Comparison on orbit precisions of different types of navigation satellites based on SLR tracking data

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Abstract. *SLR orbits of navigation satellites, including parts of GPS, GLONASS, Galileo and China's BeiDou (Compass) are evaluated and compared quantitatively. Given the amount of SLR tracking data, 7-day arcs are calculated. The post-fit residuals are a few centimeters universally. For MEO, the 3D RMS of orbit overlaps (2-day over 7-day) or comparisons with microwave orbits (7-day) are tens of centimeters, and the radial precisions are around 4-10 centimeters. The results of GLONASS satellites are slightly better than those of GPS or BeiDou in this analysis, which may be caused by different quantities of tracking data. The orbit precisions of MEO are better than GEO/IGSO (in BeiDou system) generally. Sparse observational data and non-homogeneous tracking network throw serious effects on SLR-only orbit determination of navigation satellites.*

Introduction

Multiple global and regional satellite navigation systems, including GPS of USA, GLONASS of Russia, Galileo of EU, BeiDou (BD, Compass) of China, QZSS of Japan and IRNSS of India, are in the process of enhancement or construction. SLR, as a powerful tracking tool of space targets, has been implemented on tens of navigation satellites, of which majority are running in MEO (Medium Earth Orbit), and minority are running in GEO (Geostationary Earth Orbit), IGSO (Inclined GeoSynchronous Orbit) or some other types of orbits.

For navigation satellites, SLR has been taken as a precise orbit determination (POD) method (e.g. Deleflie 2006, Steigenberger 2011, Zhao 2013) or an independent way of external validation for microwave orbits (e.g. Appleby 2000, Urschl 2007, Steigenberger 2011, 2013). This paper summarizes the status and characters of SLR observation on some major navigation satellites in recent years, describes the framework of SLR-only POD processing, assesses the SLR orbit accuracy by the form of internal fitting, orbit overlap and orbit comparison, and make discussion and recommendation on our results.

SLR observation

SLR tracking on navigation satellites began in the early 1990's. The concerned targets in this work include GPS (35/36), GLONASS (102/109/110/118/129/130), Galileo (101/102/103/104 & GIOVE A/B) and BeiDou MEO (M1/M3), BeiDou GEO (G1), BeiDou IGSO (I1/I3).

Based on the statistics of SLR Normal Point data (including CSTG format and CRD format) in an 8.5-year period from Jan, 2005 to Jun, 2013, a total of 38 SLR stations, covering most of the active stations, implemented tracking on these targets. Number of participator stations is around 30 for each MEO, 7 for each GEO and 14 for each IGSO. The temporal distribution of data is quite uneven, and sparseness or fairly large gaps present sometimes. The spatial distribution of sub-satellite points is asymmetry: there are more stations in the northern than in the southern hemisphere, and more in the eastern than in the western hemisphere. Tracking difficulty sequence from easier to harder is as the follows: GLONASS, Galileo, BeiDou MEO, GPS, BeiDou IGSO, BeiDou GEO.
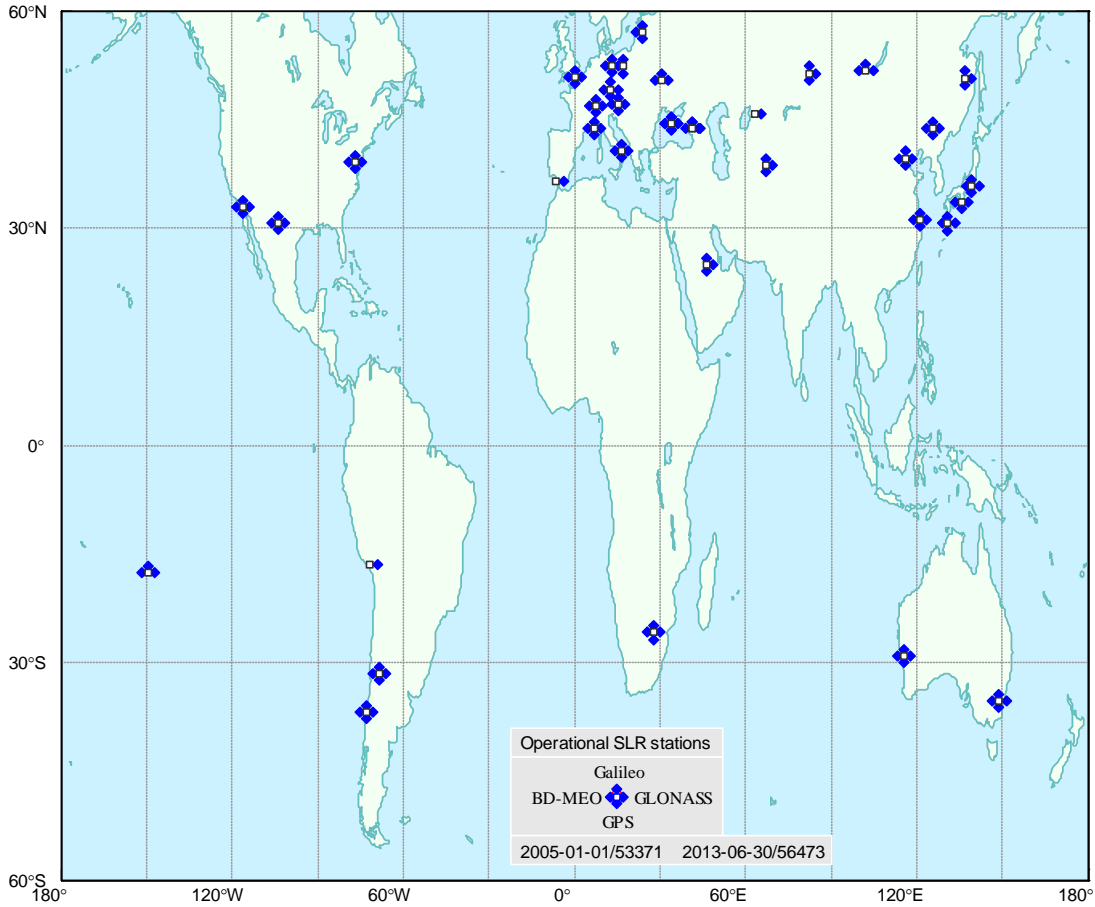
Figure 1. Geographical distribution of SLR stations (for MEO navigation satellites).

Table 1. Temporal density of SLR observation on navigation satellites

Satellite series	GPS	GLONASS	Galileo	BD MEO	BD GEO	BD IGSO
Daily mean (points)	12	20	18	17	7	9

POD Strategy

Fully dynamic approach, least-squares estimation and batch processor are implemented in SLR POD procedure. Considering the tracking data quantities, 7-day arc length is adopted in trajectory integration. The basic reference frame is J2000.0 inertial system and ITRF2000 coordinate system.

The adopted dynamic models are as the follows: GGM02C gravity model (truncated to 20×20 for MEO, 10×10 for GEO/IGSO); JPL DE405 ephemerides; solar radiation pressure (simple Box-Wing); additional Y-bias; Wahr solid tide model; CSR4.0 ocean tide model; Schwarzschild general relativistic effect; RTN empirical acceleration.

The adopted measurement models are as the follows: laser center-of-mass correction; tropospheric delay; relativistic delay; station eccentricity correction; solid tide correction; ocean tide loading; tectonic displacement.

The estimated parameters include: satellite initial state vector (3D position and velocity); solar radiation pressure coefficient; Y-bias coefficient; harmonic T/N empirical acceleration coefficients. All parameters are estimated globally.

Attitude control mode should be clarified in the calculation of non-conservative forces and center-of-mass correction. GPS, GLONASS, Galileo, BeiDou MEO and BeiDou IGSO belongs to yaw-steering mode in general (certain axis could be along negative direction), in which Z axis towards nadir, Y axis perpendicular to sun-earth-satellite plane, and X axis orthogonal with Y and Z axis. While BeiDou GEO belongs to yaw-fixing mode, in which Z axis towards nadir, Y axis perpendicular to instantaneous orbital plane, and X axis orthogonal with Y and Z axis.

Orbit internal accuracy

Expressed as RMS of residuals, internal accuracies show the fitting level of SLR tracking data to SLR orbit, and are calculated to the arcs containing no real or suspicious maneuver or attitude adjustment moment.

For each MEO, internal accuracy is around 2-4 cm; for each GEO or IGSO, internal accuracy can be better than 1cm. The utilization ratios of SLR data are over 85% usually.
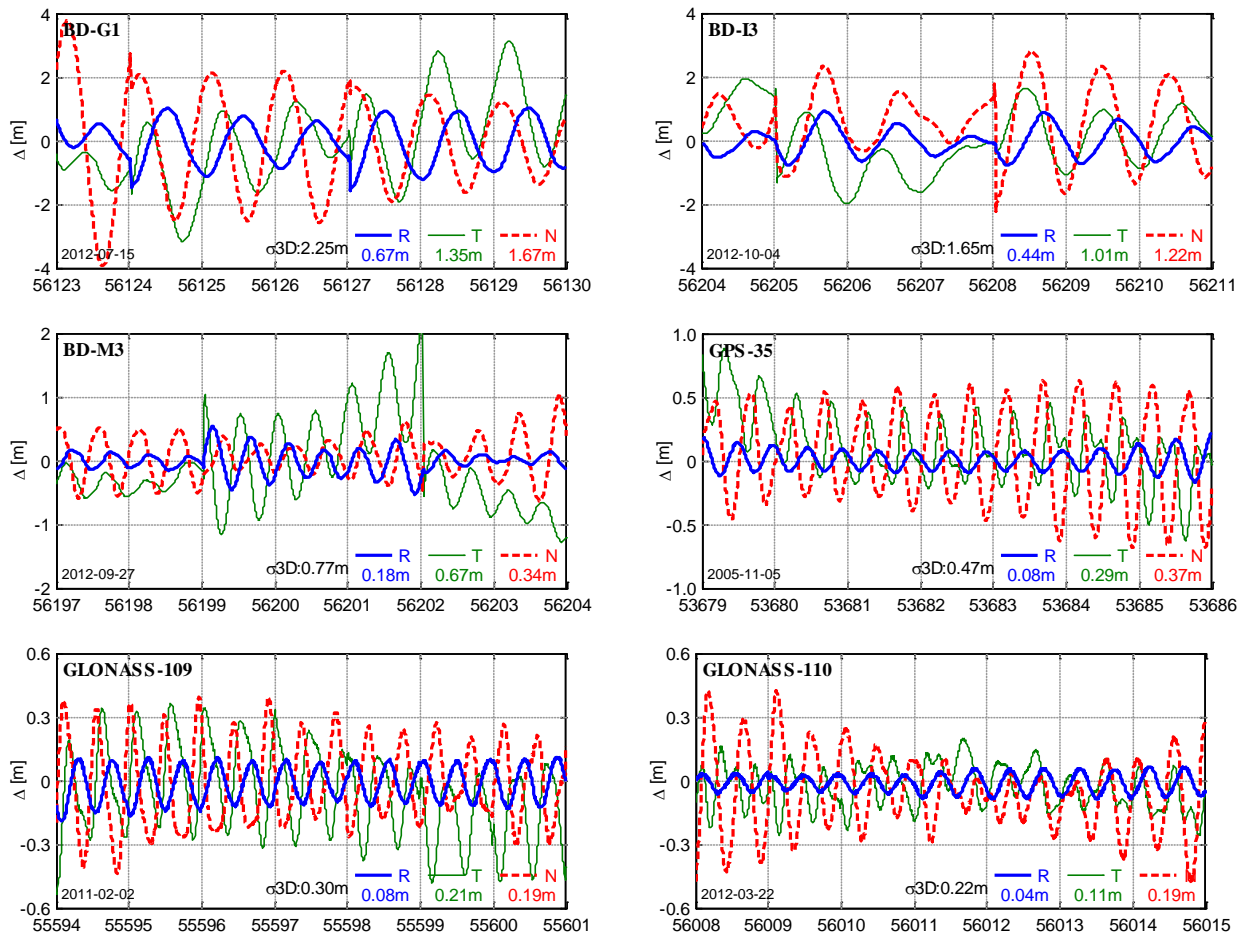
Orbit comparison

For current navigation satellites, multi-frequency microwave pseudo-range and carrier-phase signals are the major data sources in POD processing. Independent from microwave observation, SLR is almost the only other valuable technique for orbit precision analysis. For GPS and GLONASS satellites, GNSS sp3 final precise orbits are taken as reference orbits in comparison; for BeiDou satellites, microwave orbits are taken as reference orbits. The differences in 3D position and in direction R, T and N are important reflection of SLR orbit precisions.

Temporal and spatial distributions of SLR data throw great impact on the fitting of two types of orbits. The differences in R, T and N direction are relevant to the satellites' orbital periods : amplitudes of the differences present one oscillatory cycle per day for GEO and IGSO, while present two oscillatory cycles per day for MEO, which are the consequences of errors in satellites' spatial attitude control or relative model fitting. The oscillation frequencies of differences in 3D positions are twice as in R, T or N direction, which are the results of inter-modulations of periodic signals with different phases.

For GEO, the agreement between two types of orbits is the lowest: 3D position RMS more than 2m, R component more than 0.5m; for IGSO, the agreement is moderate: 3D position RMS around 1-2m, R component around or less than 0.5m; for MEO, the agreement is highest.

For MEO, GPS and BeiDou MEO show low-degree fitting compared with GLONASS on average: for GLONASS, 3D position RMS can be on the level of 20-30cm quite frequently; for GPS or BeiDou MEO, 3D position RMS 0.5m is fairly good. This situation can be attributed to two possible reasons: difference on SLR observation density or Box-Wing model accuracy. The difference in R direction is on the level of several cm.

For all of the navigation satellites, radial differences are smallest in general. In some cases, the differences in N direction are greater than those in T direction, and systemic biases or drifts present, especially in T direction and at the edges of the arc, which might be caused by the rather poor geometric configuration of SLR observation.
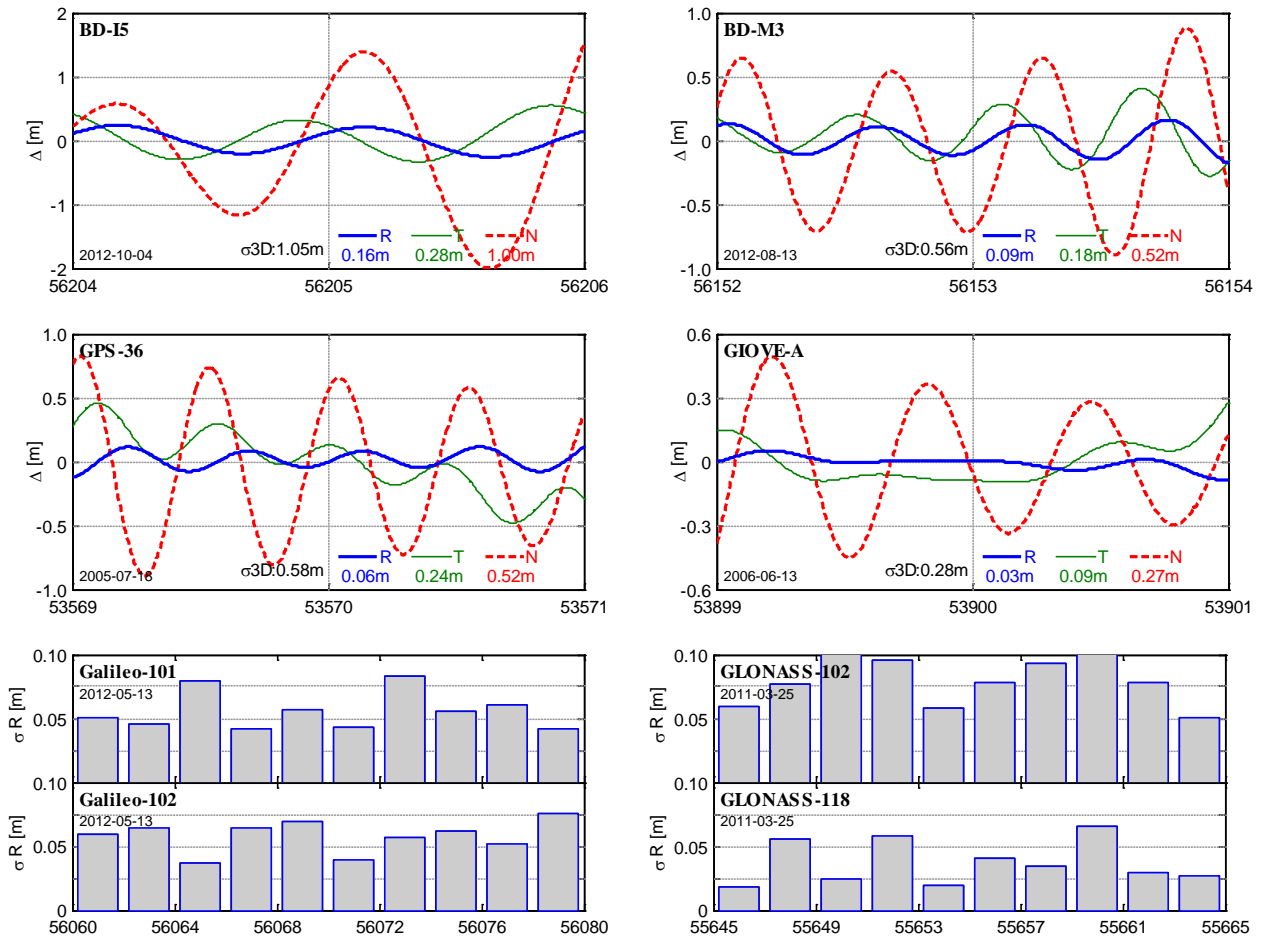
Figure 2. Comparisons between SLR orbits and microwave orbits.

Orbit overlap

2-day overlap window can be obtained from a pair of 7-day orbit arcs with 5-day difference in initial epochs. The SLR observations in such overlap window are same, but the orbits in two arcs are estimated independently and can be considered as uncorrelated. The difference in overlap window is an indication of POD quality. Compared with direct orbit comparison, overlap comparison needs the support of longer stable SLR tracking.

The differences in overlap window also show periodic characters relevant to the satellites' orbital periods. The rank of overlaps agreement in descending order is: MEO, IGSO, MEO, similar to orbit comparison. The overlaps differences in R, T and N direction also share similar characters to orbit comparison. In N direction, the difference is more significant. In R direction, the difference can be well below 10cm.

Figure 3. Overlaps between SLR orbits and microwave orbits

Summary & Perspectives

SLR orbits of certain navigation satellites, including GPS, GLONASS, Galileo and BeiDou are evaluated and compared quantitatively. Given the amount of SLR tracking data, 7-day arcs are calculated.

The post-fit residuals are a few cm universally. For MEO, the 3D RMS of orbit overlaps (2-day over 7-day) or comparisons with microwave orbits (7-day) are tens of cm, and the radial precisions are around 4-10 cm. The results of GLONASS satellites are slightly better than those of GPS or BeiDou in this analysis, which may be caused by different quantities of tracking data. The orbit precisions of MEO are better than GEO/IGSO generally.

For navigation satellites, SLR is almost the only independent POD method besides microwave solution. Global ILRS network provides the possibility of continuous tracking on multiple types of navigation satellites, but its support to POD needs to be strengthen. More stations with better geometry and intensive monitoring will be beneficial to take the potential advantage of SLR.

Further improvement in SLR POD processing would lie in accuracy of laser center-of-mass offset, refinement of POD modeling (e.g. solar radiation pressure), and proper parameter estimation configuration (piecewise methods, number of empirical parameters, etc). The verification and origin of systemic biases between SLR and microwave orbits need to be further investigated.

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