Ranging the GNSS Constellation

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Laser ranging is an indispensable independent tool for validating the precise orbits determined for GNSS satellites using microwave pseudorange observations since decades. SLR allowed it to identify orbit modeling issues. Including albedo radiation pressure and antenna thrust, among others, into the GPS orbit model allowed it to basically eliminate the observed SLR bias. For the first Galileo satellites SLR residuals indicated severe orbit modeling issues caused by the different shape of Galileo compared to GPS satellite bodies. In future all GNSS satellites will be equipped with Laser retro reflectors, a big challenge for the ILRS concerning tracking scenarios and observation planning to make economic use of the ground equipment.

1. Validation of GNSS Orbits

In 1964, only four years after T. H. Maiman built the first Laser, first echoes were obtained from NASA's Explorer 22 satellite (Plotkin et al., 1965; Degnan, 1985). Satellite Laser Ranging (SLR) rapidly developed to an indispensable tool for precise orbit determination, gravity field determination, and Earth system research (Pearlman et al., 2002). Since the early 1990's ILRS started to track Global Navigation Satellite System (GNSS) satellites supporting the independent validation of the microwave-derived precise orbits. The two GPS satellites SVN35 and 36 equipped with retro reflectors were routinely tracked from their launch 1993 resp. 1994 until their decommissioning 2013 resp. 2014 (as SVN36 was reactivated 2015 data is available until that year). Also in the 1990's ILRS started to track GLONASS satellites in support of the International GLONASS EXperiment (IGEX-98, Willis et al., 2000).

Range residuals of GPS and GLONASS satellites were studied in the early years by different groups (Degnan and Pavlis, 1994; Pavlis and Beard, 1995; Watkins et al., 1996; Zhu et al., 1997; Eanes et al. 1999; Appleby and Otsubo, 2000; Ineichen et al., 2000; Springer, 2000; Urschl et al., 2007; Flohrer et al., 2008; Sósnica et al., 2015). Most of the analyses showed a bias of about -5.5 cm for GPS satellite orbits derived from microwave tracking data by the International GNSS Service (IGS) while the accuracy was estimated to about 5 cm. For GLONASS orbits a negative bias of about -4 cm was identified too. The accuracy of the orbits was however at the 10-15 cm level. These validation results supported several model improvements for GPS orbits, in particular of solar and Earth albedo radiation pressure (Ziebart et al., 2007, Rodriguez et al., 2012), and antenna thrust, reducing the observed SLR bias to 1.3 cm (Sósnica et al. 2015) and the standard deviation to about 2 cm for GPS.

Also for the new satellite systems SLR plays an essential role for calibrating improved radiation pressure models. For Galileo satellites of early orbits generated using the classical extended CODE radiation pressure model (Beutler et al, 1994) in the framework of the IGS Multi GNSS Pilot Project (MGEX, Montenbruck et al. 2014) SLR residuals of up to 20 cm were measured for phases with low elevation of the Sun above the orbital plane. The origin of this behavior is the elongated shape of the Galileo satellites compared to the cubic shape of GPS satellites, causing much larger variations of the satellite cross section exposed to the Sun while orbiting the Earth. The SLR residuals triggered the development of improved radiation pressure models for Galileo satellites (Arnold et al., 2015; Montenbruck et al., 2015a). As the estimated longitude of geostationary GNSS satellites such as the Chinese BeiDou (or Compass) satellites is highly susceptible to biases due to their small motion with respect to the tracking stations SLR may play an important role for precise orbit determination of this category (Zhao et al., 2013). For the Indian Regional Navigation Satellite System (IRNSS) recently renamed to Navic no publicly available microwave tracking data yet exist. Precise orbit determination thus highly relies on SLR observations (Montenbruck et al., 2015b).

2. More Applications of SLR for GNSS

Because GNSS is a one-way measurement technique only pseudoranges can be measured and clock synchronization is indispensable for positioning and orbit determination. Radial orbit errors can thus be absorbed to a large fraction by satellite clock corrections. For the very stable clocks onboard Galileo satellites the SLR residuals show the same behavior as the clock corrections indicating that the clock corrections are in fact radial orbit errors (Svehla et al., 2013). SLR thus allows it to break this correlation and to separate radial orbit errors and satellite clock corrections. This makes it possible to study, e.g., temperature-induced clock variations and to characterize the physical behavior of on-board clocks.

Separation of orbit errors and satellite clock variations is crucial for using the first two FOC Galileo satellites that were released on a wrong orbit for relativistic experiments. The two satellites of a dual launch on 22. August 2014 were put to an orbit with an initial eccentricity of 0.233 and orbit height of 19'800 km due to a malfunction of the launcher third stage. With a sequence of maneuvers the satellite orbit height could be increased to 22'600 km (compared to 23'200 km) and the eccentricity decreased to 0.156. The satellites are however fully functional and the very stable hydrogen masers onboard should allow to improve the uncertainty of the relativistic redshift parameter α beyond the current value determined in 1976 with Gravity Probe A (Vessot et al., 1980). Regular SLR tracking of the two satellites plays an essential role in this experiment in order to separate clock variations due to orbit errors and caused by gravitational redshift (Delva et al., 2015).

Eventually SLR may also be used as tool for high precision time synchronization of stable GNSS clocks combining Laser one-way with two-way, similar to the concept of the European Laser Timing (ELT) experiment foreseen onboard ACES (Schreiber et al., 2009) and already tested for BeiDou satellites (Meng et al., 2013).

3. SLR Tracking of the GNSS Constellations

In the near future more than 100 GNSS satellites carrying retro reflectors will be operational. GPS Block III satellites will carry reflectors, too, starting with SV-9 (Miller et al., 2013). Tracking the full GNSS constellation will pose a big challenge for the ILRS concerning economic use of its ground equipment. Optimized tracking scenarios and session planning strategies will be indispensable.

Already today ILRS is regularly tracking a large number of GNSS satellites. Table 1 shows the number of normal points of GNSS satellites available at the ILRS data centers since 2000. As part of the LARGE project of the ILRS the tracking of GLONASS satellites was extended to the entire satellite constellation as shown in Figure 1.

Table 1: Number of normal points per year per GNSS system.

	2010	2011	2012	2013	2014	2015	2016
GPS	3369	3331	3339	2318	647	151	0
GLONASS	36929	74094	83715	77947	109169	106526	80362
Galileo	0	846	13337	19374	16857	24746	36651
BeiDou	8663	9453	8041	7289	8342	6663	7576
Navic	0	0	0	474	2637	2158	2027

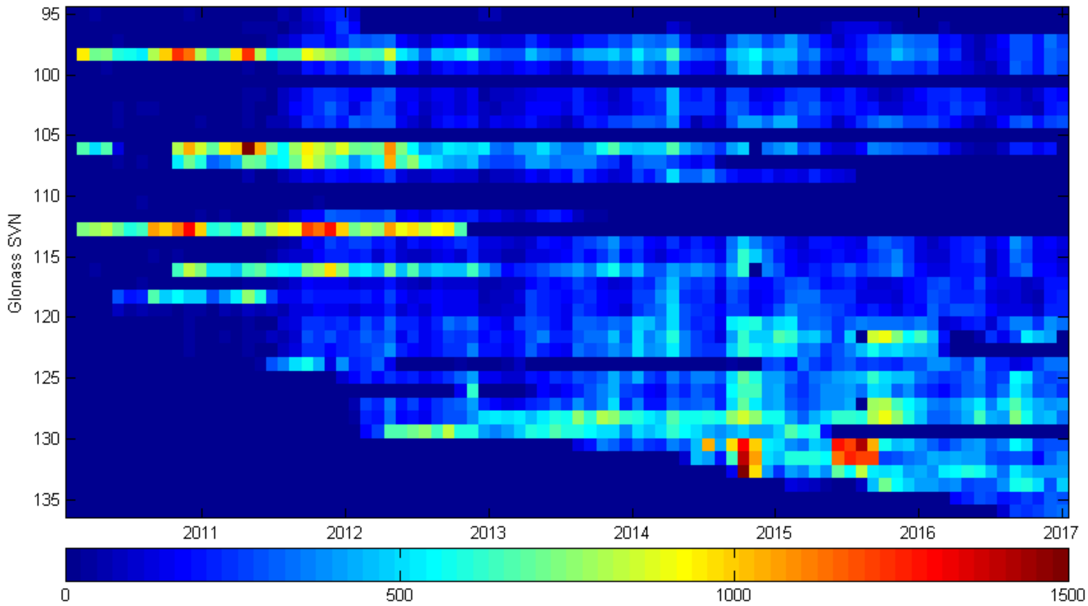

Figure 1: Number of SLR normal points per month for GLONASS satellites.

In order to assess the capability of SLR for GNSS precise orbit determination based on number of tracking stations and distribution of observations, a simple simulation was performed. The covariance analysis included observations of a single SLR station resp. of a network of 6 and 17 globally distributed stations. Per station three normal points are acquired per satellite pass for a simulated full 24-satellite Galileo constellation, two at 30° rising and setting elevation and one at culmination. No unfavorable weather conditions were considered and observations of different stations were assumed to be uncoordinated.

Formal errors of the determined orbits are shown in Figure 2 for the radial, along-track, and cross-track component. As expected, orbits determined with observations from one day of a single stations reach formal errors at the few 10 km range (first row left). If observations from three days are used for orbit determination the errors on the middle day reduce to about 100 m (first row right). The situation significantly improves if a global network of 6 stations is considered, already for a single day of observations an orbit precision of a few decimeters is reached (second row left) while the orbit uncertainty further decreases to a few centimeters if observations from three days are used (second row right). If however, in order to reduce number of observations per pass, only measurements at satellite culmination are acquired, the orbit precision is at the kilometer range for a six station network and observations from one day (third row left) and at the meter level if observations from three days are used (third row right). Three normal points per pass for a 17 station network the orbit precision reaches a few centimeters already within one day (last row left) and about 1 cm for observations from three days (last row right). It has to be noted that the covariance analysis does not consider any systematic observation or orbit modelling error.

This simulation is very simple and not very realistic but nevertheless indicates the capability of precise orbit determination for GNSS satellites using a limited number of observations per station. The simulations demonstrate two facts: Firstly, already only 2-3 normal points per satellite of a GNSS constellation occupies a significant fraction of observation time of a station. Typically a mid-latitude station can acquire about 60 normal points per day for a 24-satellite constellation, accumulating to several hours of observation time per day. Secondly, the improvement in formal orbit inaccuracy does only increase with the square root of the number of stations. More important than the number of normal points is their distribution along the orbit requiring SLR observations from several stations distributed over the globe.

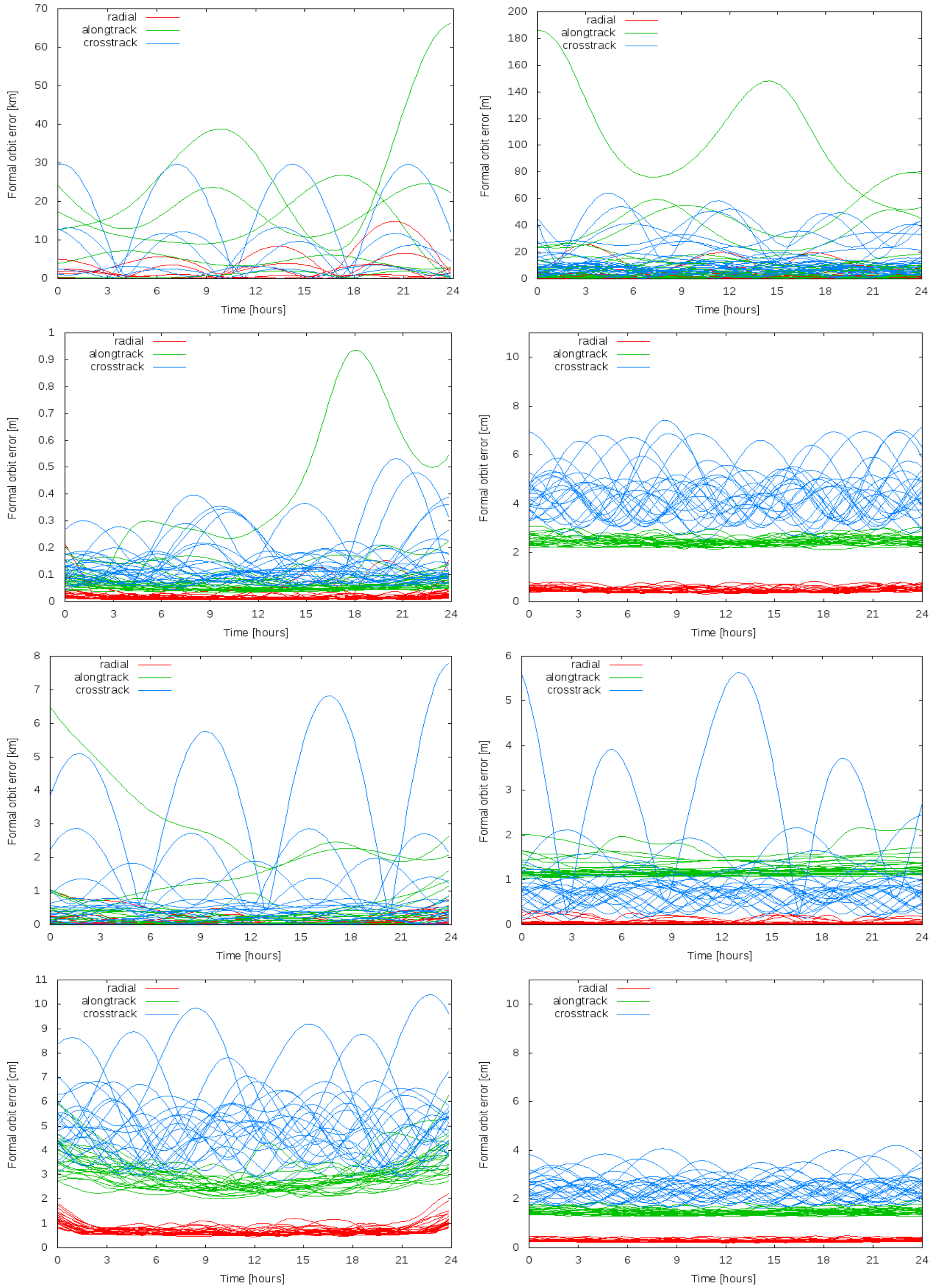

Figure 2: Formal errors of Galileo orbits in radial (red), along-track (green), cross-track (blue) directions. First row: 1 SLR station, 1 day arc (left), middle of 3 day arc (right); second row: 6 stations, 1 day arc (left), 3 day arc (right); third row: 6 stations with tracking only at culmination, 1 day arc (left), 3 day arc (right); fourth row: 17 stations, 1 day arc (left), 6 day arc (right). Y-axis in meters, note different scaling for different figures.

These two findings make it obvious that a coordination between SLR stations is indispensable to make economic use of the observing time of SLR stations while providing good coverage of normal points along all satellite orbits. In order to cope with weather conditions this coordinated scheduling of GNSS SLR tracking may have to be optimized in real time.

4. Conclusions

SLR plays an important role since decades for validating GNSS derived satellite orbits. For new GNSS constellations and new orbit types SLR proves to be essential to calibrate new radiation pressure models and allows to separate orbit- and temperature-induced variations of on-board clocks. Eventually the role of SLR becomes even more important by contributing to precise orbit determination of GNSS satellites. Given the large number of GNSS satellites from several constellations equipped with reflectors coordination of observation scheduling among SLR stations will be crucial to optimize the benefit-to-cost ratio. Eventually SLR observations may contribute, together with microwave observations, to provide operational high-precision orbit products for all GNSS constellations jointly by ILRS and IGS in the framework of GGOS.

Concerning the distribution of SLR observations over the constellations the following conclusions may be drawn:

- For the validation and calibration of radiation pressure models it is sufficient to acquire well-distributed observations along the orbit of one satellite for each block type for a range of Sun elevations above the orbital plane, i.e., of one satellite block type per orbital plane.
- For contributing to precise orbit products, optimally combined with microwave GNSS observations, the tracking of all satellites of the constellation is needed. This requires a coordinated scheduling of observations among SLR stations.
- For determination of the gravitational redshift parameter using the two Galileo satellites on eccentric orbit a good coverage of the orbits of both satellites is required (as long as the satellites run on the on-board hydrogen maser).
- For BeiDou and Navic geostationary satellites an SLR coverage is needed for all satellites in order to resolve biases in the microwave tracking technique.

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