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

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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].)

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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).

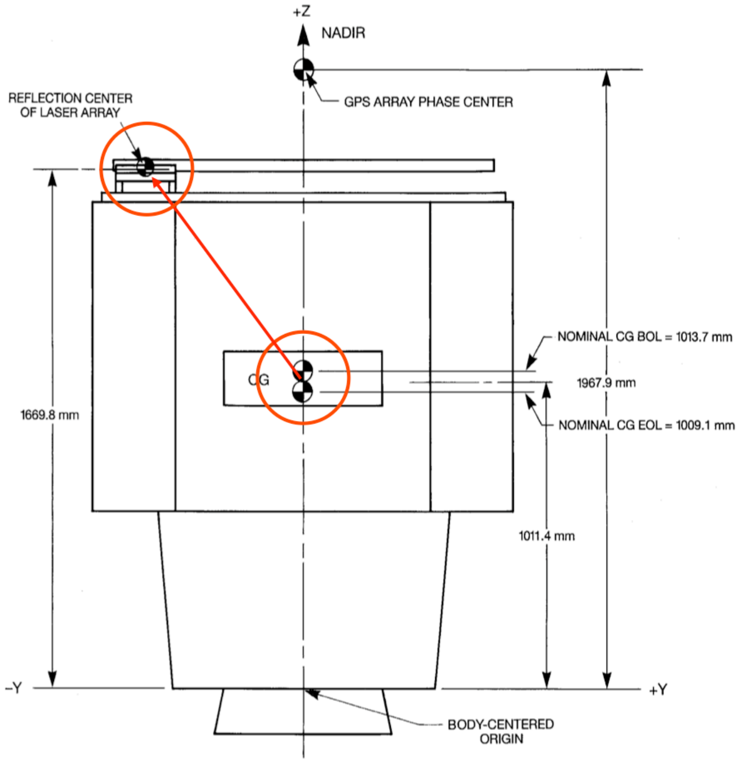

Figure 2. XY-plane view of the GPS s/c illustrating the locations of the GPS satellite center of gravity (CG), the effective laser array center of reflection, and the phase center of the L-band transmitting antenna array. The positive-Z coordinate axis is in the direction of satellite nadir.

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.

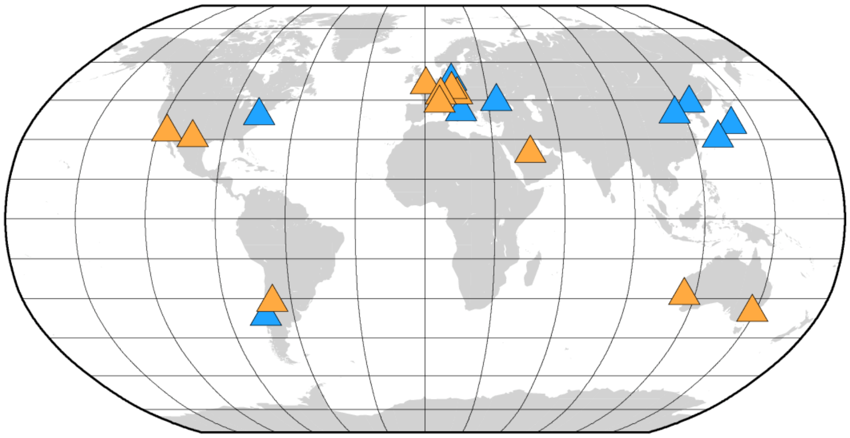

Figure 3. The SLR network (2008.0–2009.5) used for GPS tracking. Sites with fewer than 1000 observations over the period 1995.0–2009.0 are shown in blue, and those with 1000 observations or more over this time are shown in orange.

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 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.

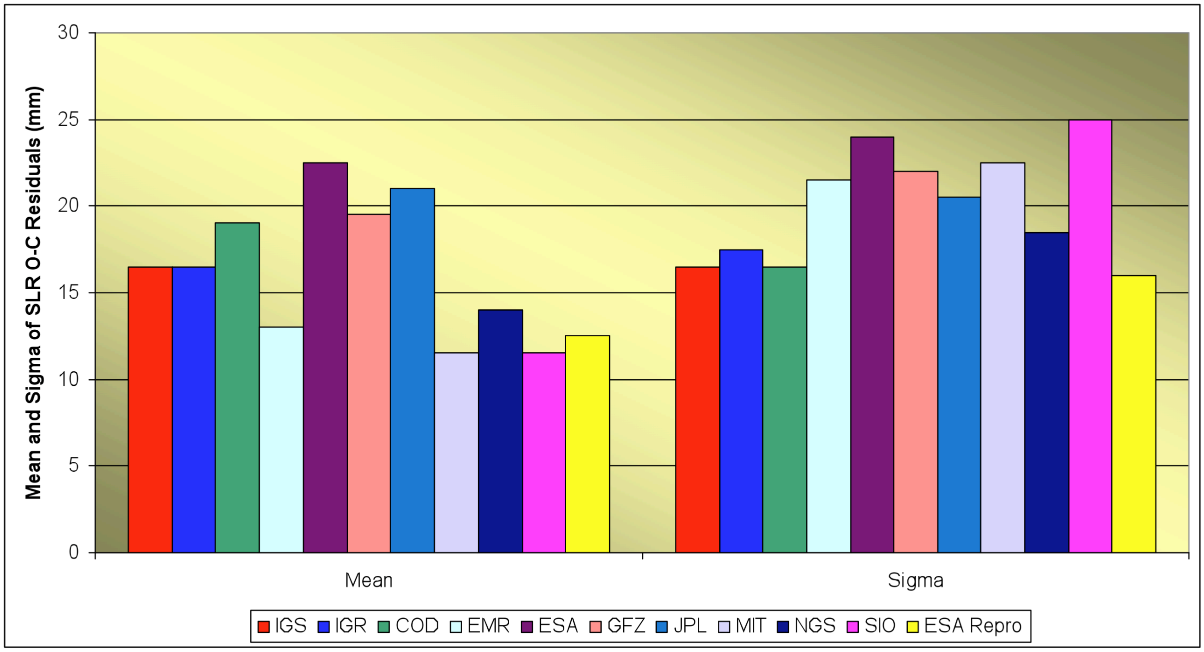

Figure 4. Mean and standard deviation of SLR range residuals to GPS satellites for the various IGS Analysis Centers final orbits. After *Springer et al.* [2008].

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.

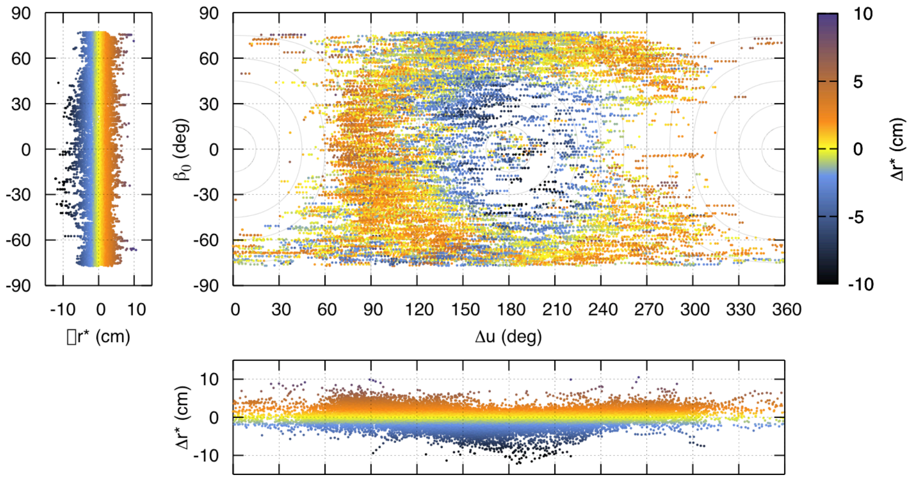

Figure 5. Color-coded de-meaned SLR range residuals determined using the ROCK SRP model [*Fliegel et al.*, 1992]. The residuals are projected into a coordinate system where β is the elevation above Sun above the satellite's orbital plane and u is the argument of latitude of the satellite relative to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

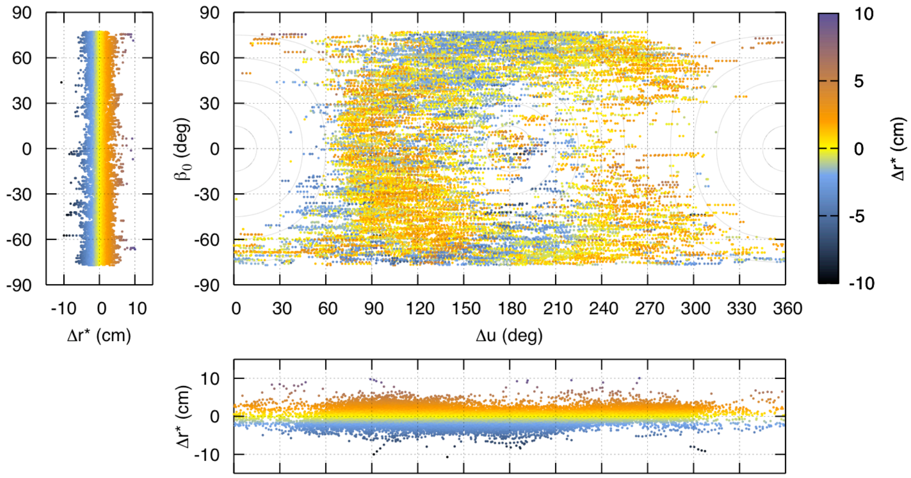

Figure 6. Same as Figure 5, except the CODE SRP model [*Springer et al.*, 1999] was used. After *Flohrer* [2008].

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.

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