How many SLR observations and how many stations are needed for deriving high-quality multi-GNSS orbits?

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Abstract. *The growth of the number of multi-GNSS satellites encourages the International Laser Ranging Service (ILRS) to provide a support in the form of special SLR-GNSS tracking campaigns and the priority list for SLR stations to track. This work summarizes three special multi-GNSS tracking campaigns which took place in the period between 2014 and 2017. Range measurements to multi-GNSS constellation typically are employed for the validation of microwave products. However, SLR observations can also be used for the multi-GNSS orbit determination or for the determination of global geodetic parameters, such as station coordinates, Earth rotation parameters and the scale of the reference frame. In this work, we aim at addressing the following questions: (1) How many SLR observations to multi-GNSS satellites are necessary to provide high-quality GNSS orbits using solely SLR data? (2) What is an optimal geometry of observations and how many stations are needed to determine GNSS orbits and geodetic parameters? We consider the whole GLONASS constellation, all active Galileo satellites, four BeiDou spacecraft (1 MEO, 3 IGSO) and the first QZSS satellite, QZS-1. The best orbit solution was obtained for the GLONASS R07 spacecraft on 15 July 2015. The 5-day solution was calculated using 129 SLR observations provided by 12 homogeneously distributed SLR stations. During the 5-day period the R07 was tracked by 2 stations from North America, 3 from Asia, 2 from Australia, and 5 from Europe, all of which provided an even and supreme geometry of observations. The RMS of differences between microwave-based and SLR-based orbits for the best 5-day solution of GLONASS R07 equals 8, 24, 19 mm in the radial, along-track and cross-track direction, respectively.*

Introduction

All new active Global Navigation Satellite System (GNSS) satellites i.e., GLONASS, Galileo, BeiDou, and QZSS are equipped with Laser retroreflector arrays (LRA) for laser ranging. Thanks to the great precision of range measurements, Satellite Laser Ranging (SLR) performs well as a validation tool for the microwave-based products such as precise orbits. Due to the fact that GNSS constellations grow continuously, SLR can contribute to the great extent to the inventorying of the systematic errors which deteriorate the consistency between SLR and GNSS solutions. As a result, at the 18th International Workshop on Laser Ranging in Japan in November 2013 the International Laser Ranging Service (ILRS, Pearlman et al., 2002) community decided to increase efforts on tracking the GNSS satellites by introducing a special Study Group called Laser Ranging to GNSS s/c Experiment (LARGE). In the frame of the LARGE project, three special tracking campaigns took place between 2014 and 2017 which contributed a significant increase in the number of SLR observation to GNSS satellites. Based on the SLR observations one can determine multi-GNSS orbit parameters using solely SLR data as an independent orbit solution which can be valuable for the multi-GNSS Experiment community (MGEX, Montenbruck et al., 2017). In this work, we summarize the special tracking campaigns in terms of the multi-GNSS orbit determination and indicate the minimum requirements for the number of SLR observations and geometry of observations in order to determine reliable multi-GNSS orbits. We also suggest a possible scenario of GNSS tracking in order to cover full multi-GNSS constellations with range measurements.

Methodology

For the orbit determination, we use the modified version of Bernese GNSS Software 5.2. We estimate 6 Keplerian parameters and 7 empirical parameters according to CODE's solar radiation pressure model – ECOM2 which does not require any a priori solar radiation pressure model. ECOM2 parameters comprise the constant term in the sun-satellite direction D_0 together with sine and cosine terms i.e., D_{S2} and D_{C2}, constant acceleration along the solar panel axis Y_0, and B_0, B_{S2}, B_{C2} parameters in an orthogonal direction which completes the orthogonal frame. We calculate orbits for the period between 2014.0 and 2016.9. We consider the whole GLONASS constellation, all active Galileo satellites, four BeiDou spacecraft (1 MEO, 3 IGSO) and the first QZSS satellite, QZS-1. In order to be as consistent as possible with MGEX, we use official MGEX products from the Center for Orbit Determination in Europe (CODE). CODE's orbits serve as both, a priori data and as a reference microwave orbits.

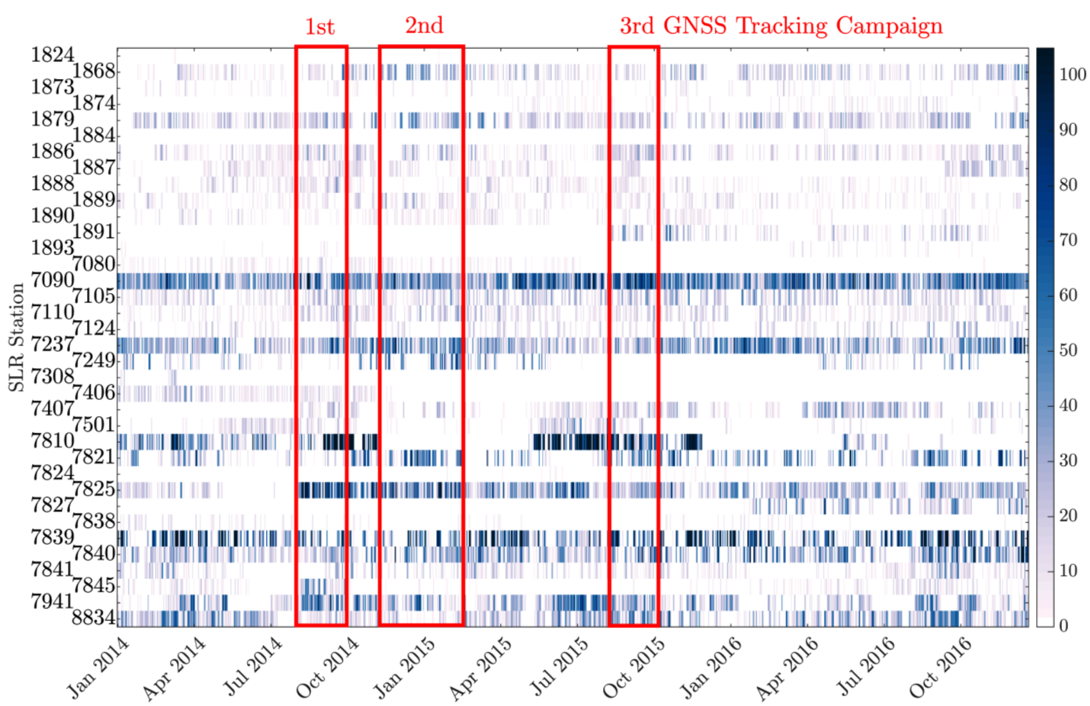

Figure 1. SLR stations' performance in range measurements to GNSS satellites. Right bar represents the number of normal points collected by each SLR station (left: ILRS ID number of SLR station) during the analysis period. The station's ID are explained in Table 1. Red boxes denote periods of special GNSS cracking campaigns.

Orbit quality is assessed as a difference between referential CODE microwave-based products and calculated SLR orbits in the radial, along-track and cross-track directions for the middle day of each solution. The biggest difference of our solutions to the CODE solution (Prange et al., 2017), besides using different observation types, is the length of the orbital arc. According to the test performed in Bury et al. (2017), we stacked 5-day orbital arcs form 1-day solutions, whereas CODE calculates 3-day arcs which do not provide a sufficient number of SLR observations.

SLR stations performance

Figure 1 and Table 1 present the performance of SLR tracking stations in range measurements to GNSS satellites during the analysis period. During the analysis period, the three special tracking campaigns were held (see red boxes in Fig. 1). For stations which track almost the whole multi-GNSS constellation the greatest increase of activities was registered for Yarragadee (7090), Zimmerwald (7810), Mt. Stromlo (7825), and Matera (7941). For the Russian stations which focus mainly on GLONASS satellites, the increase of the number of SLR observations during special tracking campaigns occurred for Komsomolsk (1986), Altay (1879), and Arkhyz (1886).

When considering the whole analysis period, the indisputable leader in providing range measurements is the Australian station Yarragadee (7090) that provided nearly 44 000 normal points which comprise over 13% of all observations of the 3-year period of analysis. Yarragadee collected also the largest amount of normal points to the Galileo constellation (over 13 000) and BeiDou (3825).

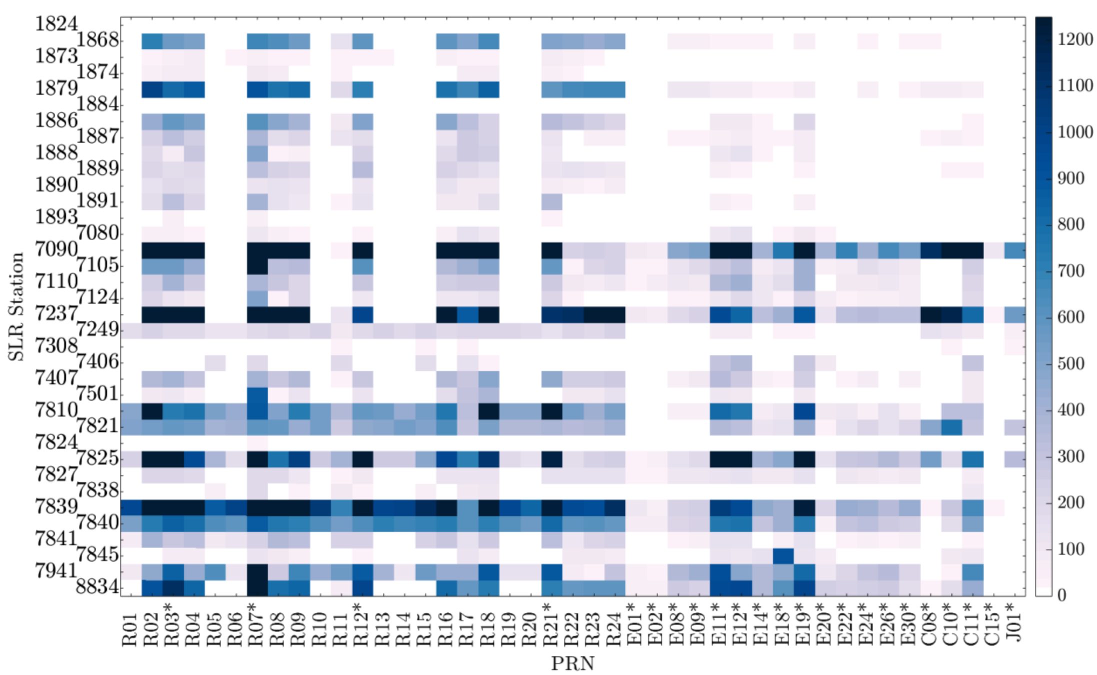

Figure 2 SLR stations' performance in range measurements to GNSS satellites. Right bar represents the number of normal points collected by each SLR station (left: ILRS ID number of SLR station) during the analysis period. The station IDs are explained in Table 1. Red boxes denote period of special GNSS cracking campaigns

Table 1 Number of observations to GNSS satellites collected by SLR stations in the analysis period

Monument	Code	Location Name, Country	GLONASS	Galileo	BeiDou		QZSS	All
					MEO	IGSO		
7090	YARL	Yarragadee, Australia	26011	13098	1331	2494	663	43597
7839	GRZL	Graz, Austria	28214	6532	279	715	0	35740
7237	CHAL	Changchun, China	18037	5408	1190	2122	558	27315
7810	ZIML	Zimmerwald, Switzerland	22534	3217	328	322	0	26401
7825	STL3	Mt Stromlo, Australia	15966	7238	186	1337	336	25063
7840	HERL	Herstmonceux, UK	16162	4725	163	522	0	21572
8834	WETL	Wettzell, Germany	11545	5631	166	468	0	17810
7941	MATM	Matera, Italy (MLRO)	12011	5054	35	654	0	17754
7821	SHA2	Shanghai, China	11000	2119	799	796	312	15026
1879	ALTL	Altay, Russia	10977	569	78	128	0	11752
7105	GODL	Greenbelt, Maryland	6418	2057	0	246	0	8721
1868	KOML	Komsomolsk, Russia	8017	326	15	38	0	8396
1886	ARKL	Arkhyz, Russia	5718	509	0	36	0	6263
7407	BRAL	Brasilia, Brazil	4781	1261	0	97	0	6139
7110	MONL	Monument Peak, California	3361	2138	0	211	0	5710
7841	POT3	Potsdam, Germany	4452	743	0	24	0	5219
7249	BEIL	Beijing, China	4512	205	127	237	40	5121
7827	SOSW	Wettzell2, Germany	2177	1227	5	62	0	3471
1887	BAIL	Baikonur, Kazakhstan	2708	313	54	52	0	3127
7124	THTL	Tahiti, French Polynesia	1901	953	0	176	0	3030
7501	HARL	Hartebeesthoek, South Africa	2568	358	0	96	0	3022
1889	ZELL	Zelenchukskya, Russia	2707	175	20	27	0	2929
1888	SVEL	Svetloe, Russia	2152	382	2	9	0	2545
7845	GRSM	Grasse, France (LLR)	831	1485	79	134	0	2529
1891	IRKL	Irkutsk, Russia	2293	170	0	17	0	2480
7406	SJUL	San Juan, Argentina	881	1025	0	300	0	2206
1890	BADL	Badary, Russia	1598	43	0	3	0	1644
7080	MDOL	McDonald, Texas	654	390	0	6	0	1050
1873	SIML	Simeiz, Ukraine	769	51	0	7	0	827
7838	SISL	Simosato, Japan	642	0	0	115	0	757
1874	MDVS	Mendeleevo 2, Russia	632	74	11	9	0	726
1893	KTZL	Katzively, Ukraine	175	50	0	9	0	234
7308	KOGC	Koganei, Japan	115	6	26	17	23	187
7824	SFEL	San Fernando, Spain	87	0	0	0	0	87
1884	RIGL	Riga, Latvia	0	17	0	0	0	17
1824	GLSL	Golosiiv, Ukraine	4	9	0	0	0	13
			232610	67558	4894	11486	1932	318480

The second best performing station is Graz, Austria (7839) that registered nearly 36 000 normal points (over 11% of all observations) and provided the highest number of SLR observations to GLONASS satellites collecting over 28 000 normal points. Changchun (7237) is the best performing station in the Asia region providing 27 000 normal points to all GNSS constellations. Despite some technical issues that cause interrupts in tracking, the Swiss station Zimmerwald (7810) is the fourth best-performing SLR station. Russian and Ukrainian station track mainly GLONASS satellites i.e., observations to Russian satellites comprise 93%, 95%, and 97% of all GNSS observations for stations Altay (1879), Komsomolsk (1868), and Badary (1890), respectively (see Table 1). SLR stations from Western Europe e.g., Graz (7839), Zimmerwald (7080), Herstmonceux (7840), Wettzell (8834) or Matera (7941) put an effort on tracking every satellite from each MGEX constellation which results in both, a satisfying coverage with range measurements and a good geometry of SLR observations.

Apart from special tracking campaigns, ILRS provides the priority list of satellites for stations to track. The list contains a set of GLONASS satellites, all Galileo satellites, BeiDou satellites, and all QZSS spacecraft. When confronting the list of satellites tracked by SLR stations with the priority list of the ILRS, we notice that e.g. Yarragadee, Changchun, Greenbelt, Monument Peak, and most of the Russian and Ukrainian stations follow the ILRS recommendations, whereas Russian stations are completely focused on tracking the GLONASS constellation.

For more statistics concerning SLR to multi-GNSS satellites see the online service for multi-GNSS orbit validation using SLR – GOVUS (www.govus.pl, Zajdel et al., 2017)

Results

The accuracy of orbit solutions is evaluated based on the differences between satellite positions calculated using our orbit solution and the microwave-based CODE solution. Differences are calculated in a 15-minute interval. The RMS of differences calculated for the radial, along-track and cross-track component is then considered as an external accuracy indicator.

In order to determine an orbit at least 13 uncorrelated and independent observations are needed (for estimating 6 Keplerian and 7 empirical parameters). However, when using 13-50 observations one may obtain an orbit of a decimetre or even meter accuracy which is insufficient for precise geodesy but still can be used for the orbit determination of inactive navigation satellites equipped with LRAs. With the increase of the number of observations to about 60, the accuracy of radial reaches 2-4 cm and for along-track 9-16 cm for MEO satellites. However, the cross-track is determined with the accuracy at the level of 20 cm which deteriorates the 3D orbit accuracy (see Table 2). In the case of BeiDou IGSO satellites, the poor geometry observation which results from the regional attitude of IGSO segment disables us to determine a reliable orbit, whereas the number of 60 observations for QZSS has never been reached. Table 2 shows the median RMS of differences between SLR and microwave derived multi-GNSS orbits for the particular constellation.

Table 2 The median RMS of differences between SLR (using 60 observations) and microwave derived multi-GNSS orbits for the particular constellation. All values are given in cm

Component	GLONASS	Galileo		BeiDou		QZSS
		IOV	FOC	MEO	IGSO	
Radial	2.9	4.0	4.3	2.3	4.6	-
Along-track	8.8	10.4	15.7	10.2	24.5	-
Cross-track	16.7	18.1	20.3	12.3	49.8	-
3D	21.4	23.3	26.2	17.9	55.6	-

With the increase of the number of observations to 100 the RMS of differences for MEO satellites reaches the level of 3, 7, and 11 cm for the radial, along-track, and cross-track component, respectively.

The number of SLR stations is crucial as well due to the fact that it provides a geometry of observations. The high number of stations itself does not provide an accurate solution without the homogenous distribution of stations. Nevertheless, the solution provided by 5 stations is insufficient with the median RMS at the level of 7, 23, and 49 cm. When observations from 10 stations supply the solution the median RMS decreases to the level of 4, 9, and 18 cm and reaches the level of 3, 7 and 11 cm in the radial, along-track and cross-track direction, respectively for 15 SLR stations.

The best orbit solution was obtained for the GLONASS R07 spacecraft on 15 July 2015. The 5-day solution was calculated using 129 SLR observations provided by 12 homogeneously distributed SLR stations.

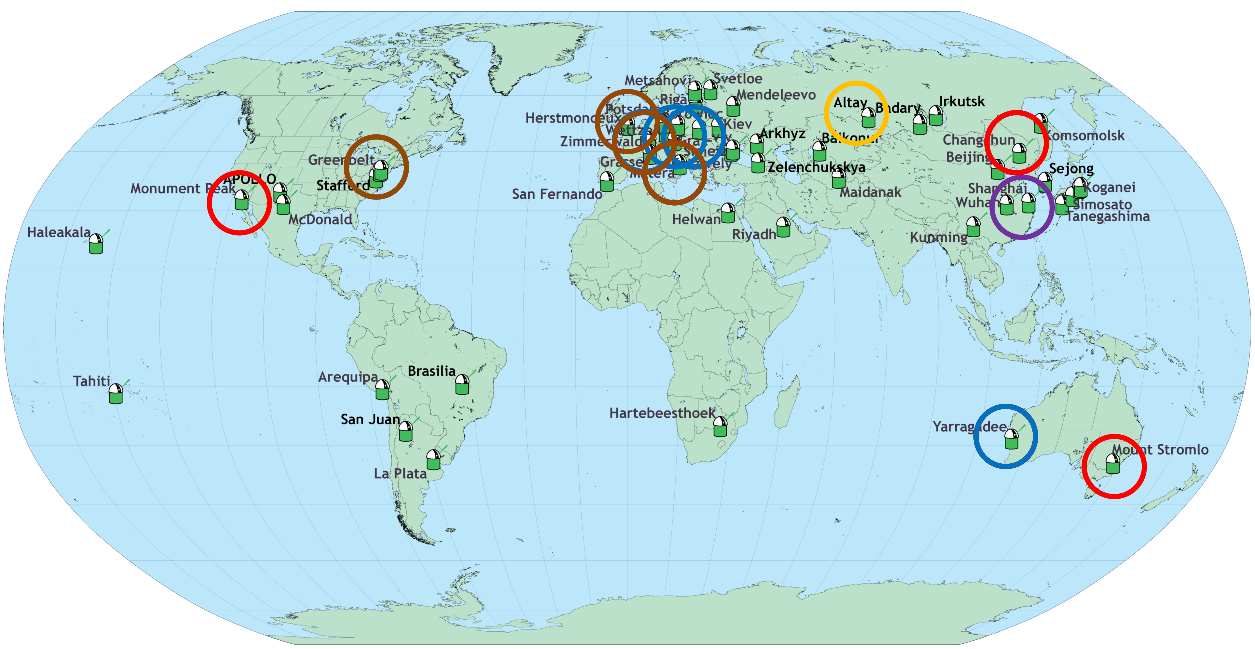

Figure 3 Visualisation of SLR stations which provide observation to the best 5-day solution for GLONASS R07. Yellow, violet, red, blue and brown circles denote stations which provide observation in respective 5 days.

During the 5-day period the R07 was tracked by 2 stations from North America, 3 from Asia, 2 from Australia, and 5 from Europe (see Fig. 3), all of which provided an even and supreme geometry of observations. The RMS of differences between microwave-based and SLR-based orbits for the best 5-day solution of GLONASS R07 equals 8, 24, 19 mm in the radial, along-track and cross-track direction, respectively.

Tracking schedule

High performing stations such as Yarragadee, Herstmonceux or Graz are capable at tracking of more than 50 targets (Kirchner and Koidl 2015). So far, the multi-GNSS constellation is not tracked homogenously i.e., some satellites such as GLONASS R07 are tracked intensively thus the solution is frequently supplied with more than 200 observations collected during the 5-day period. However, tests performed by Bury et al. (2017) indicated that more than 100 observations do not significantly improve the orbit solution thus in terms of the orbit determination it would be worthwhile tracking homogenously the whole multi-GNSS constellation rather than only selected satellites. Due to the fact that a lot of the high performing stations are located in Europe, we propose the clustering which may systematize the scheduling (see Table 3). The clustering may increase the number of SLR observations to sporadically observed multi-GNSS satellites, but on the other hand, the process can easily be disturbed by the weather conditions.

Table 3 The proposal clustering of SLR stations in terms of the homogenous tracking of multi-GNSS constellations.

	Europe	Australia
Group I	7810, 7941, 7824, 7811	7090
Group II	7839, 8834, 7841, 1884, 1886	7825
Group III	7840, 7827, 7845, 1837, 1888	-

Table 4 The proposal scheduling of the GNSS satellites tracking

		Day 1	Day 2	Day 3
Europe	GLONASS/Galileo (p 1)	Group I	Group II	Group III
	GLONASS/Galileo (p 2)	Group II	Group II	Group I
	GLONASS/Galileo (p 3)	Group III	Group I	Group II
Australia	GLONASS/Galileo (p 1)	Group I	Group II	
	GLONASS/Galileo (p 2)	Group II	Group I	
	GLONASS/Galileo (p 3)	Group II	Group I	
N&S America Pacific Africa	All station should follow the ILRS priority list			

Moreover, for stations located in regions with predominantly poor weather conditions, every short period of the cloudless sky provides an opportunity to perform range measurements, no matter of spacecraft type. Nevertheless, the subject of scheduling is worth discussing in the SLR stations community.

Conclusions

The three special GNSS tracking campaigns did not interfere the ordinary procedures at SLR stations, far from it, the number of SLR observation increased to both GNSS satellites and LAGEOS satellites (Pearlman et al., 2015; Noll et al., 2015). Based on SLR observations to GNSS satellites we determined orbit parameters of multi-GNSS constellations. In total, 60 SLR observations are needed to determine an orbit of cm-quality in the radial and along-track component. About 100 SLR observations provided by at least 10 homogenously distributed stations are needed to determine GNSS orbit with the 3D accuracy at the cm-level. We also provided a proposal of scheduling of GNSS satellite tracking by dividing the high-performing station into clusters. However, this aspect should be further discussed with the station community.

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