**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 orbits. 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 experiment comprised a 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” and to “the significant contribution of GNSS to the development of GNSS measurement accuracy through co-location with SLR and other measurement techniques”. Today, all active GLONASS satellites are tracked by many SLR stations, which gives us a very good tracking record of different GNSS satellites (see Fig. 1), and allows us to combine SLR and GNSS techniques using the collocations in space and time.

We validate the GNSS orbits from CODE repro5 campaign: the 3-day-long arc solutions CO2 and clean 1-day solutions CF2.

**SLR validation of GPS orbits**

We process the SLR observations to GNSS satellites collected in 1994-2014 by the IERS stations. 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 3 shows that, for Yarragadee (7090), Graz (7839) and Herstmonceux (7840) the mean residuals were positive in early nineties, whereas they were negative for the remaining time span. For Zimmerwald (7810), a detector change in 2006 can be easily recognized.

Figure 4 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 2004 CO2 and CF2 seem to show a similar performance. After 2008, as well, the RMS of residuals increases in both solutions possibly due to worse quality of GPS orbits or new SLR stations and fact stations affected by earthquakes without well-established coordinates in ITRF2008. Table 2 shows that CO2 solution shows better performance than CF2 solutions as a function of orbital plane, satellite type, coating, and LRA shape.

To validate the GNSS orbits from CODE repro5 campaign: the 3-day-long arc solutions CO2 and clean 1-day solutions CF2.

**SLR validation of GLONASS orbits**

Although all GLONASS satellites are equipped with laser retroreflector arrays (LRAs), only three GLONASS satellites were recommended for tracking by the IERS in the period of 2002-2010 (typical one per year). In 2010 the IERS decided to increase the number of tracked GLONASS satellites to six - two s/c per satellite. Despite the IERS’ 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, Simeqz, Alley, Arkhyz, and some other IERS stations.

GLONASS satellites are equipped with LRAs of different types (rectangular arrays, regular hollow circular arrays, or irregular shape covering the front side of the satellites). GLONASS LRAs consist of 112, 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 cubic retroreflectors (see Table 3). Table 4 shows that the RMS of SLR residuals is 42.0, 34.9, and 30.7 mm for satellite type, coating, and LRA shape, respectively. This shows that the RMS of SLR residuals to GLONASS is still about 30% larger than the corresponding value for GPS. Figure 6 shows, however, that the GLONASS satellites launched after 2007 have in general smaller RMS of residuals than the GLONASS satellites launched before 2007. 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 4). The RMS of residuals for recently launched GLONASS without coating is also smaller (31.8 mm on average) than for GLONASS with coating (38.3 mm on average, see Figure 6). Uncoated 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 coated and uncoated LRAs, respectively with the mean RMS is 0.02 and 1.15 mm, respectively (Ploner et al., 2014). Thus, the station- and satellite-specific range biases have to be considered when increasing SLR data to GNSS satellites. Figure 6 shows that the RMS of SLR residuals for GLONASS is smaller for CO2 solution, in particular before 2010. For some satellites there is also a dependence of mean residuals w.r.t. the time of observation, e.g., for GLONASS-124, see Fig. 7.

**Summary**

SLR observations to GNSS satellites yield a remarkably important tool in a sense of validation of GNSS orbits and the assessment of deficiencies in solar radiation pressure modeling (see Fig. 3). The mean SLR residuals to GNSS s/c are at a level of 23 and 35 mm for GPS and GLONASS, respectively. The CO2 CODE repro5 solution shows a better performance than the CF2 solution, in particular in early years of reprocessing, when the global coverage of GNSS stations was limited.

The SLR residuals depend on many constituents, e.g., on: GNSS satellite type/blocks (see Tab. 3), shape and size of LRA, and number of corner cubes in LRAs (see Fig. 4), LRA coating (see Tab. 4, Fig. 5), Time of the observation (day/night, see Fig. 7), Equipment used at SLR stations (see Fig. 3), including laser and detector types, Modeling of GNSS orbits and arc lengths (see Fig. 4).

**References**


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**Figures**

- **Fig. 1:** Number of SLR observations to GPS and GLONASS in 2013 collected by IERS stations. Areas of the circles are proportional to the number of collected observations.
- **Fig. 2:** Validation of GNSS orbits using SLR data.
- **Tab. 1:** SLR residuals to GPS satellites from CO2 solution [mm].
- **Tab. 2:** Amplitudes of draconitic harmonics from SLR validation of GPS-35 orbit [mm].
- **Tab. 3:** RMS of residuals and mean offsets of SLR observations to GLONASS from CO2 as a function of orbital plane, satellite type, coating, and LRA shape. Values in mm.
- **Fig. 3:** RMS of SLR residuals to GPS satellites for solutions and solutions [mm].
- **Fig. 4:** RMS of SLR residuals to CO2 solutions for CO2 and CF2 solutions [mm].
- **Fig. 5:** RMS of SLR residuals as a function of GLONASS satellite type and coating from CO2 solution. Satellites are sorted according to the lanuch date.
- **Fig. 6:** Relationship between the SLR residuals, argument of satellite latitude, Δω, and the Sun elevation angle above the orbital plane, β for GPS [left] and GLONASS [right] from CO2. Small variations of mean biases can be observed for different arguments of satellite latitude w.r.t. the Sun. E.g., for GPS when Δω is between 120° and 240°, the mean bias reaches -20 mm, otherwise the mean bias is close to 0 mm. An opposite picture is for GLONASS, indicating some deficiencies in solar radiation pressure modeling.

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