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.