	HY-2A 2010/11 launch	Future ocean altimetry	precise orbit determination

CLARREO, Climate Absolute Radiance and Refractivity Observatory; SMAP, Soil Moisture Active-Passive; ICESat, Ice, Cloud, and land Elevation Satellite; DESDynI, Deformation, Ecosystem Structure, and Dynamics of Ice; HyspIRI, Hyperspectral Infrared Imager; SWOT, Surface Water and Ocean Topography; LIST, Lidar Surface Topography; GRACE, Gravity Recovery and Climate Experiment; SCLP, Snow and Cold Land Processes; GPSRO, Global Positioning System Radio Occultation; T/P, TOPEX/Poseidon; ESA, European Space Agency; ERS, European Remote Sensing; ENVISAT, Environmental Satellite; SARAL, Satellite with Argos and Altika; ISRO, Indian Space Research Organization; CNES, Centre National d'Etudes Spatiales; CNSA, China National Space Administration

With improved, more accurate and reliable predictions we can plan far better and at an earlier stage the mitigation and control of undesirable phenomena. This is the main focus of the Global Geodetic Observing System – GGOS, which has made the integration of the techniques one of its primary tasks, realizing that only through such an effort we will be able to meet the stringent accuracy requirements placed on us by the current scientific requirements: a reference frame accuracy of 1 mm and a stability of 0.1 mm/y with comparable limits on the scale and orientation.

A number of US Federal Organizations (NASA, NGA, NOAA, USGS, NRL, USNO) have recommended to the Interagency Forum on Operation Requirements (IFOR) that a very important step toward this accuracy target of 1 mm accuracy and 0.1 mm/y stability is to provide systematic co-location in space through the precision orbit determination of GPS satellites via the global network of laser ranging stations supported by these agencies and GGOS. The required improvements in the ITRF are approximately 10-20 times its current accuracy. The most recent determination of the ITRF (Altamimi et al, 2007) is estimated to be accurate to something less than 1 part per billion, which translates to about 6 mm of sea level change on the Earth's surface. Most models of sea level change, which is on the order of 3 mm/yr (Beckley et al, 2007), attempt to resolve sea level change to 0.1 mm/y resolution. The World Climate Research Program publication on sea level -*Understanding Sea-level Rise and Variability*, (2006, in press) calls for a reference frame that is accurate to 1 mm and stable to 0.1mm/y (Neilan et al., 2009). The report goes on to state that the ITRF origin (the Earth's Center of Mass) and the ITRF Scale (determination of absolute distance) are the most important parameters in the realization of an accurate ITRF for sea level. Meeting this accuracy requirement for the ITRF is not possible with the existing architecture of the networks supporting GGOS.

Co-locating GNSS and SLR in space and on the ground, along with the improved measurement and monitoring of the corresponding reference points in space and on the ground, will provide us with improved GNSS orbits and products and a geometrically more robust space segment for the SLR network. The latter at the moment relies on essentially two targets to develop the required input to ITRF for its origin and scale: the two LAGEOS satellites. If the gamut of targets were to increase by including several of the GNSS spacecraft on which the LRAs were properly designed and calibrated, then the SLR sensitivity to the origin and scale of the frame could be "transferred" to those GNSS targets and consequently the products derived on their basis. In early 2009, NASA commissioned a simulation effort to address the feasibility of this option and the extent to which we would have to couple the two techniques in space and on the ground to meet the required level of accuracy.

This simulation will quantitatively document the utility of SLR tracking of the GPSIII constellation as the means of achieving the Geodetic Requirement for GPSIII of the 1 mm accuracy and 0.1 mm/y stability of the International Terrestrial Reference Frame and its derivative- the WGS84. This study assumes that if we remove the systematic errors through careful tracking and modeling of the GPS satellite orbits with SLR, that the increased numbers of GPS satellites tracked will result in an ITRF that meets the GGOS requirements. The study will eventually extend beyond the GPS constellation alone and address the benefits from a similar approach for all constellations, quantifying at the same time the subsequent benefits for SLR.

The interim conclusion is that periodic SLR ranging to all GPS satellites supported by an enhanced SLR tracking network currently under development will provide the necessary measurements to achieve the required goal. But equally important is that GPS will then provide a means to accurately and uniformly distribute this new accuracy to all systems utilizing GPS whether civilian or military, scientific or commercial. The improved GPS orbits will also provide a more accurate and cost effective means to transfer the ITRF to a multitude of applications including land, air, and space-borne applications. The results do demonstrate also the value of tracking the GPS satellites within the Geodetic Satellite Laser Ranging network in the fulfillment of the GGOS requirements for a stable and accurate ITRF (Plag and Pearlman, 2009).

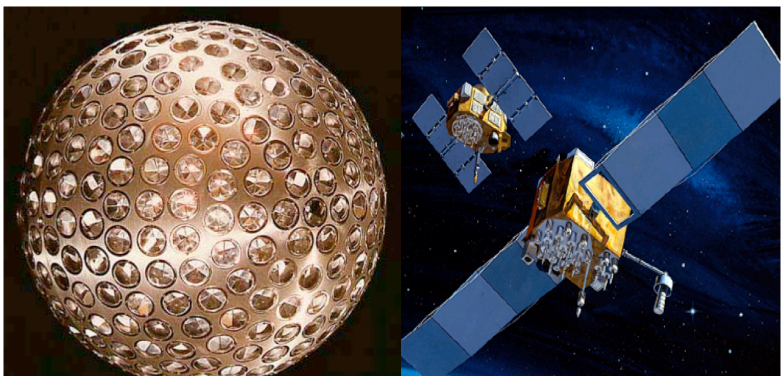


Figure 3. LAGEOS spacecraft and a pair of typical GPS spacecraft.

Key factors for a successful "marriage" of the two techniques

A requirement for meaningful results in the laser ranging of the GPS satellites is the very precise knowledge of the location of the effective reflecting plane of the corner-cube reflector (CCR) array with respect to the center of gravity (CoG) of the spacecraft. The scale of the ITRF is directly related to this "CoG offset" correction that must be applied to the ranges. For the two LAGEOS satellites we need to be at or below the 1 mm and taking into account the size of the orbits for the GNSS spacecraft (Fig. 3), we estimate that the CoG offset must be significantly less than 1 cm for the GNSS case.

Another area of importance to effective precision orbits and clocks for the GNSS satellites is the detailed description of the spacecraft geometry and its attitude routine. The geometry will be crucial in defining an accurate model of non-conservative forces acting on the s/c, to be applied to dynamic models of the spacecraft and its POD. The s/c attitude and dynamics are also important, so any future use of the GNSS s/c will require a full knowledge of the attitude routine and description of any maneuvers or at least notification of attitude changes to exclude data taken over critical time intervals. It is highly likely that these parameters will vary from spacecraft to spacecraft as well as from block to block. This variability underscores the need to track all satellites over time and to develop spacecraft specific models.

Outline and assumptions behind the simulation studies

The results that are summarized herein were obtained on the basis of a simulation representing **one week** of SLR tracking of the GPS constellation. It must be noted here that the ITRF is defined on the basis of a data set that spans several decades, so that in practice, additional averaging of errors is expected, leading to even better results. But most importantly we seek to identify and model systematic errors in the GPS orbits. Models of the systematic errors will allow us to relax the SLR tracking schedules for the GPS satellites. It is unlikely that the resources exist to continuously track all GPS satellites. Instead we assume that the continuous tracking of the entire constellation is a proxy for the development of accurate POD models that will evolve over time from the intermittent tracking and modeling of a subset of the GPS constellation.

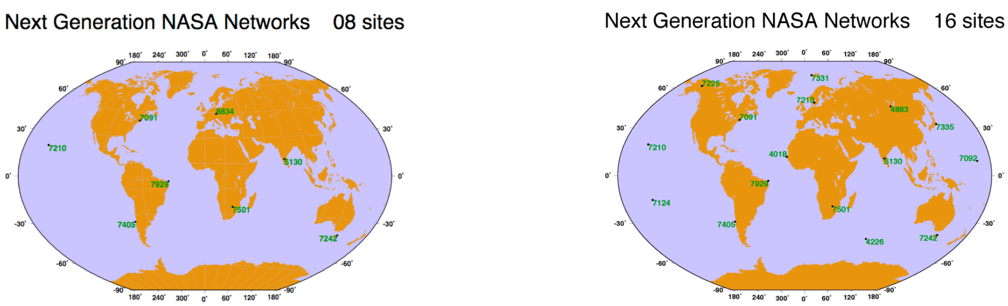


Figure 4. The two networks of SLR tracking stations examined in this study.

The ground SLR tracking network is comprised of stations with capabilities envisioned for NASA's next generation global geodetic networks, i.e. equipped with automated NGSLR, VLBI, and GNSS systems. In addition to colored noise on the SLR data, we degraded the orbital model used to recover the site locations from the simulated data by ad hoc accelerations at the orbital frequency, and with amplitudes typical of what is encountered today in the analysis of real GPS data. This is a conservative approach since one can estimate such accelerations on the basis of the GPS data taken on these s/c. It was decided however that at this point we should stay on the conservative side, until more detailed simulations are performed and the consideration of GPS-derived information can be taken into account.

Given the heavy burden on the current SLR networks and the high altitude of the GPS orbits, we decided to limit the simulations to networks of small extent compared to what is generally envisioned as the GGOS network of the near future, which may number 25-40 SLR stations. We expect that a subset of these stations of the order of 10 or more stations will be tasked to take this responsibility. Therefore, we examined the results that one obtains from the 8-site and 16-site networks (Fig. 4) that were previously used for simulations related to the optimization of NASA's next generation global geodetic networks. The selected sites in either network have a fairly uniform global distribution and reside on geographic locations that are or were occupied by a geodetic observatory.

We performed the analysis based upon three variant simulations of the ground network and the GPS constellation for the equivalent of a week-long tracking period.

1. 26 GPS s/c using 16 and 8 site networks
2. 6 GPS s/c, one s/c in each plane, using both the 16 and 8 site networks
3. Sensitivity analysis to the removal of selected stations from the 16-station network

The simulations also included solutions that tested the sensitivity to the systematic and random "CoG offset" errors for each satellite. The CoG offset is the distance between the optical center of the LRA and the satellite center of gravity. These cases were:

1. a reference case, i.e. the CoG offset is perfectly known to better than 1mm;
2. a fixed 10 mm error in the CoG offset of all 26 GPS s/c;
3. an extreme 100 mm error in the CoG offset of all 26 GPS s/c; and
4. a random error in the CoG offset with a 10 mm dispersion for all 26 GPS s/c.

Tables 2 and 3 that follow represent the interim results of this simulation. The effect on the ITRF **scale** accuracy is represented by the mean change in height for the network (Mean Δh [mm]), that is the vertical deviation of a position on the surface of the Earth with respect to the "true" model position. The variability of the determination of the scale is characterized by the standard deviation of the mean network height (Std. dev. Δh [mm]) over the course of the simulated week-long measurements. The effect on the ITRF **origin** accuracy is represented by ΔX_g , ΔY_g, and ΔZ_g that are the deviations in the mean position of the reference frame's **origin** (a.k.a. Earth's Center of Mass) from the model's true position. These measurements represent one week of observations therefore, we might expect that the random errors would reduce by another factor of seven over the course of a year's observation. Systematic errors in the orbits will persist however and will require careful study to identify and model for their removal from the final results.

Summary and discussion of the results

The first group of simulations demonstrates that a 16-site SLR network tracking all 26 GPS s/c can certainly meet the GGOS requirements of 1 mm accuracy and 0.1 mm/y stability of the ITRF. It is also concluded that the results from the 8-site network are also very close to meeting the requirements, indicating that with a 16-site network in place, we would have a rather large margin for station outages, without the fear of incurring significant degradation of the results, provided these outages do not last for a prolonged time period.

The importance of the accuracy with which the "CoG offset" correction is known *a priori* is highlighted by the three sub-cases we examined, where we introduced constant and random errors for that parameter. Constant errors for the CoG correction affect the results directly, with 80-90% of the error showing up in the scale of the network, although the definition of the origin seems rather impervious to such an effect, due to the uniform site and data distribution (Table 2).
Table 2. Simulation results using all 26 GPS spacecraft as SLR targets for **<u>one week</u>**.

Cases:	**8 sites Reference**	**16 sites Reference**	**16 sites R_b=10 mm**	**16 sites R_b=100 mm**	**16 sites R_b=10 mm (random)**
Mean Δh [mm]	-1.4	-0.5	8.0	-90.5	6.0
Std. dev. Δh [mm]	3.1	2.3	2.4	8.3	2.8
ΔX_g [mm]	-1.2 ± 1.9	-0.1 ± 1.0	0.1 ± 1.8	-2.2 ± 18.7	-0.2 ± 1.4
ΔY_g [mm]	-1.2 ± 1.1	0.4 ± 0.7	-0.3 ± 1.2	6.6 ± 11.0	-0.4 ± 1.2
ΔZ_g [mm]	2.5 ± 1.2	1.0 ± 0.5	3.6 ± 1.3	-27.4 ± 12.2	2.5 ± 1.1

In the case of random errors, the effect is slightly diminished, reaching only 60% of the assumed error in the CoG. This supports our intuitive estimates, indicating that when we track a large number of targets and the CoG correction errors are random amongst them, we can relax the accuracy with which this correction is required to be known *a piori* from ground calibration, to about 10 mm.

Table 3. Simulation results using **only** 6 GPS spacecraft as SLR targets for **one week**.

Cases:	**8 sites Reference**	**16 sites Reference**	**16 sites R_b=10 mm**	**16 sites R_b=100 mm**	**16 sites R_b=10 mm (random)**
Mean Δh [mm]	1.0	1.2	9.6	-86.9	13.4
Std. dev. Δh [mm]	3.6	4.7	4.5	14.9	4.3
ΔX_g [mm]	0.8 ± 1.8	-1.2 ± 1.8	-1.0 ± 2.2	-3.7 ± 18.5	-1.1 ± 2.7
ΔY_g [mm]	-1.4 ± 1.3	-1.2 ± 1.0	-1.8 ± 1.9	5.7 ± 13.5	-1.8 ± 2.5
ΔZ_g [mm]	-0.2 ± 1.9	1.6 ± 1.2	3.8 ± 1.8	-24.9 ± 9.5	4.8 ± 2.2

Tracking a reduced constellation of only six GPS s/c indicated that either the 16 or the 8-site networks perform equally well (slight increase in the scatter of the results from the reduced constellation) to tracking the full constellation (Table 3). This implies that our system is not noise-limited. In practical terms, we have more than enough tracking from six spacecraft to average the noise and we need only be concerned how we can use that data to eliminate the systematic errors.

Conclusions

The integration of techniques and in particular the exploitation of SLR LRAs on GNSS spacecraft will greatly benefit Earth science, precise positioning and navigation. In addition to improving the GNSS-based products, SLR will also benefit from the increase in targets and will be able to extend its gamut of products (e.g. EOP) and their robustness due to the improved geometry of the tracked space segment. Figure 5 is taken from the Geodetic Requirements submission to the IFOR. It depicts the historical and projected evolution of PNT accuracy requirements for the GPS system. The hatched blue zone identifies current scientific user requirements that lie within the zone of 0.1 to 1 mm well beyond the current capability of the GPS system.

To improve the GNSS products beyond the present level, the elimination of systematic errors is "the" key factor and the fundamental reason for the calibration of GNSS satellite orbits with SLR. Removal of the systematic errors after a modeling step is assumed in the presented study. Therefore we must track all satellites over time because systematic errors are inherent in the system and do vary in time. These systematic errors can be related to individual satellites, blocks of satellites or to environmental phenomena affecting differently the various orbital planes.

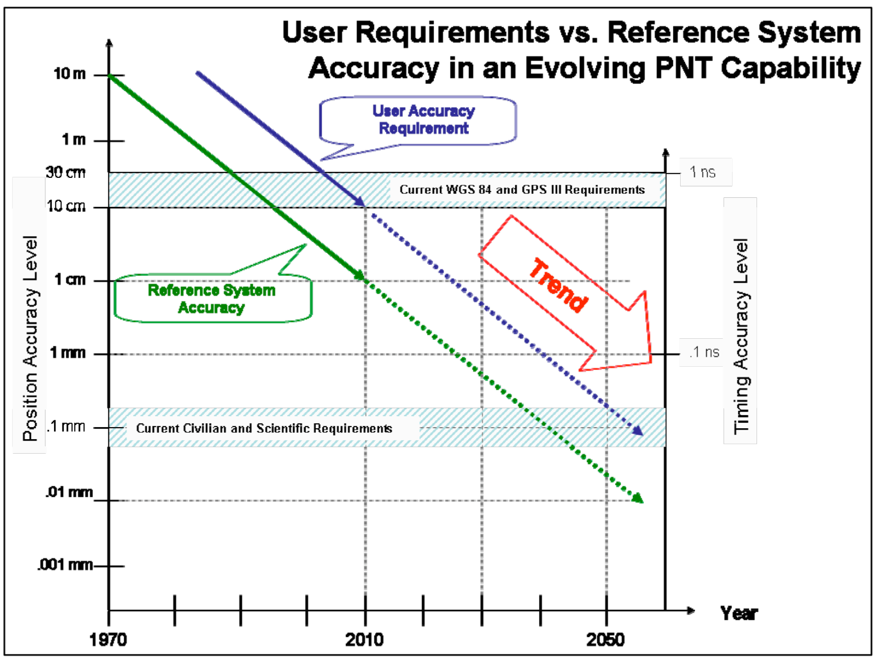


Figure 5. The figure illustrates the evolution of user accuracy requirements versus positioning system accuracy capability using an extrapolation of the historical trends of the past four decades.

As indicated above the CoG offset errors are a proxy for the systems response to both random and systematic errors. The "Reference CoG" column can be considered as the case where only random errors remain with all systematic errors removed through careful tracking and modeling of the satellite orbits with SLR. The 10 and 100 mm CG errors are very simple fixed systematic errors while the random CoG offset reflects the more difficult to resolve non constant systematic errors. It should come as no surprise that the Reference zero systematic error simulation provides the best results. The Random CoG offset systematic error also is consistent with intuition in that the larger error results from the tracking of the smaller subset (6) of six satellites. Systematic errors such as the CoG offset, need to be eliminated through careful measurement and modeling of both the spacecraft and the network operations. Well-developed models can then be applied to the POD of the constellation to augment periodic tracking of a subset of the constellation to eliminate random or environmental errors. Though more study is required, a preliminary conclusion is that we should track all GNSS satellites to understand and remove systematic errors. The addition of the GNSS spacecraft as SLR targets to the existing pair of the two LAGEOS geodetic satellites is expected to be the single most important factor that will enable us to meet GGOS' Geodetic requirements of 1 mm accuracy and 0.1 mm/yr stability in the ITRF. We do not expect that the noise characteristics of future SLR systems will change dramatically from the current state of the technology. Accurate SLR tracking augmented by sub-centimeter dynamic models for the GNSS orbit propagation models **will** enable us to meet the GGOS requirements. The distribution of the SLR tracking network utilized in the simulation is in keeping with present plans for a more uniform network compared to the present situation.

References

Altamimi, Z., X. Collilieux, J. Legrand, B. Garayt, C. Boucher, ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters, Journal of Geophysical Research, September 2007, vol. 112, p. 9401.

Beckley, B. D., F. G. Lemoine, S. B. Luthcke, R. D. Ray, and N. P. Zelensky, A reassessment of global and regional mean sea level trends from TOPEX and Jason-1 altimetry based on revised reference frame and orbits, *Geophys. Res. Lett.*, *34*, L14608, doi:10.1029/2007GL030002, 2007.

Bertiger , W. et al., 2009, Jason-2/OSTM Precise orbit determination with GPS and extending the Topex, Jason-1, Jason-2 climate data record, OST Science Team meeting, Seattle, WA.

Neilan, R., Z. Altamimi, G. Blewitt, J. Davis, R. Gross, C. Kuo, F. Lemoine, A. Moore, H.-P. Plag, M. Rothacher, C. Shum,. M. G. Sideris, T. Schöne, P. Tregoning, and S. Zerbini, Geodetic observations and global reference frame contributions to understanding sea level rise and variability, in *Understanding Sea-level Rise and Variability*, edited by T. Aarup, J. Church, S. Wilson, and P. Woodworth, in press, Blackwell, Oxford, 2009.

Plag, H.- P. and M. Pearlman (eds.), (2009), *GGOS2020: The Global Geodetic Observing System,* GGOS/IAG, *in press,* Springer-Verlag, New York, 2009.

Understanding Sea-level Rise and Variability, edited by T. Aarup, J. Church, S. Wilson, and P. Woodworth, in press, Blackwell, Oxford, 2009.

Technology Challenges for SLR Ranging to GNSS Satellites

Michael Pearlman, Scott Wetzel, Graham Appleby

In Satellite Laser Ranging (SLR) we consolidate full rate data into normal points at the stations prior to shipment to the data centers. The normal points originated with lunar ranging back in the late 1960's. SLR normal points span time intervals as short as 5 seconds for very low satellites to 5 minutes for GNSS satellites. The interval is chosen to keep the orbital perturbation effect insignificant during the normal point interval. All of the analyses are done with normal points except for engineering studies on system performance and diagnoses.

The technology challenges to SLR ranging to GNSS Satellites are:

- Getting enough laser photons on the satellite;
- Collecting enough photons back at the ground station;
- Separating the desired returning photons from the undesired photon noise (daylight ranging);
- Having sufficient range accuracy;
- Connecting SLR with other co-located space techniques;
- Having sufficient geographic coverage.

Getting enough photons on the satellites

Getting enough laser photons to the satellite per second is the first part of the range equation – it depends on the emitted laser average power and beam divergence.

Laser Output

Typical legacy lasers (older systems) fire 5 – 10 pulses per second with pulse energies from millijoules to 100's of mjoules. Newer systems are firing lower energies at much higher rates, from 100 to 2 KHz. Although these have about the same average power, the lower energy, higher repetition rate provides some statistical benefit. Satellite acquisition and data accumulation can be more rapidly achieved; normal points can be populated faster and more satellites can be tracked. This enhances the ability to interleave passes on different satellites. As can be seem in figure 1, short laser pulse (about 35 ps) at Graz, Austria show remarkable detail; patterns from individual corner cubes can be distinguished. On the other hand – the analysis is more complicated because the pattern has to be interpreted or modeled. Similar laser are installed or being installed at Herstmonceux, Changchun, Wuhan, Kunming, and TROS.

Another strategy with the 2 KHz lasers being used with the NGSLR at GSFC uses wider laser pulses (about 300 ps) so that the averaging is done in ranging machine itself. This option has less single point precision, but it has an eye safety advantage. At the wider pulse width, the eye safety threshold is higher. Eye safety may be an issue for consideration for fully automated systems.

Output beam divergence

With reasonably good lasers, output beam divergence is a matter of telescope aperture size and quality of pointing. SLR systems use blind pointing (with good predictions) which means that stability of the mount and accuracy of pointing is really the limitation. We use searching techniques, but the more searching that has to be done, the less data will be received and fewer satellites tracked. Pointing accuracy down at the level of a few arcsec requires state-of-the-art, well calibrated encoder systems and good mount stability.

Collecting enough photons back at the ground station

Retroreflecting enough photons back at the ground station is a function of the telescope aperture and the effective cross-section of the satellite array. The aperture size is a function of cost.

The performance of the array depends on the properties of the corner cubes and the structure of the array. Corner cube issues include: size and material of the cubes, whether or not the corner cubes are back-coated, vertex offset angle (to accommodate velocity aberration); and thermal mounting conditions (thermal gradients can degrade optical properties). Issues with array include array size (number of cubes), shape (as compact as practicable), accessibility (is the array obstructed), and thermal conditions.

A critical aspect with the array is the vector offset between the "optical center" of the array and the satellite center of mass of the satellite. Any error in this vector measurement will be included in the range measurement. Accurate vector measurements, good engineering drawings, and accurate models of how satellite center of mass will change over time in flight are essential.

Some of the typical arrays are shown in Figure 3. With the exception of Lageos 1 and 2 and more recently ETS-8 and COMPASS – 3M, all of the present ILRS tracked satellites have back-coated corner cubes. The uncoated cubes on Lageos, ETS-8 and COMPASS depend on total internal reflection like the lunar array cubes. The uncoated cubes (total internal reflection) have a larger effective cross-section, but a narrower field of view; which lends itself very well to the higher satellites with flat arrays. However, the uncoated cubes do have a polarization effect that could influence range accuracy if provisions are not made at the ground system.

Using models from Dave Arnold, estimates for return signal strengths from the current GNSS satellites have been calculated and compared to Lageos (see Table 1). GNSS signal strengths run from 3 – 8% of that from Lageos. Glonass with a very large array and COMPASS with uncoated cubes run about 3 times as large as signal strengths from GPS and GIOVE satellites. Ranging tests from the Graz station with the 2 KHz system show similar results (see Figure 4).

A test conducted on GPS 35 and 36 conducted for a two month period in early 2008, with the satellites at high priority conditions, gave an average of 33 passes combined on the two satellites with 8 stations providing the bulk of the data (see Table 2).

The "best" stations range to LAGEOS in both daytime and night-time; to GLONASS at night with some success in daylight; and to GPS nighttime only. We expect that other stations will undertake upgrading and new stations will be built.

Based on our experience The ILRS has developed a Retroreflector Standard for GNSS satellites:

- Retroreflector payloads for GPS, GLONASS, and COMPASS satellites should have an "effective cross-section" of 100 million sq. meters (5 times that of GPS-35 and -36) for GNSS satellites;
- *Added Recommendation: Retroreflector payloads for satellites such as Galileo in higher orbits should scale the "effective cross-section" to compensate for the R**4 reduction in signal strength;*
- The parameters necessary for the precise definition of the vectors between the effective reflection plane, the radiometric antenna phase center and the **center of** mass of the spacecraft be specified and maintained with mm accuracy.

Separating the ranging photons from the noise photons (daylight ranging);

Daylight ranging requires careful filtering and signal discrimination to avoid being overtaken by daylight noise. The first stages of filtering are through narrow receiver field of view (again pointing accuracy dependence), spectral filtering, and temporal filtering (range gate). With good predictions, which should certainly be achievable with operating GNSS satellites, range gates may be set down at a few 100 nsec. Systems that use fast response detectors (PMT's) can also use multi-stop timers that can record several returns (signal and noise) for later discrimination.

Sufficient Range Accuracy

System accuracy is certainly influenced by system parameters such as pulse repetition rate, pulse width, etc. However, unmodelled system biases will corrupt range measurements and aliased scientific results. Careful and comprehensive calibration combined with good engineering design and practices are critical.

Connecting SLR with other co-located space techniques

Ground Survey techniques

SLR like the other space geodetic techniques are now making measurements over global distances to mm precision, but one of the fundamental problems with the co-location regime is the measurement of the vector between the invariant reference points (intersection of axes, GPS antenna reference points, etc.) on the co-located instruments. Invariant points are almost always inaccessible and the determination of these vectors includes a survey between accessible points on each instrument plus extrapolations to points that are not directly accessible. This extrapolation process includes careful examination of engineering drawings, laboratory measurements, dynamic local surveys, etc. Sub-mm accuracy may also require a monitoring component in order to understand what is happening in real or near real-time. Small motions may be corrupting our measurements and subsequently our realization. Current ground survey techniques can provide closure to properly configured ground monuments to mm accuracies, but these measurements -tend to be very expensive and infrequent. In addition, as discussed in Ray and Altamimi (2005), survey measurements must be extrapolated to invariant reference points (i.e., intersection of the axes on SLR and VLBI and physical GNSS antenna reference points) on each of the space geodetic instruments in order to provide closure.

We need to develop an economical approach that will measure or even monitor the inter-system vectors with sufficient spatial accuracy and temporal resolution to support reference frame requirements now projected at 1 mm accuracy and 0.1 mm/year stability. A promising solution at the moment is based on ground based surveys using commercially available Robotic Total Station (RTS) survey systems and a local network of ground reference pillars,

See http://ilrs.gsfc.nasa.gov/docs/TLS_2008Workshop_Report.pdf

These instruments are programmable and should be operable by local personnel. Continuous monitoring of the SLR, VLBI, and GNSS instruments with ancillary measurements such as tilt meters, temperature sensors, laser gauges, etc. may be sufficient to provide continuous monitoring. A major issue in this ground survey process is the integration of in-ground monument targets. The process must be designed to permit automated inter-technique baseline vector monitoring and extrapolation to the instrument reference points. The technique must provide for verification of baseline quality monitoring.

Geodetic Reference Antenna in Space

Another option that may prove very powerful in the long term is the Geodetic Reference Antenna in Space (GRASP) concept being developed at JPL. Rather than doing the co-location with ground survey techniques and vector extrapolation, this technique would invert the survey problem and determine the inter-technique vectors through co-location on space with a multi-technique equipped satellite. The method would have the advantage of taking measurements directly to the technique reference points and could be done continuously. GRASP could be realized as a low cost micro-satellite, specifically designed to support mm-level calibration and stability between the electromagnetic/optic phase centers of its radio and optical sensors, nominally a GPS, receiver, an SLR retroreflector, a VLBI transceiver, and a DORIS receiver.

Preliminary analysis of the GRASP mission calls for orbital altitudes of approximately 2000-2500 km, to minimize atmospheric drag mismodeling, no moving parts on the satellite to optimize solar pressure modeling and extend the satellite lifetime.

Sufficient Geographic Coverage

Over the last decade the network has expanded most notably in the Southern Hemisphere, but there are still large geographic gaps in particular in Africa and the Indian Ocean. Programs such as GGOS are focusing on these gaps with an eye toward bringing new groups into space geodesy activities to help fill the existing gaps.

The Next Generation SLR Systems

The next generation systems will operate with:

- higher repetition rate (100 Hz to 2 kHz) lasers to increase data yield and improve normal point precision;
- photon-counting detectors to reduce the emitted laser energies by orders of magnitude and reduce optical hazards on the ground and at aircraft (some are totally eye-safe);
- multi-stop event timers with few ps resolutions to improve low energy performance in a high solar-noise environment; and
- considerably more automation to permit remote and even autonomous operation;
- more frequent survey vector measurements.

Many systems will operate at single photon levels with Single Photon Avalanche Diode (SPAD) detectors or MicroChannel Plate PhotoMultiplier Tubes (MCP/PMIs).

Some systems are experimenting with two-wavelength operations to test atmospheric refraction models and/or to provide unambiguous calibration of the atmospheric delay.

Table 1. Relative Return Signal Strengths for High Satellites compared to Lageos (Provided by Dave Arnold)						
Satellite	**Altitude (MM)**	**Effective Cross Section (MSqM)**	**Relative Return Signal Strength**			
			Zenith	30 deg	45 deg	60 deg
Lageos1/2 *	5.8	15	1.0	1.0	1.0	1.0
Etalon1/2	19	55	.032	.037	.044	.058
GLONASS	**19**	**80**	**.046**	**.054**	**.065**	**.084**
GPS 35/36	**20**	**20**	**.009**	**.011**	**.013**	**.018**
COMPASS *	**21.5**	**80**	**.028**	**.033**	**.041**	**.054**
GIOVE-A	**23.9**	**45**	**.010**	**.012**	**.015**	**.021**
GIOVE-B	**23.9**	**40**	**.009**	**.011**	**.014**	**.018**
ETS-8 (sync)*	36	140	.006	.008	.010	.014
* Uncoated Cubes						

Table 2 GPS Tracking Campaign (25-Mar-2008 through 26-May-2008)			
Site Name	**Station #**	**No. Passes**	**No. Normal Points**
Beijing	7249	1	3
Changchun	7237	2	8
Graz	7839	28	251
Greenbelt	7105	2	4
Herstmonceux	7840	23	77
Katzively	1893	1	6
Koganei	7308	2	9
Matera	7941	1	6
McDonald	7080	10	42
Monument Peak	7110	4	9
Mount Stromlo	7825	11	40
Riyadh	7832	20	99
San Juan	7406	60	375
Simeiz	1873	2	50
Tanegashima	7358	29	149
Wettzell	8834	18	79
Yarragadee	7090	70	267
Zimmerwald	7810	15	61
Totals:	18 stations	299	1535
			Averaging 33 passes per week

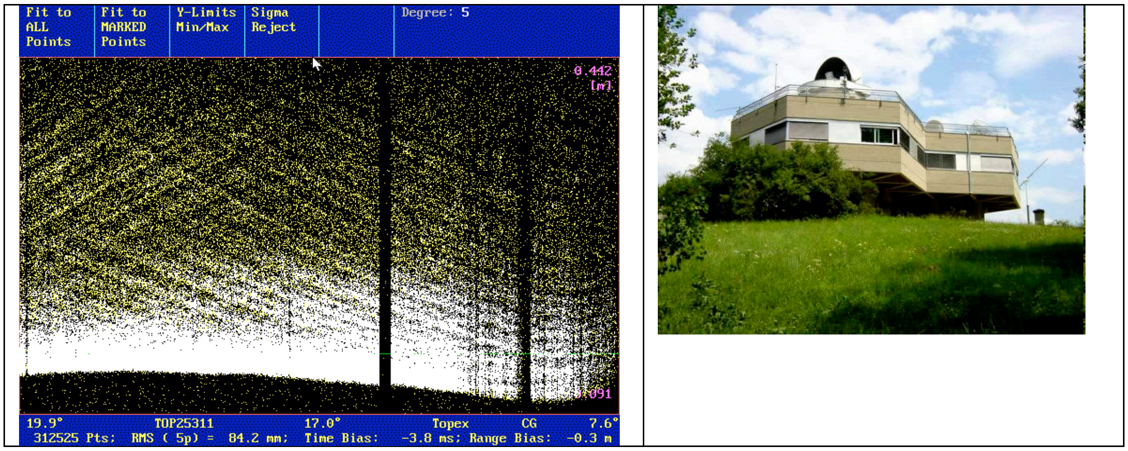


Figure 1 2 KHz returns from Graz Station with a 35 ps pulse width on the TOPEX Satellite (provided by Georg Kirchner)

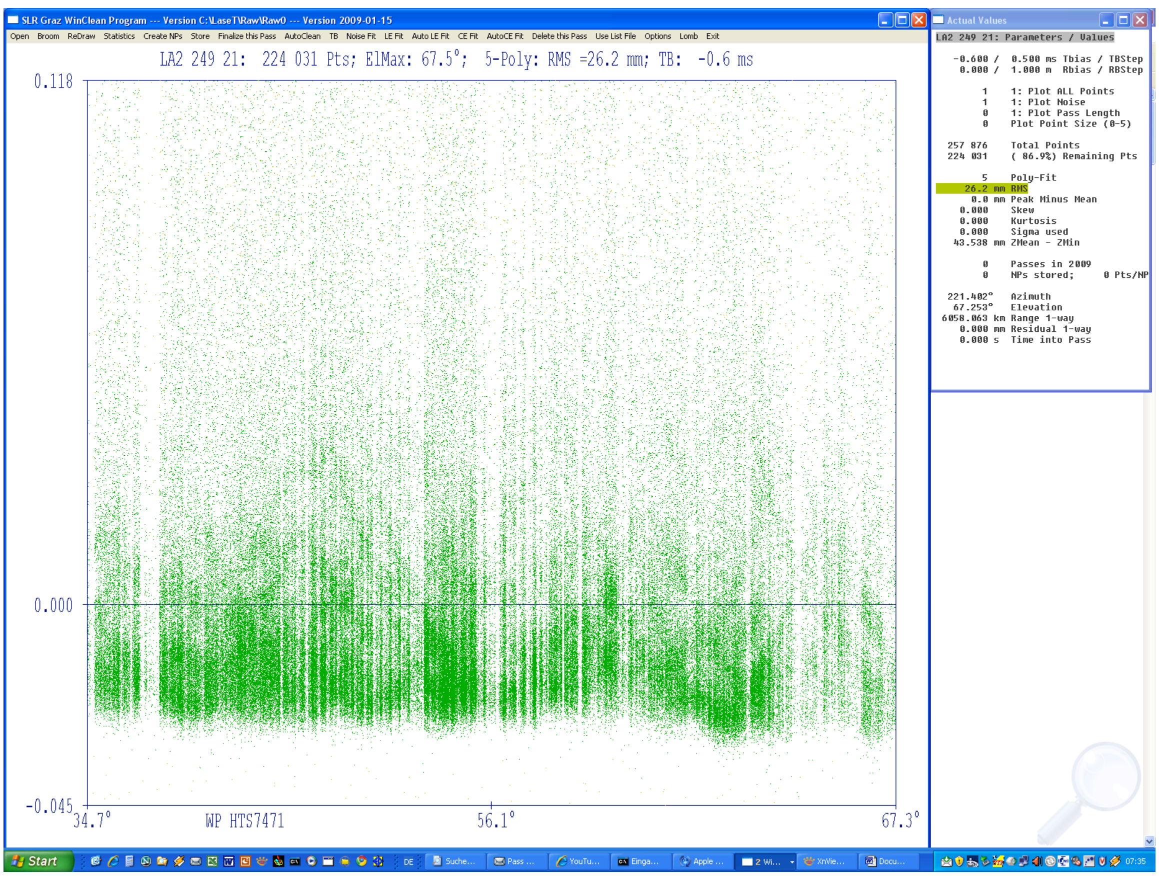


Figure 1b 2 KHz returns from Graz Station with a 35 ps pulse width on the Lageos 2 Satellite (provided by Georg Kirchner)

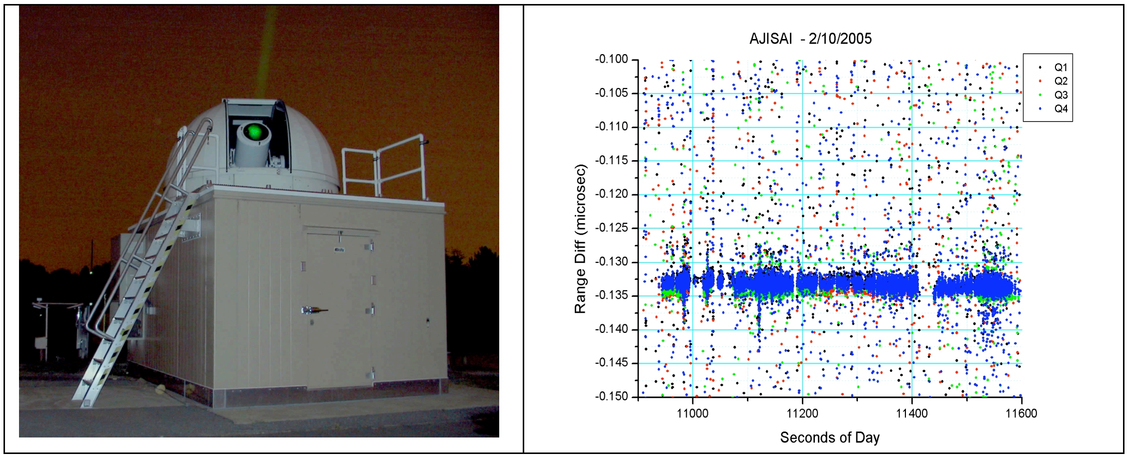
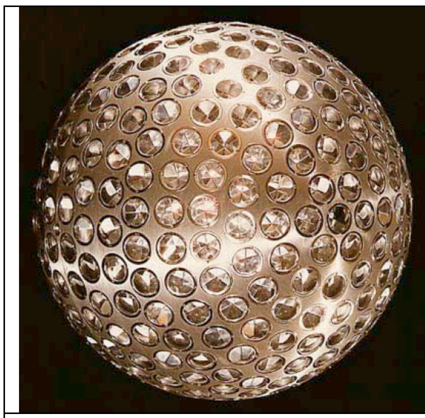
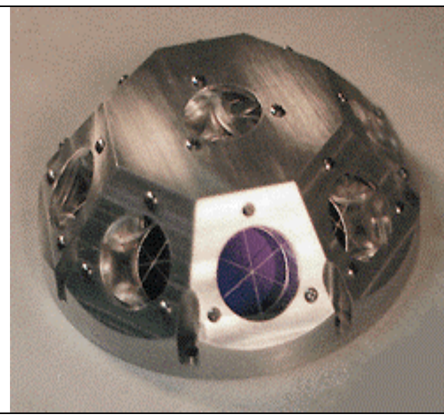


Figure 2 2 KHz returns from the NGSLR Station with a 300 ps pulse width on the Ajisai Satellite (provided by Jan McGarry).



LAGEOS



JASON

GPS – 36

COMPASS

Figure 3 Examples of Retroreflector Arrays (From the ILRS website)

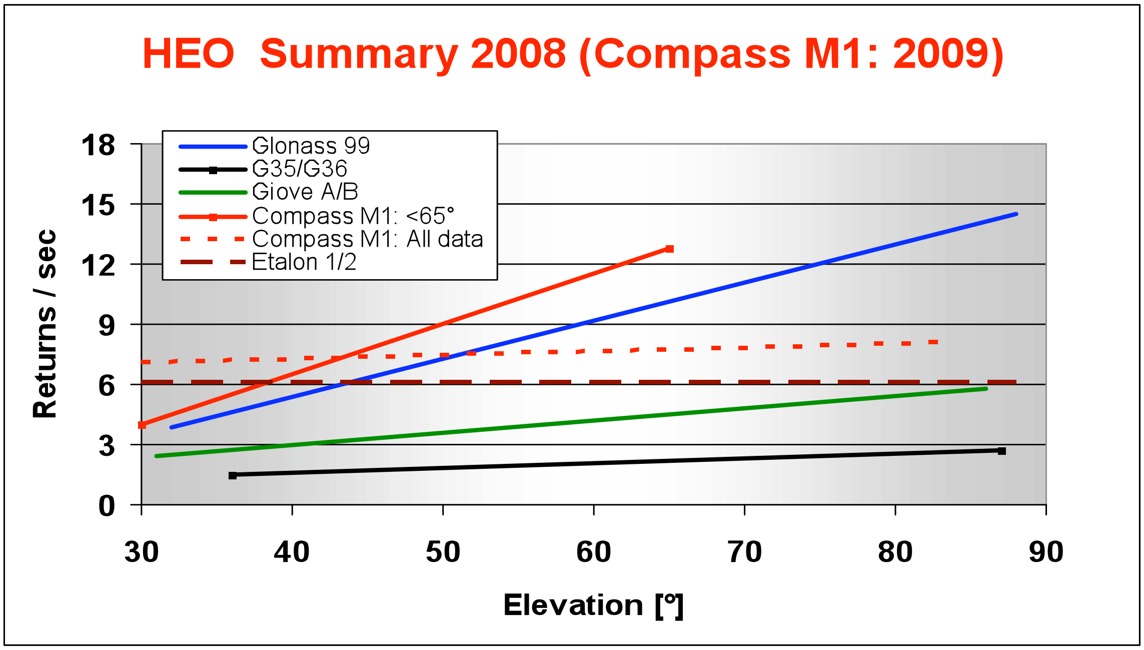


Figure 4. GNSS return signal test at Graz station (provided by Georg Kirchner)

SLR Tracking of GNSS vehicles: Operational Issues

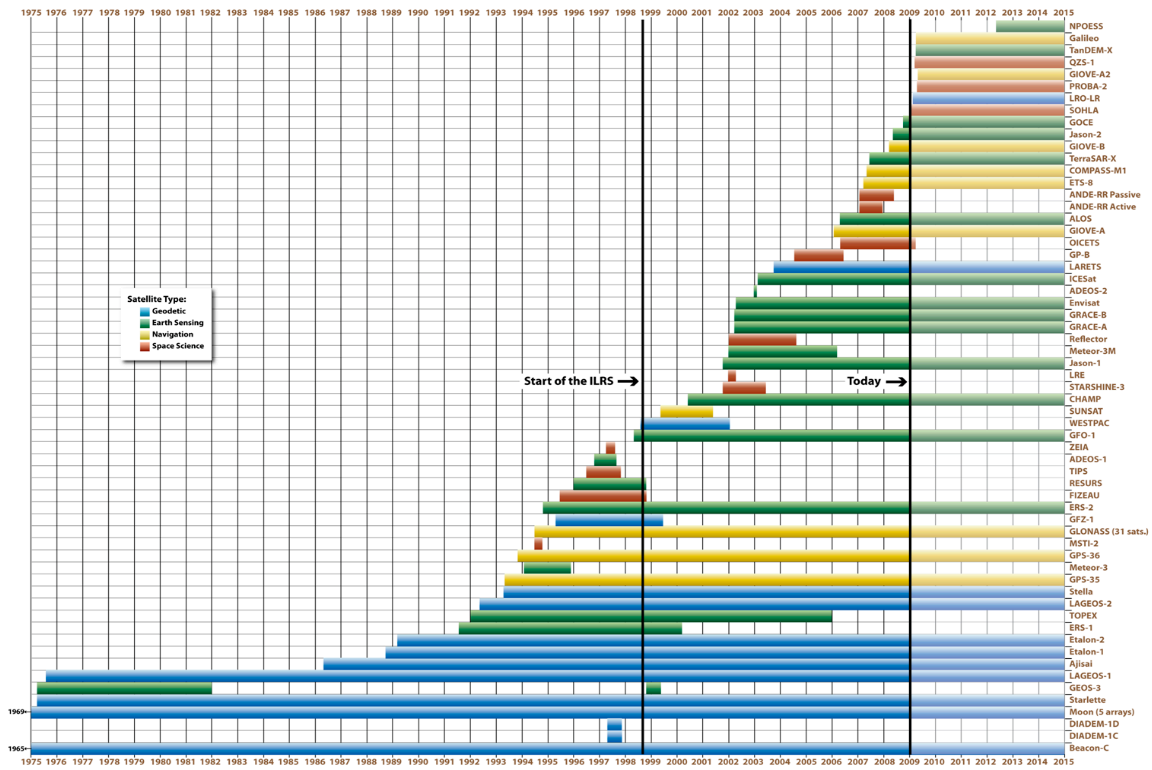
Graham Appleby, Scott Wetzel, Michael Pearlman

Overview

The tracking stations of the International Laser Ranging Service (ILRS) currently support a diverse constellation of satellites that in turn address a wide range of scientific investigations in the broad field of Earth and planetary research. The satellites that are routinely tracked include vehicles from each of the growing number of constellations of Global Navigational Satellite Systems (GNSS). With new GNSS asking for ILRS support, including the Chinese COMPASS, JAXA Quasi Zenith Satellite System (QZSS) and EU GALILEO systems, it is becoming more important than ever to develop a strategy in partnership with the missions in order both that the stations are able to cope with the increased tracking demands and that the missions get the support that they require.

Introduction

Established in 1998 as a service under the International Association of Geodesy (IAG), the ILRS collects, merges, analyses, 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 components of the Service are the Tracking Stations and Sub-networks, Operations Centres, Global and Regional Data Centres, Analysis and Associate Analysis Centres and the Central Bureau. From the work of these components, the ILRS produces standard products for the scientific and applications communities. There are currently 30 Earth-Orbiting, one Lunar-Orbiting and five Lunar-based targets on the ILRS priority list. Shown below in Figure 1 is a schematic showing the full ILRS (and pre-ILRS) current and known future missions supported by laser ranging.



Most stations track all the Earth-Orbiting satellites, a small number of stations carry out Lunar Ranging and a few stations also take part in one-way tracking the Lunar Reconnaissance Orbiter

(LRO) in collaboration with NASA. The ILRS assigns priorities to each of the Earth-Orbiters, largely based upon their semi-major axes; the lower the satellite, and hence the shorter in time each pass over a station, the higher the priority. By following this priority scheme, most of the highly-productive stations are able to interleave their tracking efforts, leaving for example a Medium Earth Orbiter (MEO) geodetic satellite such as LAGEOS, with a pass duration of up to 50 minutes, for a few minutes perhaps several times in order to catch passes of for example Low Earth Orbiting satellites (LEO) such as GRACE, ENVISAT, JASON, etc.
The future challenges for the Network of this flexible approach to ranging will clearly be to continue to serve the existing scientific needs of the community whilst at the same time making sufficient effort to track the growing numbers of GNSS vehicles such that the needs of that, mainly technologically-based, community can be met. This technology emphasis may also bring funding issues to bear at the individual station level, since often the specific funding models include arguments for support of mainly scientific, Earth Observation, missions. Although tracking new GNSS systems such as GALILEO will open up new scientific opportunities, for instance in improving definition of the International Terrestrial Reference Frame (ITRF), the main benefit of the tracking will be in support of the operational aspects of those commercial navigational systems themselves.

In more detail, we now discuss various ILRS operational aspects of tracking GNSS.

Pass Interleaving
As discussed in the introduction, most of the major ILRS stations operate a pass-interleaving strategy which in effect allows them to multi-task their satellite tracking efforts. The principle behind the technique is that the scientific value of the laser ranging data from a particular pass is not compromised if the tracking data is not continuous throughout the pass. Various discussions with the analysis community including the experiences of the Lunar Laser Ranging community strongly suggest that most of the scientific value of a given pass can be extracted provided that data is obtained for sufficient time as the satellite rises, reaches highest elevation and approaches its setting minimum elevation. As far as we are aware, no rigourous tests on the effectiveness and sufficiency of this strategy have been carried out, but we have no reason to believe that the data so obtained is as a result any less useful for most applications. To emphasise this standard practice, we show below in Figure 2 a real example of pass interleaving; the observations from the Yarragadee Station in Western Australia show a good deal of 'multi-tasking' via rapid switching between satellites.

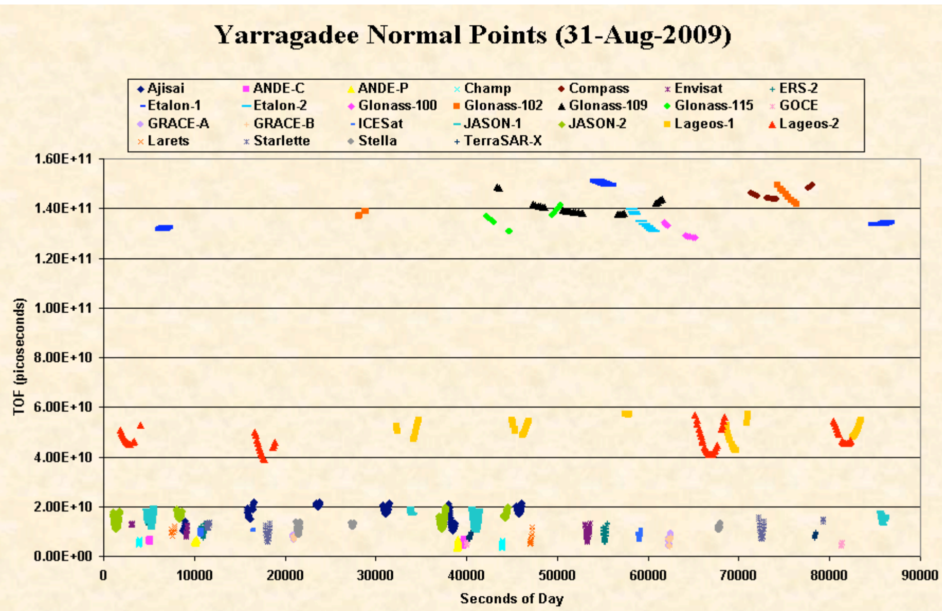


Figure 2 Interleaving of satellite tracking at Yarragadee in one 24-hour period

It is anticipated that as the demand for support for more GNSS (and in fact also for LEO) vehicles increases, the need for rapid interleaving by the major, high-productivity, stations will increase. It is recommended that all parties with a vested interest in the quality of the laser tracking data, from analysts to mission managers, perform tests and simulations in order to inform the tracking community on the effectiveness and in particular any degradation of the products as a result of the extension of this policy over the coming years.

Capacity.

In the context of increasing demand on the stations for tracking support, it is also very timely to ask whether it is physically possible for a given station to add more satellites to its schedule; how much, if any, spare capacity currently exists in the system. To begin to address this question, we have looked at the current schedule of typical Northern and Southern hemisphere stations from the point of view of all satellites up to the height of the LAGEOS geodetic spheres, with semi-major axes of 12,300km. For a one-year period, we computed the percentage of time during each day when no satellites up to the height of LAGEOS were above the stations' operational elevations of 20° or 25°. The plots of Figure 3 below display the remarkably consistent results, for our two representative stations, that for some 60% of each day there are none of these satellites available for tracking.

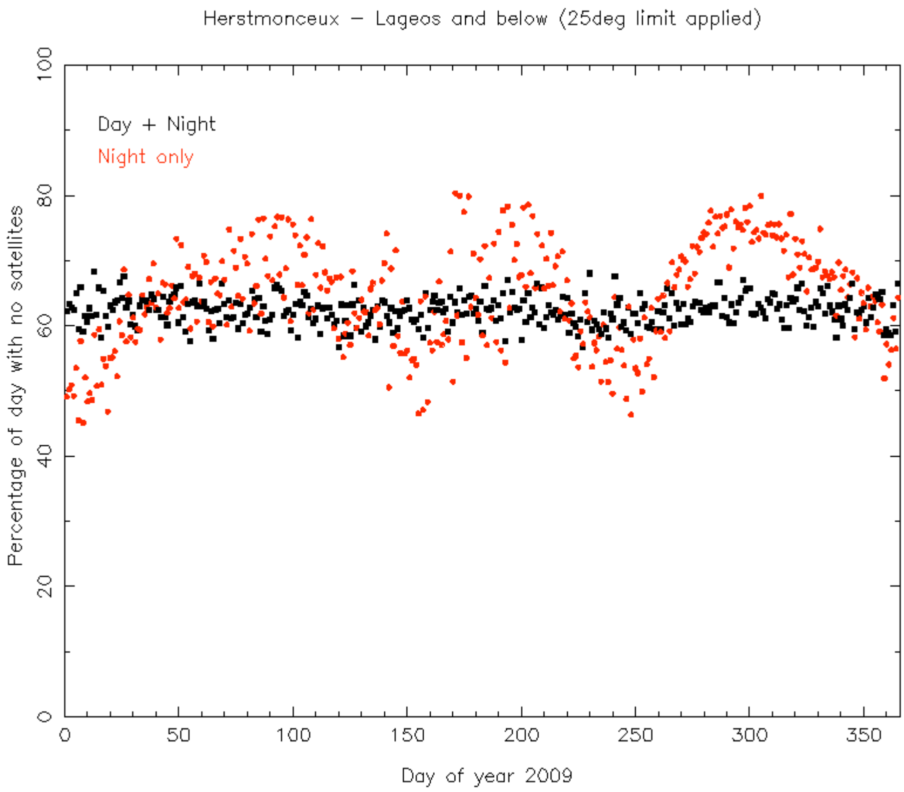


Figure 3 (a) Percentage of time per day when no LEO->LAGEOS satellites are available

For the Northern hemisphere station (Herstmonceux), the night-time period has been examined as well, leading to more variability in the available tracking time as the times of darkness vary throughout the year.

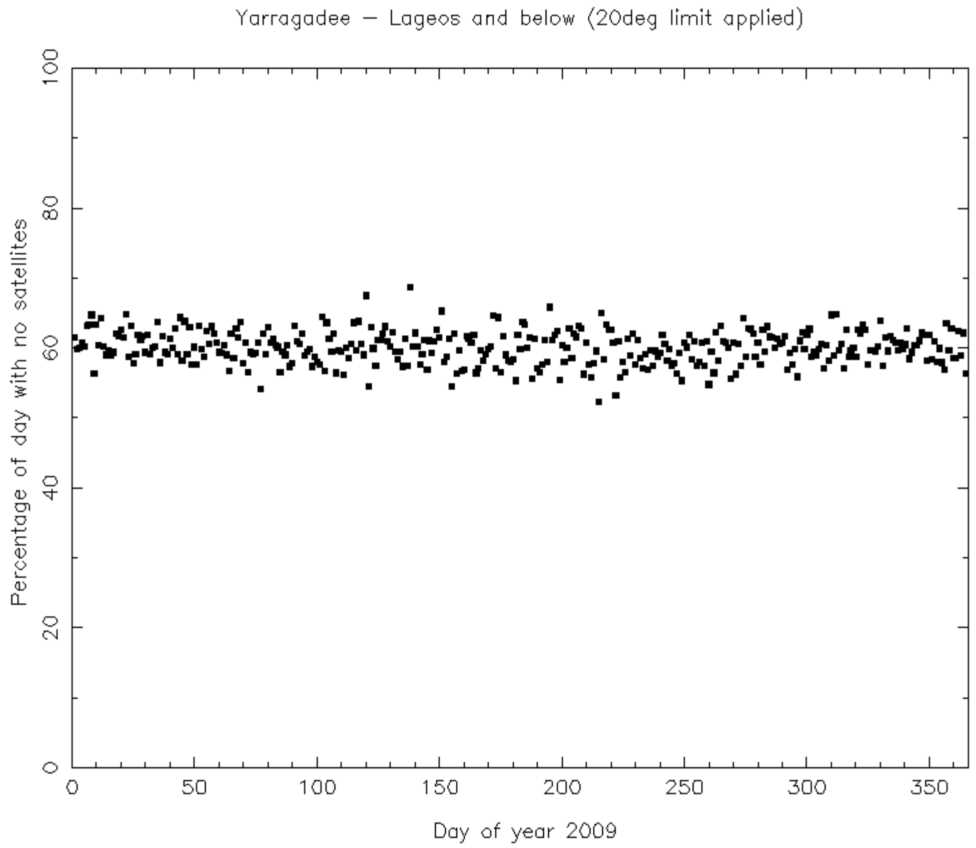


Figure 3 (b) Percentage of time per day when no LEO-> LAGEOS satellites are available.

The conclusion is that, provided that the scheduling and funding models permit, some 40 to 60% of each 24-hour period is potentially available for high-satellite tracking, which of course includes the GNSS vehicles. Note, however, that this computation does not take account of time required for ground-target calibration ranging, which may take several minutes each hour during the day depending on each station's operational practice.

Current tracking records for HEO/GNSS

It is likely that only the most capable of the current network stations are and will continue to add significantly to the tracking data for the more difficult, high-orbiting GNSS satellites. Those stations that can rapidly carry out interleaving, have the power to reach the high satellites, the mount stability to point accurately and have the best weather conditions will inevitably contribute most of the data. An indication of the current capability of each ILRS station is obtained by the most recent ILRS-generated tracking-record plots for the year up to the end of March 2009. The plot, in Figure 4, shows that the 15 or so 'top' stations that contribute most to tracking the LEO and MEO missions also contribute most to HEO/GNSS tracking. It is interesting in this context also to look at the situation ten years ago, at a time when the stations were tracking the-then full constellation of nine GLONASS vehicles. Of course, there were less LEO satellites then, but the plot, again from the ILRS website and shown here in Figure 5, suggests that relatively speaking, more effort was expended on the HEO/GNSS tracking. One could speculate that this was the result of greater interest then generated by the missions, but it does perhaps indicate that the network can respond positively to greater demands placed upon it.

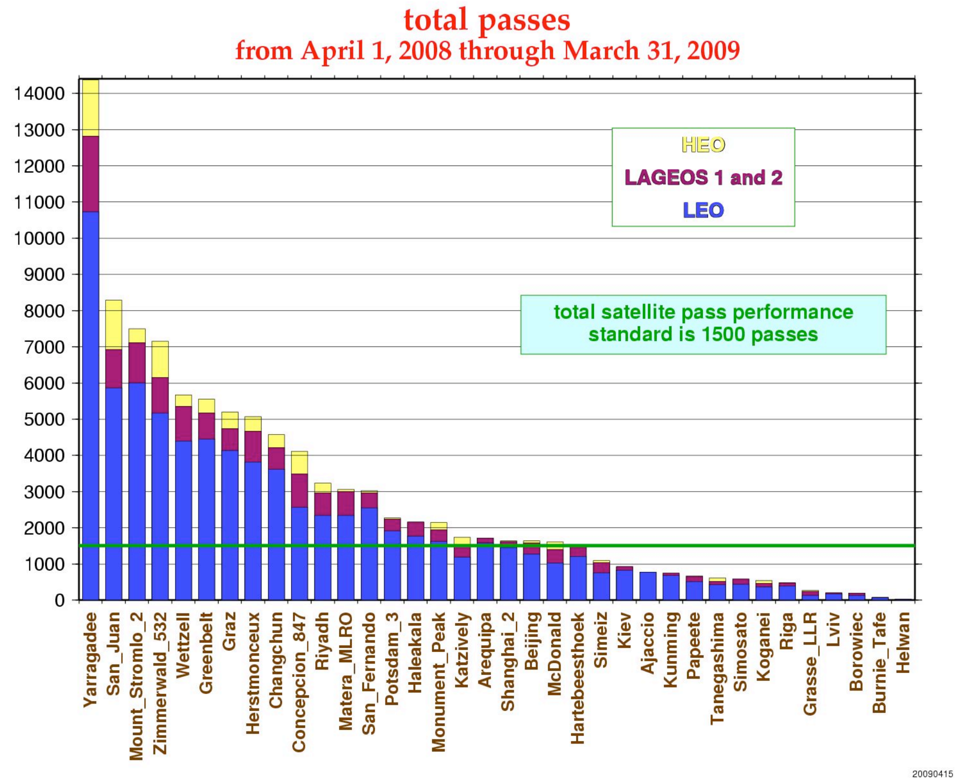


Figure 4 Tracking record in pass numbers for each station during the past year. (ILRS web)

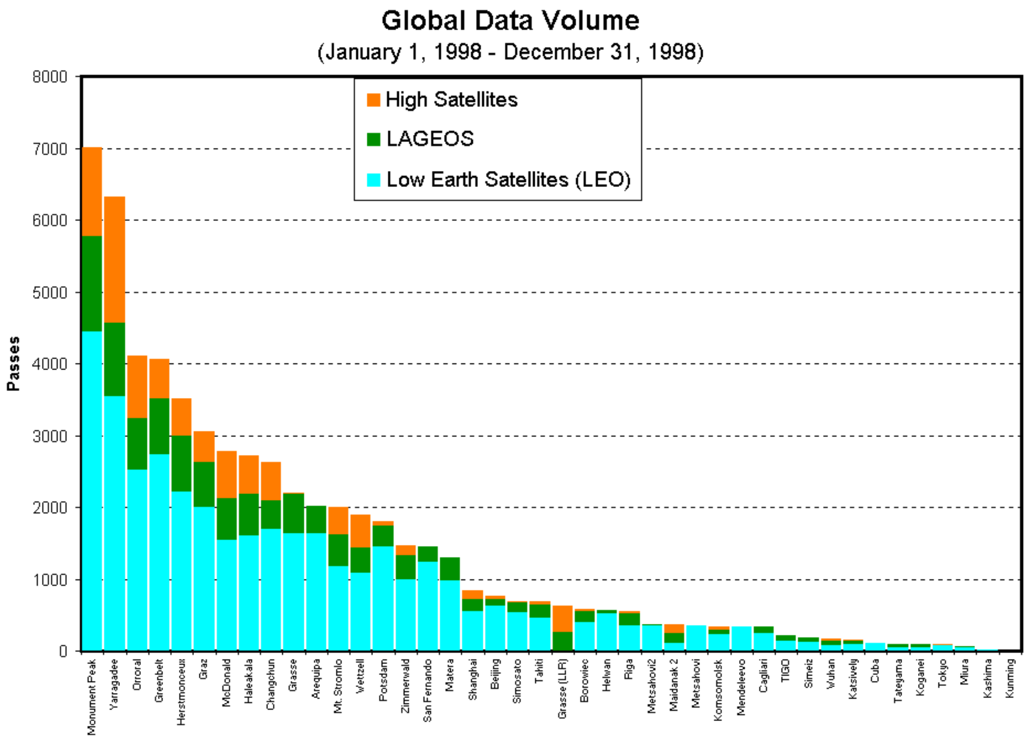


Figure 5 Tracking record in pass numbers for each station during 1998 (ILRS web)

General Issues

For completeness and for information to potential missions new to the ILRS, we outline here some further general issues that are part of the ILRS Operational 'culture'. Safety to persons onboard over-flying aircraft is of paramount importance at every station, as is adherence to any mission-designated Restricted Tracking requirements. Also important, especially for high-altitude GNSS tracking, are station upgrades and maintenance in order to maximise the quality and quantity of the data.

Data Availability
It is standard ILRS practice that observational data is made freely available to the community at large as quickly as possible, either directly from the Stations to the Date Centres, or via Operations Centres. The routine ILRS product is the range Normal Point data, whereby at agreed time-intervals (5 minutes for HEO satellites, including GNSS), mean ranges are computed from the full-rate data taken during those time-intervals. The Normal Point data are usually available at the European and US data centres (EDC and CDDIS) within an hour of the end of each pass, and the full-rate data itself with a delay of perhaps a day or so. However, some consideration will have to be made on the best approach to forming Normal Points for the GNSS satellites; it may be that the current standard practice of forming 5-minute Normal Points from often shorter-than 5-minutes continuous observing could be improved upon, perhaps to reflect the actual data distribution during the nominal 5-minutes. This is another issue that should be discussed with a view to mission requirements.

Aircraft safety
For all satellite ranging and currently for all the ILRS stations, the emitted laser pulses are optically hazardous. Individual stations and sub-networks have developed efficient methods that remove this risk from their operations. Methods employed include radar systems that track along with the SLR telescope and emit high-repetition pulsed radar energy; radar returns from aircraft that enter the field of view rapidly and automatically prevent laser pulses being emitted. This is the method employed by many stations, including the NASA sub-network; an example system associated with the Greenbelt, Maryland MOBLAS-5 system is shown in Figure 6.

Figure 6 The NASA MOBLAS-5 SLR system in Greenbelt, Maryland; the aircraft RADAR is at top-right

Other or additional measures taken at some stations include realtime links to local Air Traffic Control systems, visual spotters and optical/radio detector systems. The design specification for NASA's Next Generation SLR is to emit pulses with energy below the statutory eye-safe limit, which completely will remove the need for aircraft detection.

Restricted Tracking
ILRS authorization to track ILRS-approved satellites is already constituted and governed by an approved Mission Support Request Form. All SLR stations within the Service agree to adhere to any applicable ILRS Restricted Tracking Procedures that may include: station-by-station authorization by the Mission; time and viewing angle constraints; energy/power constraints; web-

based go/no-go switch. Thus if new GNSS are likely to have time-wise, satellite-attitude or any other tracking constraints that will apply at some stage(s) of the mission, the ILRS infrastructure is already in place to enforce station adherence to such restrictions. Satellite missions that currently and successfully impose restrictions include ICESat and LRO, both in these instances in order to protect sensitive onboard detectors.

Station upgrades

It is always important, and especially so for the relatively low-energy return signals from the high GNSS vehicles, that the laser ranging systems are working to specification in terms of optical and mechanical efficiency. For example, optical surfaces must be clean and re-coated if necessary, telescope-pointing models optimised and satellite predictions up-to-date for efficient use of clear-sky time on these quite challenging targets. The following bullet points are taken from a recent NASA station upgrade programme, and represent best practice guidelines for the NASA systems and of course for the whole Network:

- Precision co-alignment of transmit and receive optics (bore-sight)
  - Perform periodic bore-sight alignments, sometimes weekly or more often to compensate for temperature effects
- Use of intensified camera allowing visual viewing of sunlit GNSS satellite
  - Precision co-alignment of intensified optics with the transmitted laser beam
  - Precise identification mark on intensified camera readout (mark on CRT) of transmit and receive optics co-alignment point
  - Observe satellites that are sunlit in camera to ensure pointing
- Precision mount model (star calibration)
  - Use of intensified camera for mount model
  - Precise alignment of star image with the intensified camera identification mark
  - Understand diurnal stability of optical system and compensate as necessary
  - Perform mount models often, sometimes weekly or every couple of days
  - Monitor, document and utilize history on system angle bias for different portions of the sky and apply when GNSS targets on in that portion of the sky
- Transmit and receive optics are as stable as possible
  - Mirror mounting is stable
  - Mirror mounts are stable
  - Mirror mounts are free of mechanical wear
- Transmit and receive optics are clean
  - Optical coatings correct for laser wavelength used
  - Optical coatings are in good shape
- Gimbal servo system is highly tuned to ensure tightest possible tracking at GNSS orbits
- Spatial and temporal filters are precision aligned and verified often
- Laser divergence is nominal or optimized for GNSS vs. LEO or MEO
- Laser output power is maximum sustainable
- Maintain record of point biases with respect to gimbal azimuth and elevation pointing
- Use of receive signal amplifier and co-aligned constant fraction discriminator
- Use of low signal-loss, temperature-stabile receive cable
- Use the most current, best predictions available.
- Coordination with other ILRS stations (via the realtime EUROLAS status exchange for close systems), or notes to other stations
- Maximize scheduling through a central scheduling group to monitor and measure the successes of the ranging community and re-prioritize the tracking priorities in a near-real-time manner
  - Note that the system to support this important option has already been put in place by the ILRS:

- http://ilrs.gsfc.nasa.gov/products_formats_procedures/predictions/dynamic_priorities.html and
- http://sgf.rgo.ac.uk/priority/latest_priority.html

Conclusion

This Position Paper presents an overview of the ILRS operational practice, and raises issues specifically in the light of increasing demand for support of HEO GNSS missions. It is concluded that the Network does have the time-capacity and operational capability to increase its support for new GNSS vehicles. However, an issue that may well have to be addressed by some stations is funding for work that increasingly might fall outside the local funding model that may well have been developed for support of non-commercial, science missions. It is recommended that the Missions, Networks and Analysis communities together continue to consider how best the observational elements can support the mission needs.

Workshop Sponsors

International Laser Ranging Service - 2009