Processing 20 years of SLR observations to GNSS satellites

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Abstract. *We process 20 years of SLR observations to GPS and GLONASS satellites using the reprocessed 3-day and 1-day microwave orbits provided by the Center for Orbit Determination in Europe (CODE) for the period 1994-2013. We study the dependency of the SLR residuals on the type, size, and a number of corner cubes in satellite laser reflector arrays (LRA). We show that the mean SLR residuals and the RMS of residuals depend on the coating of LRA and the block or type of GNSS satellites. The SLR mean residuals are also a function of the equipment used at SLR stations including detector types and detecting modes.*

Introduction

Satellite Laser Ranging (SLR) observations to GNSS satellites provide an independent validation of the orbits determined from microwave observations; thus, allow us to assess the quality of the GNSS orbits. This includes, e.g., deficiencies in the solar radiation pressure modeling for GNSS satellites (e.g., Urschl et al., 2007, Fritsche et al., 2014).

The 18th International Workshop on Laser Ranging, which was held in Fujiyoshida (Japan) in November 2013, recognized the increasing importance of SLR to the improvement of GNSS performance. The LAser Ranging to GNSS s/c Experiment (LARGE) group was established in the aftermath of this workshop. The resolution of the workshop paid special attention to “the necessity of the SLR technique to the improvement of time, frequency, and ephemeris data products from GNSS”. Today, all active GLONASS satellites are tracked by many SLR stations, which gives us a very good tracking record of different GNSS satellites and allows us to, e.g., combine SLR and GNSS techniques using the co-locations in space (Thaller et al., 2011).

We validate the GNSS orbits from CODE reprocessing2 campaign, i.e., an IGS reprocessing campaign in the framework of the preparation of the ITRF2013/ITRF2014. We use two CODE products: the 3-day long-arc solutions (CO2) and clean 1-day arc solutions (CF2). We process the SLR observations to GPS satellites collected in 1994-2013 and to GLONASS satellites collected in 2002-2013 by the ILRS stations.

SLR validation of GPS orbits

Table 1 shows that the mean SLR residuals for both GPS satellites are about -13 mm with the RMS at a level of 23 mm. The SLR residuals are, however, station-, satellite-, and time-dependent.

Figure 1 shows the comparison of CODE 3-day solutions (CO2) and 1-day solutions (CF2). The RMS of SLR residuals is typically smaller for CO2 solution, on average by 4%. The differences between CO2 and CF2 are largest in 1994 and in the period 1999-2003. After 2008, CO2 and CF2 seem to show a similar performance. After 2008, as well, the RMS of residuals increases in both solutions, which can be related on one hand to an increasing number of newly-established SLR stations which were not considered in ITRF2008 solutions and have only approximate coordinates in SLRF2008, and on the other hand, it can be related to the aging process of GPS satellites. GPS satellites of Block IIA were designed for 7.5 years, whereas their real life-time was exceeded by a factor of there (about 21 years). The center of mass of GPS satellites was expected to change its position over the life time of the mission due to the fuel combustion during satellite maneuvers. Figure 2 shows that the equipment changes have also an impact on the estimated SLR residuals. For example in Zimmerwald (7810) in 2002 a new photomultiplier tube for infrared laser was installed enabling the daytime tracking and then a double receiving system was used until 2008: for the blue laser a compensated single-photon avalanche diode (CSPAD) system (with two replacements in 2003 and 2006), and for the infrared laser a photomultiplier tube. Different wavelengths and different detectors showed systematic biases between infrared and blue laser ranges. A new laser was installed in March 2008 (Gurtner et al., 2009). Since then, the station uses only the green laser with the CSPAD detector operating at low-energy mode (detecting single to few photons). All these equipment improvements are reflected in different values of range biases for Zimmerwald (7810).

Figure 2 shows that the NASA SLR stations (7080, 7090, 7105, and 7110) observing in the multi-photon mode have a larger negative mean bias typically in the range from -10 to -35 mm, whereas the stations operating at low return rate (7810 after 2008, 7839, and 7840) have the mean biases between +10 and -15 mm. The SLR stations operating in the single-photon mode are free from the issues related to different incidence angles of a laser beam for flat LRAs, because each detected photon can have originated from anyone of the retro-reflectors and the spatial distribution of the whole array is mapped over the course of many detections (Otsubo et al., 2001, Wilkinson and Appleby, 2011). On the other hand, the NASA SLR stations, e.g., McDonald (7080), Yarragadee (7090), Greenbelt (7105), and Monument Peak (7110) are typically equiped with micro-channel plates with a high detection level, which are characterized by negative SLR biases and a nadir-dependancy of SLR observations to satelliteas with flat LRAs.

Table 1. Summary on the SLR observation residuals to GPS satellites

Satellite	No obs.	Mean Bias [mm]	RMS [mm]
GPS-35	52868	-12.8	22.8
GPS-36	57797	-13.5	23.6

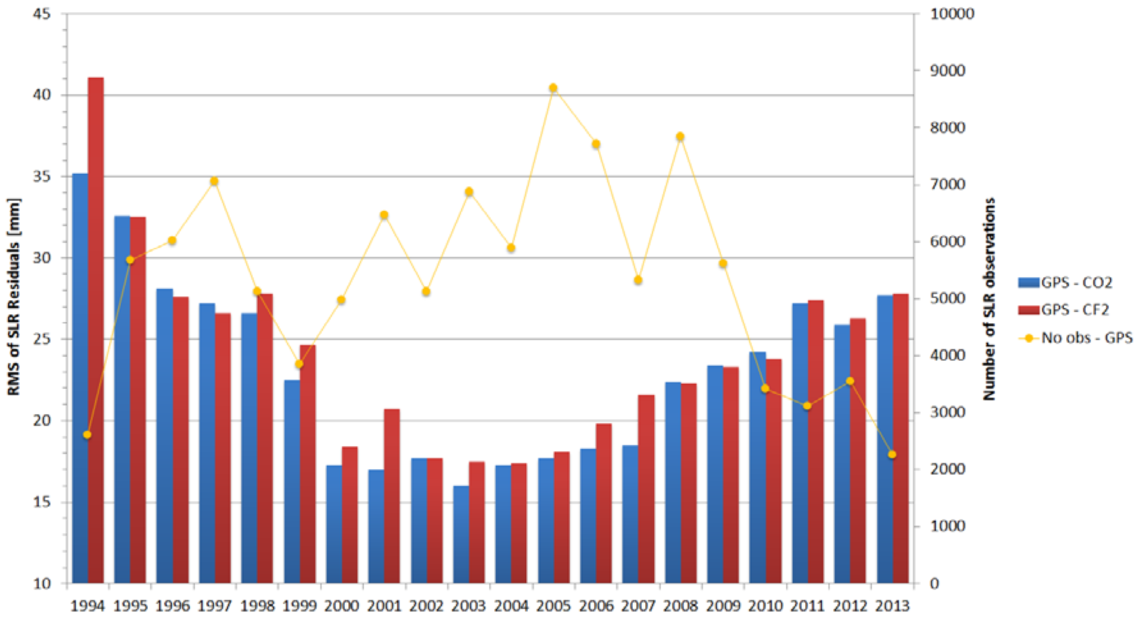

Figure 1. Mean RMS of SLR residuals to GPS satellites in 1994-2013 for 1-day satellite arcs (CF2) and 3-day satellite arcs (CO2).

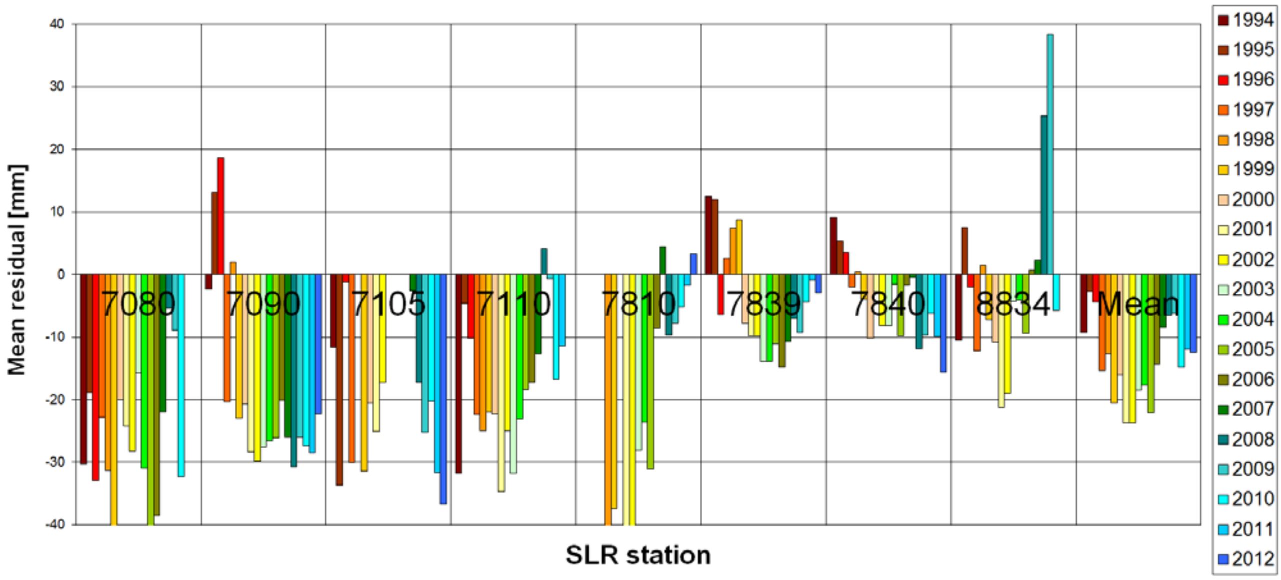

Figure 2. Mean biases of SLR residuals to GPS-36 in 1994-2012 for best performing SLR stations.

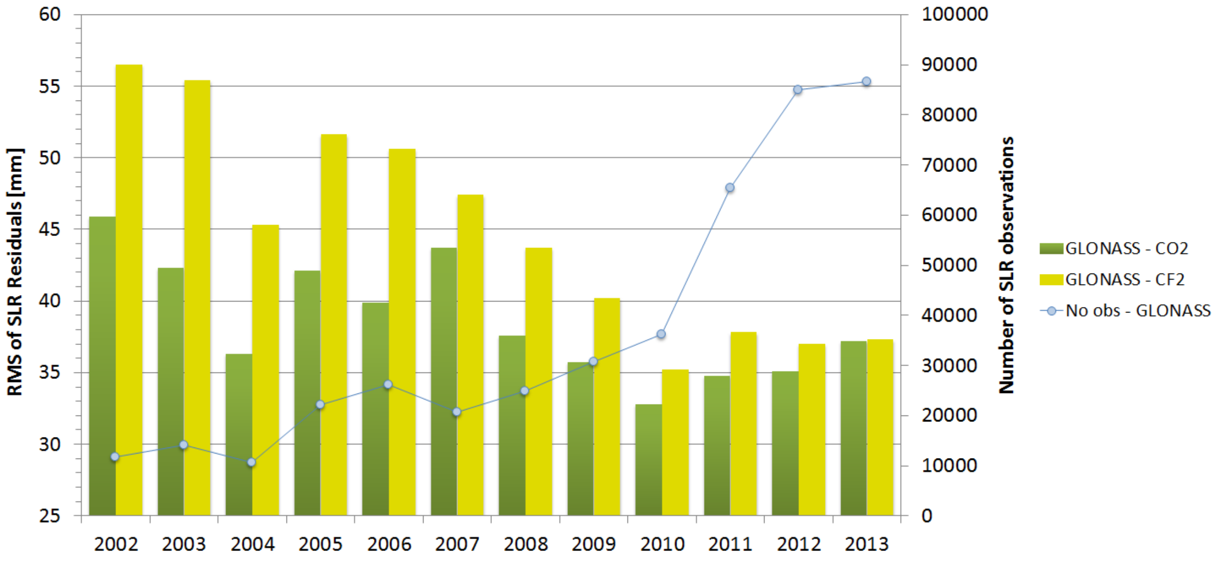

Figure 3. Mean RMS of SLR residuals to GLONASS satellites in 2002-2013 for 1-day satellite arcs (CF2) and 3-day satellite arcs (CO2).

Table 2. Summary on the SLR observation residuals to GLONASS satellites

Type	No obs.	Mean Bias [mm]	RMS [mm]
GLONASS	76892	-1.2	42.0
GLONASS-M	351308	-0.4	34.9
GLONASS-K	2969	-6.2	30.7
GLONASS-M coated	242557	2.1	36.3
GLONASS-M uncoated	108751	-5.9	31.8
GLONASS-M Plane 1	126952	-2.6	32.8
GLONASS-M Plane 2	123053	0.6	37.1
GLONASS-M Plane 3	93646	0.4	34.4

SLR validation of GLONASS orbits

Although all GLONASS satellites are equipped with laser retro-reflector arrays (LRAs), only three GLONASS satellites were recommended for tracking by the ILRS in the period of 2002-2010 (typical one per plane). In 2010 the ILRS decided to increase the number of tracked GLONASS satellites to six - two s/c per plane. Despite the ILRS recommendations, several SLR stations started tracking in 2010 and 2011 the full constellation of GLONASS satellites. The first station which initiated the tracking of the whole GLONASS constellation was Herstmonceux, followed by Zimmerwald, Graz, Yarragadee, Potsdam, Changchun, Shanghai, Simeiz, Altay, Arkhyz, and some other ILRS stations.

GLONASS satellites are equipped with LRAs of different types (rectangular regular arrays, regular ring arrays, or of irregularly distributed corner cubes covering the front side of the satellites). GLONASS LRAs consist of 112, 123, 124, 132 or 396 corner cubes. The older-class GLONASS satellites are typically equipped with aluminum coated corner cubes, whereas the recently launched satellites have typically uncoated corner cube retro-reflectors.

The RMS of SLR observations to all GLONASS is 46 and 57 mm in 2002 for CO2 and CF2 solutions, respectively, and it is reduced to 37 mm in 2013 (see Figure 3). It implies that even in the last years the accuracy of GLONASS orbits still did not reach that of GPS orbits. However, the number of SLR observations to GLONASS has been substantially increased in 2011, when more and more ILRS stations started tracking the full GLONASS constellation. The mean number of SLR observations to the both GPS satellites is 5,400 with a maximum in 2005 amounting to 8,700. The number of SLR observations to all GLONASS varies from 10,700 observations in 2004 (3 GLONASS satellites were tracked in this period) to 87,000 in 2013, when the full constellation was observed.

Figure 3 shows that the RMS of SLR residuals is typically smaller for 3-day CO2 solutions than for the 1-day CF2 solutions, from 30% in 2002-2005 to 1% in 2013 for GLONASS. In the 3-day GNSS solutions, the Earth rotation parameters have imposed continuities at the day boundaries (Lutz et al., 2015), and as a result, the 3-day solutions are much more stable than the 1-day GNSS solutions. Figure 3 shows that the 3-day arc definition is advantageous in particular for incomplete satellite constellations observed by the sparse and inhomogeneously distributed ground network of GLONASS receivers in the early years of GLONASS solutions (i.e., before 2008).

Table 2 shows that the RMS of SLR residuals is 42.0, 34.9, and 30.7 mm for older-class GLONASS satellites, GLONASS-M, and GLONASS-K, respectively. This implies that the RMS of SLR residuals to GLONASS is still about 30% larger than the corresponding value for GPS.

GLONASS-M satellites with uncoated LRAs have a slightly smaller value of the mean residuals (−5.9 mm on average) than the GLONASS-M satellites with coated LRAs (+2.1 mm, see Table 2). The RMS of residuals for recently launched GLONASS without coating is also smaller (31.8 mm on average) than for GLONASS with coating (36.3 mm on average). Coated GLONASS LRAs have different characteristics of returning photons, e.g., in the Zimmerwald observatory the median number of registered full-rate observations per one SLR normal point is 500 and 300 for uncoated and coated LRAs, respectively with the mean RMS of 0.92 and 1.15 mm, respectively (Ploner et al., 2014). The RMS of SLR residuals is, on the other hand, rather independent from the GLONASS orbital plane (see Table 2).

SLR validation of GNSS orbit models

SLR observations to GNSS satellites yield a remarkably important tool in a sense of the validation of GNSS orbits and the assessment of deficiencies in solar radiation pressure modeling. For many years, the Empirical CODE Orbit Model (ECOM) was used for generating high-precise GNSS orbits and GNSS products (Beutler et al. 1994, Springer et al. 1999) due to its high efficiency in mitigating the impact of the solar radiation pressure. In the recent months, it was found that the classical ECOM is well-suited for near cubic-shaped GPS satellites, whereas the orbit quality of elongated cylindrical-shaped GLONASS-M satellites suffers from some modeling deficiences. This led to the series of theoretical and empirical investigations with the outcome of the new extended ECOM model. Details on the development of the new ECOM can be found in Arnold et al. (2015).

Figure 4 illlustrates dependancy of the SLR residuals for different β_0 angles (the elevation angles of the Sun over satellite orbit planes) and different satellite arguments of latitude from the analysis of the reprocessed GLONASS orbits using classical ECOM. A maximum positive bias of approximately +60 mm is observed for $\Delta u=180°$ and $-40°<\beta_0<40°$. The maximum negative bias (approximately -80 mm) is observed when $\Delta u=0°/360°$ and $-40°<\beta_0<40°$.

This systematic pattern is related to modeling defficiences of the solar radiation pressure. When using the new ECOM, most of the systematic effects are reduced (see Figure 5), and as a results, the determined GLONASS orbits are less affected by modeling issues of the solar radiation pressure.

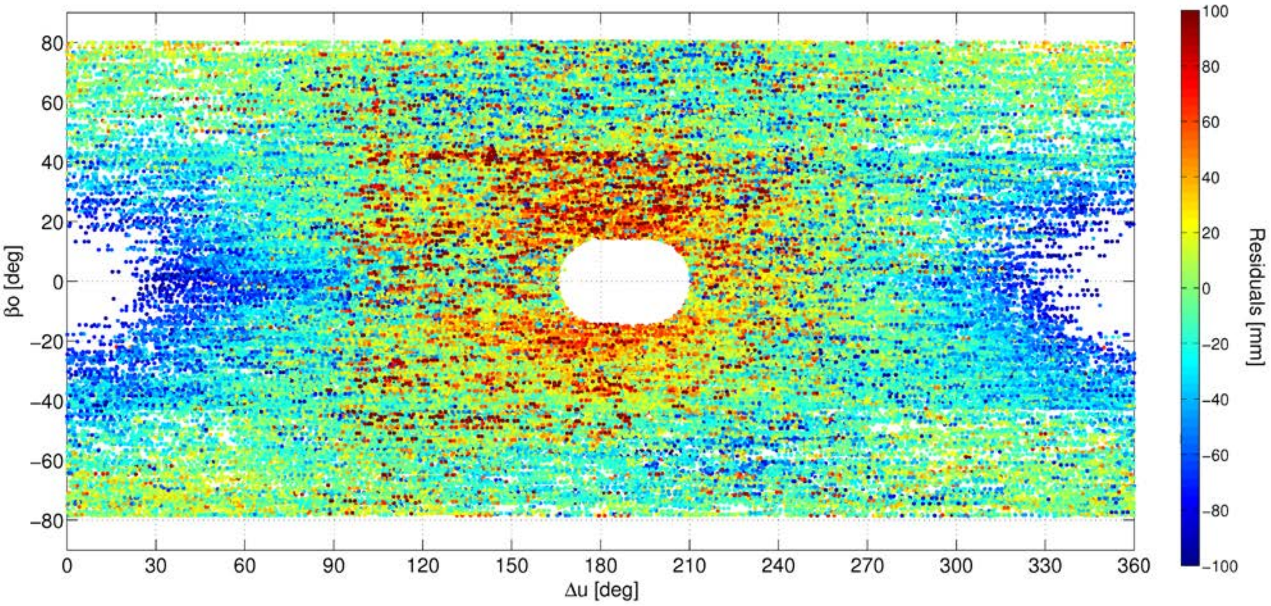

Figure 4. Relationship between the SLR residuals, satellite argument of latitude w.r.t. the Sun Δu, and the elevation angle of the Sun over orbital plane β_0 for GLONASS satellites using old ECOM. Satellites in the Earth's shadow and up to 30 minuntes after leaving the shadow are excluded.

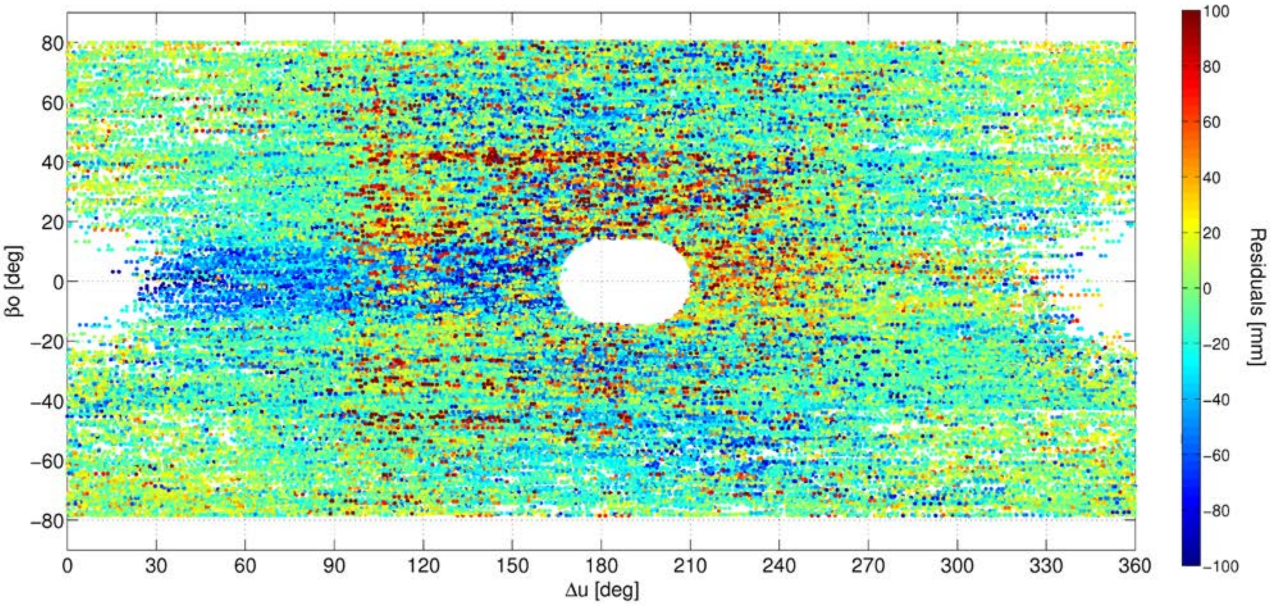

Figure 5. The same as Figure 4, but the new ECOM model is used.

Summary

We processed 20 years of SLR observations to GPS and 12 years of SLR data to GLONASS using the reprocessed microwave-based CODE orbits. The mean SLR residuals to GPS satellites are -12.8 and -13.5 mm for GPS-35 and GPS-36, respectively with the RMS of 22.8 and 23.6 mm, respectively. The largest RMS of residual for GPS is in 1994, amounting to 35 mm, whereas the smallest RMS of residuals is for the period 2000-2007. In 2003 the RMS of observation residuals amounted to just 16 mm. The mean SLR bias is time-dependent due to the equipment changes in the ground network. The SLR stations operating in the multi-photon mode have a larger negative mean bias to GPS typically in the range from -10 to -35 mm, whereas the stations operating at low return rate (CSPAD, i.e., single-photon stations) have the mean biases between +10 and -15 mm.

The RMS of SLR observations to GLONASS is 46 mm in 2002 and it is reduced to 37 mm in 2013. However, the number of SLR observations to GLONASS has been substantially increased in 2011, when more and more ILRS stations started tracking the full GLONASS constellation. The RMS of SLR residuals is typically smaller for 3-day arc solutions than for the 1-day solutions, on average by 4% for GPS, and from 30% in 2002-2005 to 1% in 2013 for GLONASS.

SLR confirmed that CODE's new empirical orbit model remarkably reduces the spurious behavior of most of GLONASS satellites, and as a results, substantially improves GNSS solutions. The new ECOM reduces the dependency of SLR residuals w.r.t. the Sun-satellite argument of latitude. This confirms that SLR observations of GNSS satellites yield a remarkably important tool in a sense of the validation of GNSS orbits and the assessment of deficiencies in solar radiation pressure modeling. More results concerning processing of SLR observations to GPS and GLONASS satellites can be found in Sośnica et al. (2014, 2015) and in Arnold et al. (2015).

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