GNSS orbit validation using SLR at CODE

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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 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" and to "the significant contribution of GGOS 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 co-locations in space (see Fig. 2).

We validate the GNSS orbits from CODE repro2 campaign: the 3-day long-arc solutions **CO2** and clean 1-day arc solutions **CF2**.

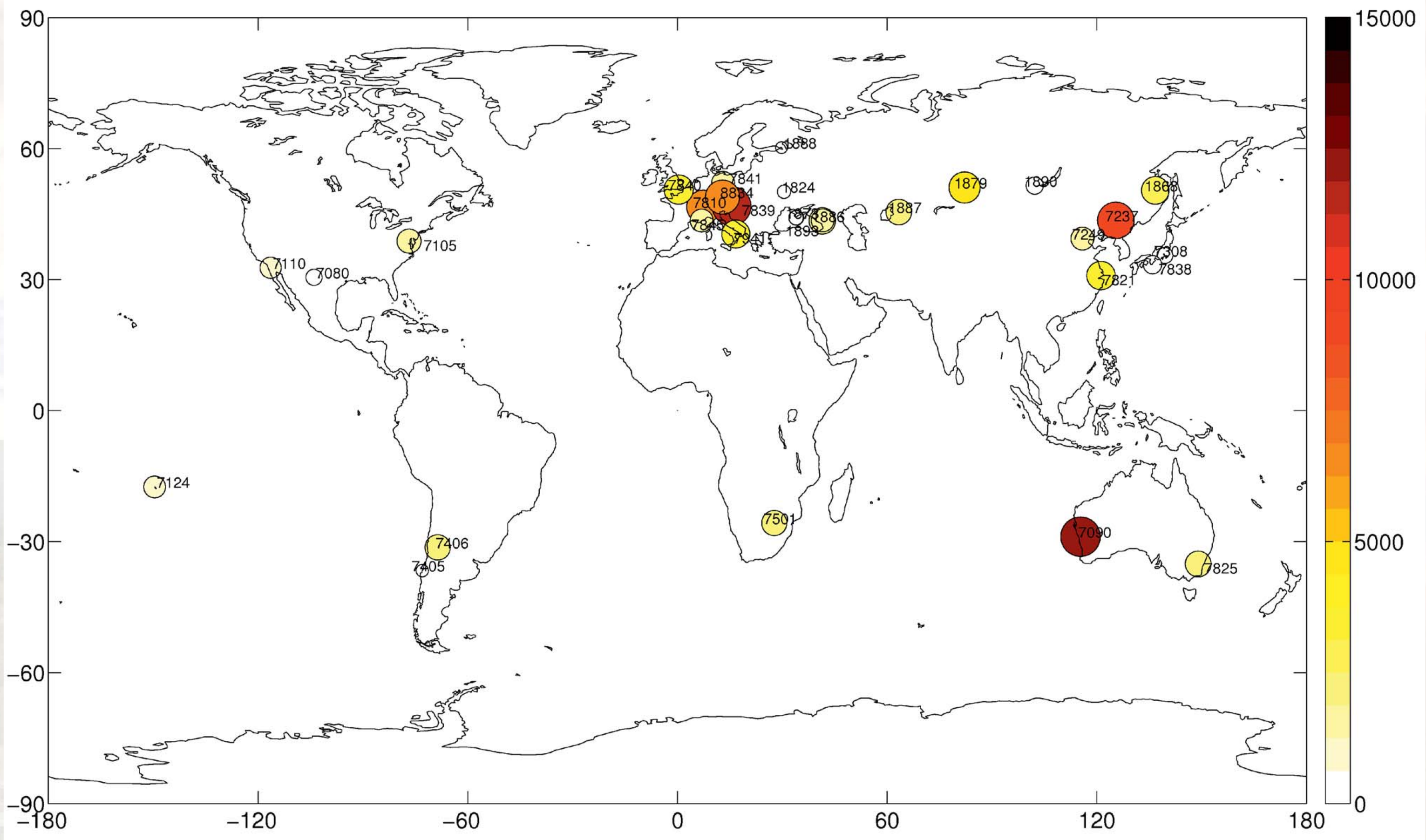

Fig: 1: Number of SLR observations to GPS and GLONASS in 2013 collected by ILRS stations. Areas of the circles are proportional to the number of collected observations.

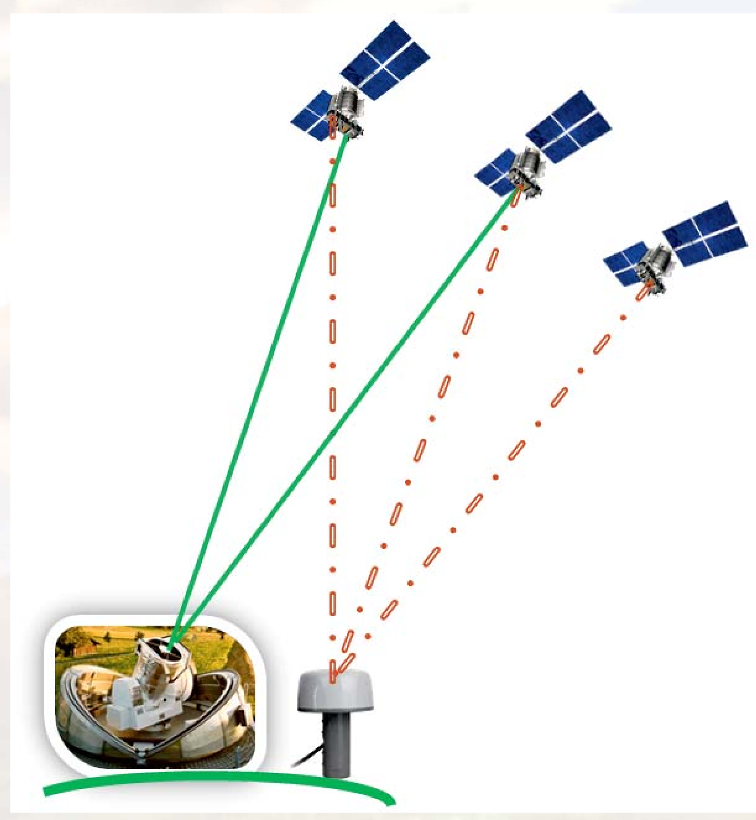

Fig: 2: Validation of GNSS orbits using SLR data.

SLR validation of GPS orbits

We process the SLR observations to GNSS satellites collected in 1994-2014 by the ILRS 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, e.g., 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 2008 **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 SLR stations affected by earthquakes without well established coordinates in ITRF2008. Table 2 shows that **CO2** solution shows typically smaller amplitudes of GPS draconitic harmonics from the SLR observation residuals than the **CF2** solution.

Satellite	Plane	No of obs.	Mean resid.	RMS
GPS-35	2	52868	-12.8	22.8
GPS-36	3	57797	-13.5	23.6

Tab: 1: SLR residuals to GPS satellites from **CO2** solution [mm].

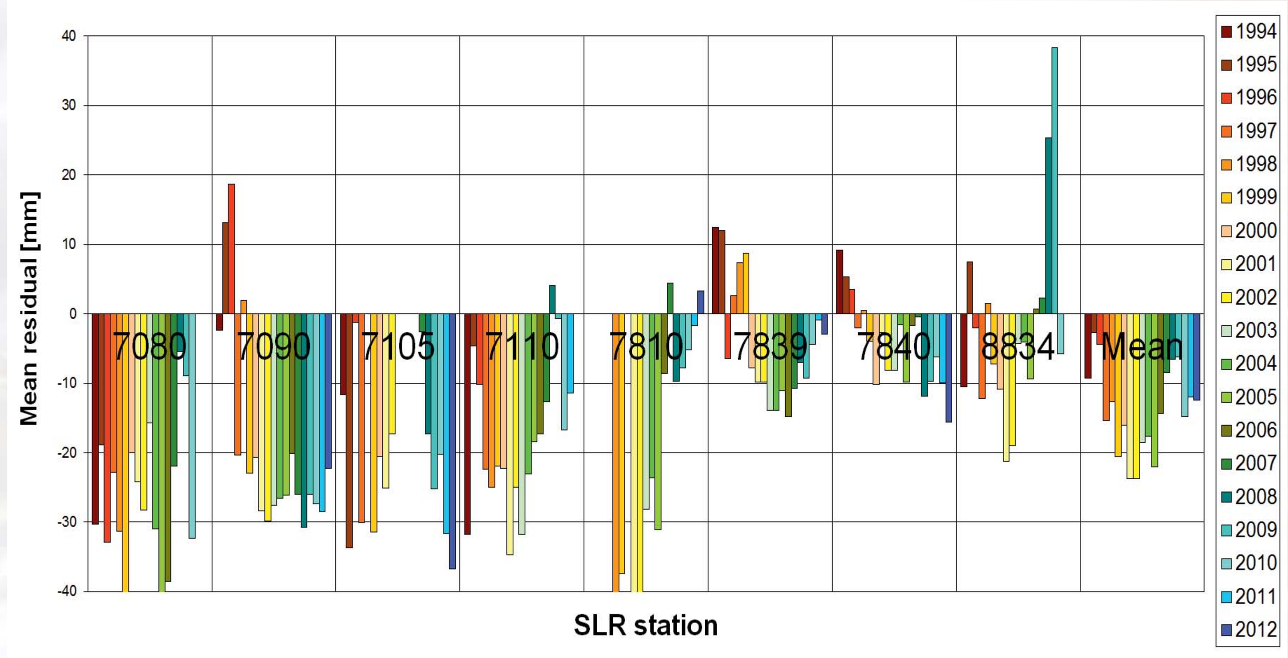

Fig: 3: Mean SLR residuals to GPS-36 satellite (**CO2**) for high-performing SLR stations.

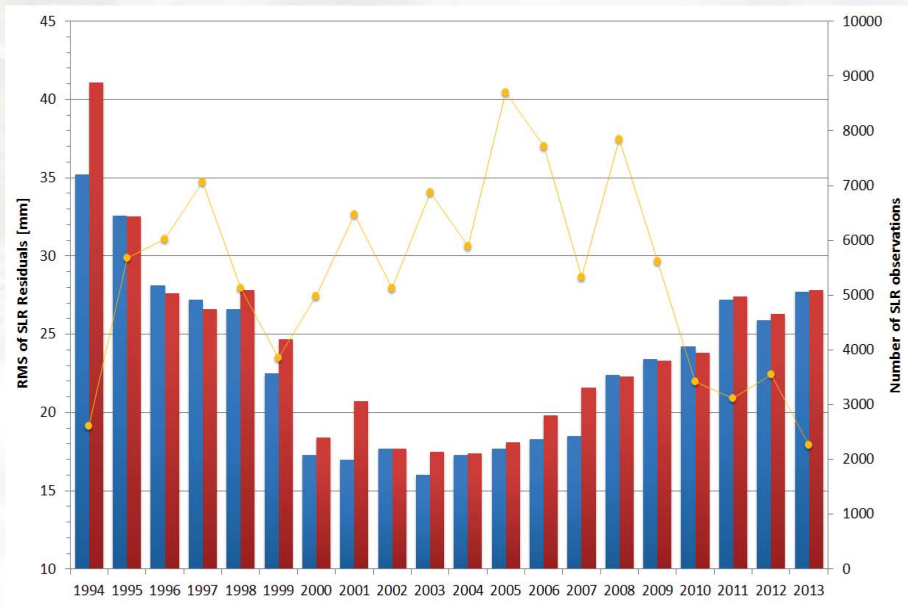

Fig: 4: RMS of SLR residuals to GPS satellites for **CO2** solutions (based on 3-day arcs) and **CF2** solutions (based on 1-day arcs).

	1st	2nd	3rd	4th	5th	6th	7th
CO2	2.8	3.6	2.8	0.7	0.5	1.1	0.2
CF2	4.5	5.1	2.1	1.4	0.5	0.8	0.7

Tab: 2: Amplitudes of draconitic harmonics from SLR validation of GPS-35 orbit [mm].

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 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 hollow circular arrays, or of 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 aluminium coated corner cubes, whereas the recently launched satellites have typically uncoated corner cubed retroreflectors (see Table 3).

Table 4 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 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 lauched after 2007 have in general smaller RMS of residuals than the GLONASS satellites lauched before 2007. GLONASS-M satellites with uncoated LRAs have a sligthly 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 lauched GLONASS without coating is also smaller (31.8 mm on average) than for GLONASS with coating (36.3 mm on average, see Figure 6). 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 is 0.92 and 1.15 mm, respectively (Ploner et al., 2014). Thus, the station- and satellite-specific range biases have to be considered when processing 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 dependance of mean residuals w.r.t. the time of observation, e.g., for GLONASS-124, see Fig. 7.

Type	ILRS No	SVN No	Slot	COSPAR	Plane	Coating	LRA Shape	No cubes	From	To	No obs	Mean offset	RMS
-	82	779	R01	1998-077A	1	Aluminium	Irregular planar	396	2002	2002	1194	2.6	44.9
-	86	790	R06	2001-053C	1	Aluminium	Hollow Greek Cross	124	2002	2002	4643	8.5	46.4
-	87	789	R03	2001-053B	1	Aluminium	Hollow Greek Cross	124	2002	2007	38546	-0.6	42.4
-	89	791	R22	2002-060A	3	Aluminium	Irregular planar	396	2003	2007	32509	-3.4	40.8
M	95	712	R08	2004-053B	1	Aluminium	Rectangular	112	2005	2013	23005	6.9	37.0
M	99	713	R24	2005-050B	3	Aluminium	Rectangular	122	2007	2009	18883	-2.5	40.8
M	100	714	R18	2005-050A	3	Aluminium	Rectangular	122	2009	2011	1686	11.2	55.2
M	101	715	R14	2006-062C	2	Aluminium	Rectangular	122	2009	2013	5345	4.2	38.0
M	102	716	R15	2006-062A	2	Aluminium	Rectangular	122	2007	2013	48798	12.1	37.5
M	103	717	R10	2006-062B	2	Aluminium	Rectangular	122	2009	2013	6002	13.0	40.4
M	105	719	R20	2007-052B	3	Aluminium	Rectangular	122	2009	2013	5108	6.5	33.3
M	106	720	R19	2007-052A	3	Aluminium	Rectangular	122	2009	2013	5248	5.8	28.5
M	107	721	R13	2007-065A	2	Aluminium	Rectangular	122	2009	2013	5757	-0.3	29.7
M	109	723	R11	2007-065C	2	Aluminium	Rectangular	122	2008	2013	41748	-12.8	39.8
M	110	724	R18	2008-046A	3	Aluminium	Rectangular	122	2009	2013	17985	0.8	32.5
M	111	725	R21	2008-046B	3	Aluminium	Rectangular	122	2009	2013	4535	3.0	35.9
M	113	728	R03	2008-067A	1	Aluminium	Rectangular	122	2009	2013	4603	-18.5	28.4
M	115	729	R08	2008-067B	1	NO	Rectangular	122	2009	2012	37183	-15.5	30.5
M	116	730	R01	2009-070A	1	Aluminium	Rectangular	122	2010	2013	5781	3.4	35.6
M	117	733	R06	2009-070B	1	Aluminium	Rectangular	122	2010	2013	4797	4.7	32.9
M	118	734	R05	2009-070C	1	Aluminium	Rectangular	122	2010	2013	19813	6.3	33.1
M	119	731	R22	2010-007A	3	Aluminium	Rectangular	122	2010	2013	4679	-0.4	29.9
M	120	732	R23	2010-007C	3	Aluminium	Rectangular	122	2010	2013	13249	1.2	33.1
M	121	735	R24	2010-007B	3	Aluminium	Rectangular	122	2010	2013	5535	6.6	32.7
M	122	736	R09	2010-041C	2	NO	Rectangular	122	2011	2013	2856	2.3	33.8
M	123	737	R12	2010-041B	2	NO	Rectangular	122	2010	2013	9769	-2.1	31.7
M	124	738	R16	2010-041A	2	NO	Rectangular	122	2011	2013	8780	1.3	33.7
K	125	801	R26	2011-009A	3	Aluminium	Hollow Circle	123	2011	2013	2969	-6.2	30.7
M	126	742	R04	2011-055A	1	NO	Rectangular	122	2011	2013	7204	1.8	32.5
M	127	743	R05	2011-065C	1	NO	Rectangular	122	2012	2013	3068	2.1	33.4
M	128	744	R03	2011-065A	1	NO	Rectangular	122	2011	2013	7678	-0.5	33.9
M	129	745	R07	2011-065B	1	NO	Rectangular	122	2011	2013	13820	-0.8	31.2
M	130	746	R17	2011-071A	3	NO	Rectangular	122	2011	2013	16738	-4.8	31.7
M	131	747	R02	2013-019A	1	NO	Rectangular	122	2013	2013	1655	6.6	38.7

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.

Type		Mean offset	RMS
GLONASS-M	coated	2.1	36.3
GLONASS-M	uncoated	-5.9	31.8
GLONASS-M	Plane 1	-2.6	32.8
GLONASS-M	Plane 2	0.6	37.1
GLONASS-M	Plane 3	0.4	34.4
GLONASS		-1.2	42.0
GLONASS-M		-0.4	34.9
GLONASS-K		-6.2	30.7

Tab: 4: SLR residuals to GLONASS from **CO2** solution [mm].

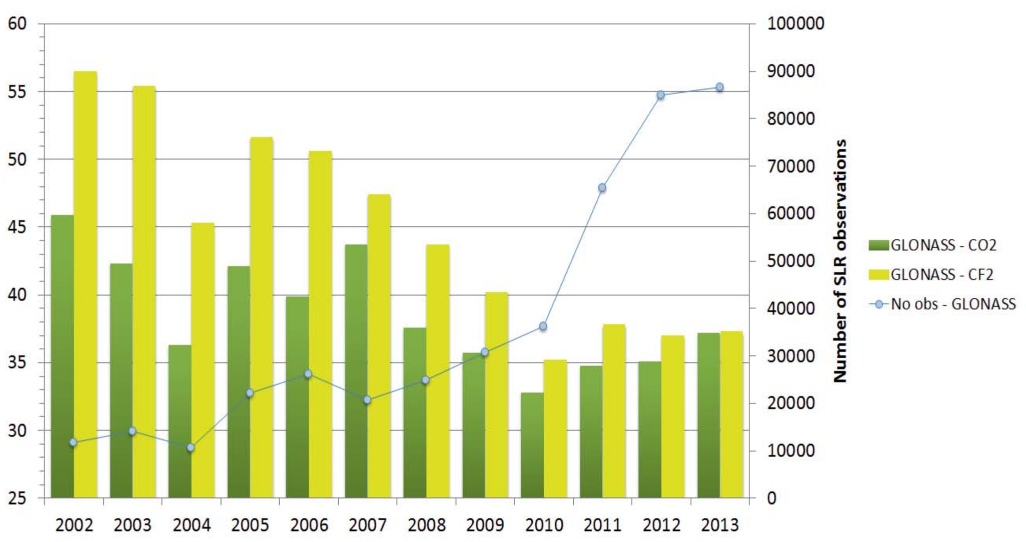

Fig: 6: RMS of SLR residuals to GLONASS satellites for **CO2** solutions and **CF2** solutions [mm].

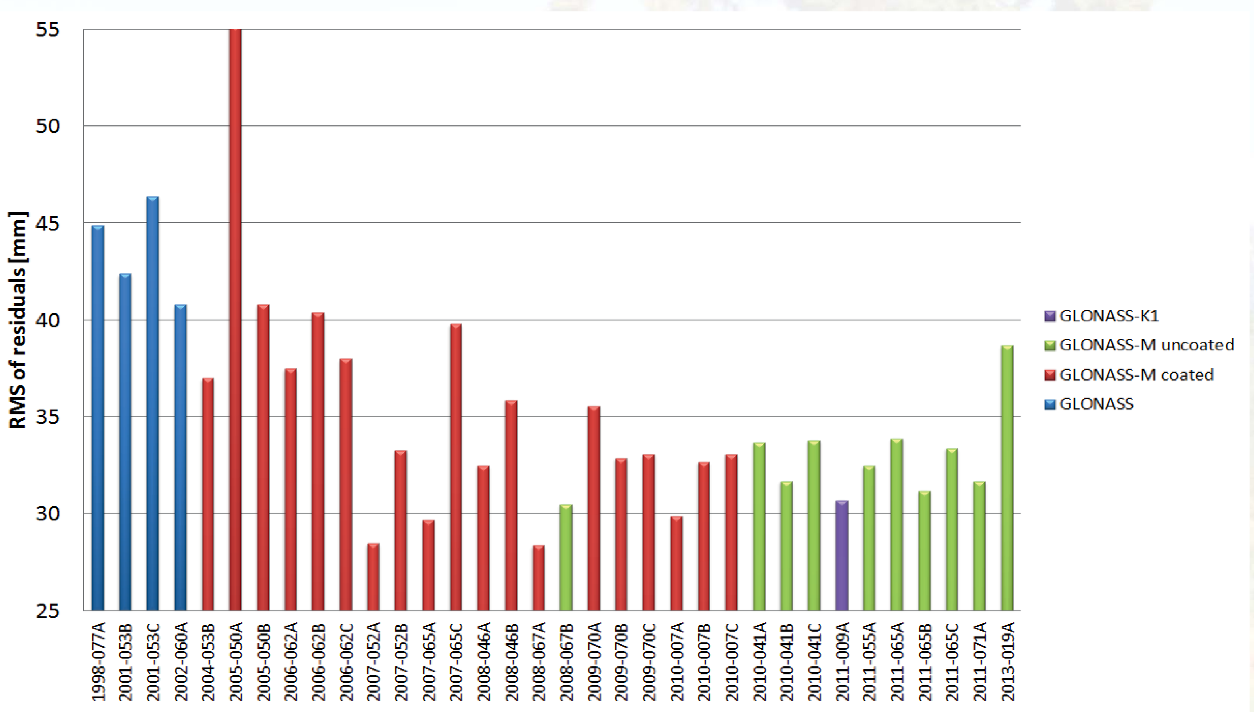

Fig: 5: RMS of SLR residuals as a function of GLONASS satellite type and coating from **CO2** solution. Satellites are sorted according to the lanch date.

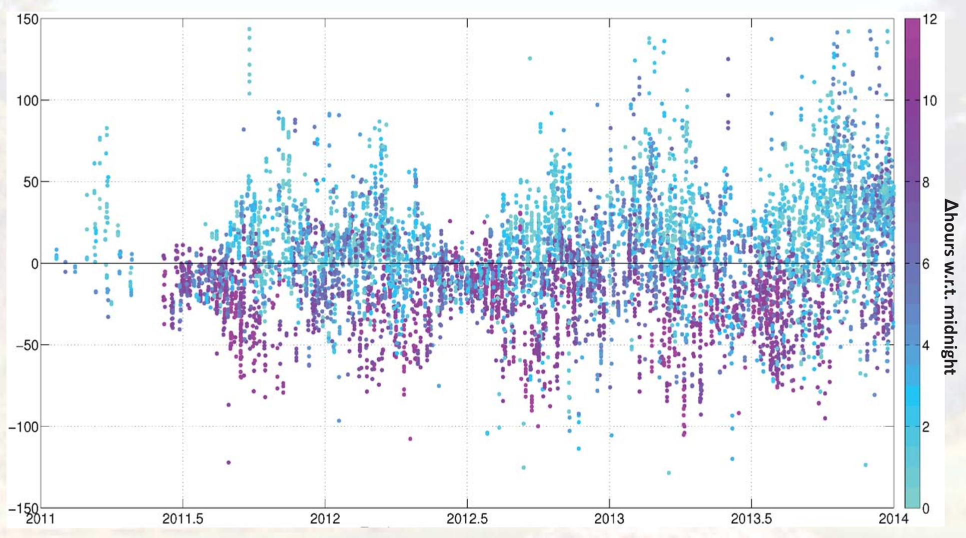

Fig: 7: Dependance of SLR residuals to GLONASS-124 on the local time of observation from **CO2**. Day-time obs. are shown in magenta, night-time obs. in cyan. Values in mm.

Summary

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 (see Fig. 8). The mean SLR residuals to GNSS s/c are at a level of 23 and 35 mm for GPS and GLONASS, respecively. The **CO2** CODE repro2 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/block (see Tab. 3),
* Shape and size of LRA, and number of corner cubes in LRAs (see Tab. 3)
* 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, 6).

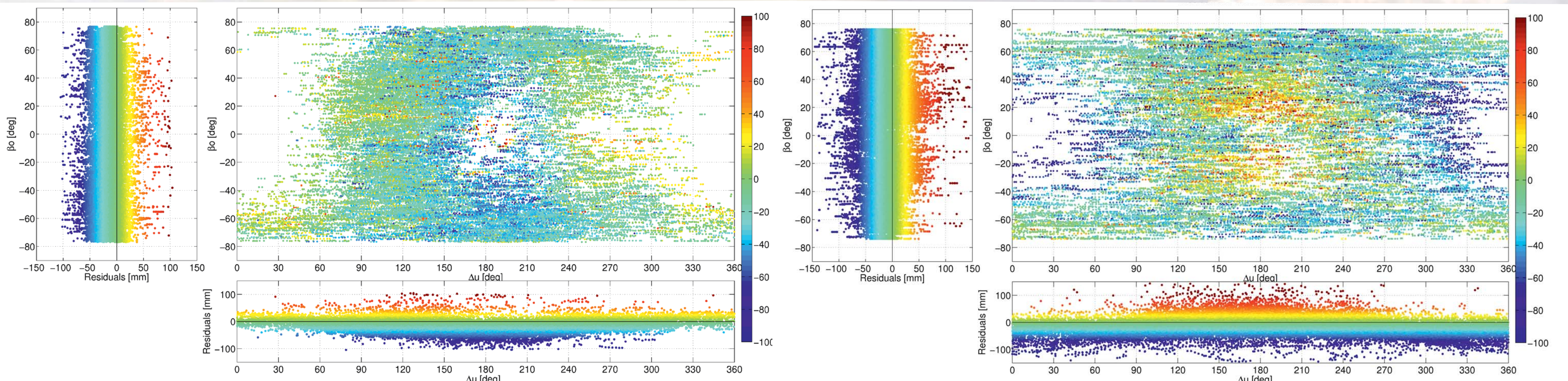

Fig: 8: Relationship between the SLR residuals, argument of satellite latitude Δu, and the Sun elevation angle over orbital plane β for GPS (left) and GLONASS (right) from **CO2**. Small variations of mean biases can be observed for different arguments of satellite latitude w.r.t. the Sun. E.g., for GPS when Δu 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.

References

Ploner M., J. Utzinger, P. Lauber, M. Prohaska, P. Schlatter, P. Ruzek, T. Schildknecht, K. Sośnica, A. Jäggi; 2014: Status of the Zimmerwald SLR station. Proceedings of the 18th International Workshop on Laser Ranging, 11-15 November 2013 Fujiyoshida, Japan.

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