The SLR Contribution to Precise Orbit Determination in the GPS Era

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Abstract

Precise Orbit Determination (POD) of Low Earth Orbiting (LEO) geodetic satellites has long relied on the high accuracy and robust tracking data provided by the global Satellite Laser Ranging (SLR) network. In fact, for nearly three decades SLR has been the primary tracking data for numerous high-profile geodetic satellites such as LAGEOS and TOPEX/Poseidon. Over the past decade significant advances in the Global Positioning System (GPS) itself, and GPS data processing algorithms and data distribution, have positioned this technology as the primary tracking technique to support POD in the new era of geodetic satellites. High-profile geodetic missions such as CHAMP, Jason-1, GRACE and ICESat all carry aboard a dual-frequency codeless GPS receiver as the primary POD tool. With this development, the role of SLR in POD has changed, but it continues to fulfill an essential role. Experience with CHAMP and Jason-1 POD has demonstrated that the SLR tracking is an invaluable tool in the calibration and validation of the GPS orbit solutions. POD processing of GPS one-way measurements is quite complex requiring the orbit determination of over 27 satellites and the estimation of a plethora of system parameters (e.g., clock, ambiguity biases, tropospheric scale biases). The unambiguous, direct ranges obtained from SLR systems provide a high-accuracy (i.e., sub-cm level) absolute observation of the orbit. This characteristic has been invaluable in calibrating the GPS solutions, and validating and improving their accuracy. Results from Jason-1 GPS orbit solutions will be discussed with a focus on the role and performance of the SLR tracking data.

Introduction

Satellite Laser Ranging (SLR) has long been the primary tracking tool for Precise Orbit Determination (POD) of geodetic satellites. For nearly three decades SLR has provided the primary tracking data for numerous high-profile geodetic missions such as LAGEOS and TOPEX/Poseidon (T/P). Much of the overall success of the T/P mission can be directly attributed to the remarkable improvement of the radial orbit accuracy over the original error budget and the continued delivery of high accuracy orbits [*Chelton et al.*, 2001]. The T/P POD is based on SLR and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) data as its primary tracking data. The current radial orbit accuracy being achieved for T/P (±2 cm) has significantly reduced orbit positioning as the dominant error source for altimeter investigations and represents a major achievement for both astrodynamic force modeling and laser tracking technology improvements [*Tapley et al.*, 1994; *Marshall et al.*, 1995].

We now enter a new era of geodetic missions with even more stringent requirements for POD accuracy. For example, the Jason-1 mission, being the follow-on to T/P, has significantly higher expectations with a ±1 cm radial orbit accuracy goal. In order to meet these aggressive POD accuracy goals, the new high-profile geodetic missions such as Jason-1, CHAMP, ICESat and GRACE all carry aboard a dual-frequency codeless GPS receiver as the primary POD tool. Over the past decade significant advances in the Global Positioning System (GPS) itself, and GPS data processing algorithms and data distribution, have positioned this technology as the primary tracking technique to support POD in the new era of geodetic satellites. The GPS data provide the near-continuous temporal coverage and the strong geometric distribution needed to meet the high-accuracy POD requirements of these new missions [*Haines et al.*, 2002].

Therefore, the question should be asked: does SLR still have a unique and important role for these new missions in terms of POD? Is SLR more than just a backup to the GPS tracking system? In order to explore the answer to these questions we will use data from the Jason-1 mission. Jason-1 provides an excellent POD test-bed with its four independent tracking data types, including near-continuous tracking from the dual-frequency codeless BlackJack GPS receiver, SLR, DORIS, and the altimeter range itself in the form of crossover constraints. Even more fortunate is the fact that the Jason-1 tracking data systems all represent a significant advancement over those used on T/P [*Haines et al.*, 2002]. Other missions such as CHAMP only have the GPS and SLR data, and therefore when considering the results obtained for Jason-1 the contributions from SLR serve an even more important role. The SLR data alone cannot support the POD goals of the Jason-1 mission. However, as will be shown in this paper, SLR has been invaluable in calibration, validation, and improvement of the GPS-based POD solutions.

SLR as a calibration tool

POD processing of the GPS one-way measurements is quite complex, requiring the orbit determination of over 27 satellites and the estimation of a plethora of system parameters (e.g., clock, ambiguity biases, tropospheric scale biases) [*Bertiger et al.*, 1994]. Our Jason-1 GPS-based POD processing uses double difference LC (DDLC) phase observables to account for clock errors [*Luthcke et al.*, 2003]. A typical 30-hour arc solution will have nearly 2000 ambiguity biases and tropospheric biases estimated every hour for each of the approximately 33 stations used in our GPS station complement. In order to fully exploit the near-continuous tracking provided by the GPS data we employ a reduced dynamic solution technique solving for empirical one-cycle-per-revolution (1-cpr) along-track and cross-track accelerations at a high rate (every 20 – 45 minutes) [*Rowlands et al.*, 1997]. The reduced dynamic technique can reduce the force mismodeling that arises from multiple sources (e.g., gravity and surface forces) that effect orbit solutions [*Yunck et al.*, 1994]. One of the greatest strengths of the GPS data is that they provide both the temporal and spatial observability to solve for a high frequency of empirical accelerations to account for dynamic modeling error [*Luthcke et al.*, 2003]. However, in order to fully exploit the GPS data towards this end, the complex measurement modeling must be done to a high degree of accuracy and the reduced dynamic parameterization must be “tuned” to get the optimal balance between force model and purely data defined orbital positioning.

The details of our reduced dynamic technique are given in *Rowlands et al,* [1997] and *Luthcke et al,* [2003], but for the purposes of this discussion it is important to know that the 1-cpr acceleration frequency (parameter / how many minutes), correlation time and correlation sigma must all be empirically derived, or “tuned” in order to produce the best possible POD solution. Therefore, a performance metric and, preferably, independent information is needed to discriminate among the various test solution parameterizations. As our solutions move to a more “reduced dynamic” solution, both the orbit overlap and GPS DDLC range residuals become more meaningless as an orbit precision and accuracy metric, since the orbit is forced to exclusively fit the data to an increasingly greater extent. When more parameters are estimated a better fit will obviously be obtained, but not necessarily a better orbit. Also, increasing the frequency of the empirical accelerations means that you have less independent data for each set of parameters during an orbit overlap period and therefore, the traditional orbit overlap tests for measuring precision become less indicative of the true orbit precision. For Jason-1, the independent SLR, DORIS and altimeter crossover data fit can be used as a performance indicator to discriminate between solutions when these data are withheld from the solution. However, for satellites such as CHAMP and GRACE, DORIS and altimeter crossovers are not available. Additionally, SLR data provide the only independent high-accuracy, direct and unambiguous observation of the orbit when testing GPS-derived solutions. The SLR data are quite easily modeled and included in the POD process for all arcs. Therefore, the SLR data fit is the most useful independent metric, and for some missions, the only independent metric to calibrate the complex GPS-based POD parameterization. For our Jason-1 POD solutions the SLR data played an invaluable role in calibrating our reduced dynamic parameterization: along-track and cross-track 1-cpr empirical accelerations every 30 minutes, 60 minute correlation time, 1.0E-9 m/s^2 correlation sigma. This calibration went a long way towards our GPS-based solutions reaching the 1 cm radial orbit accuracy goal [*Luthcke et al.*, 2003].

In addition to calibrating the reduced dynamic parameterization, the SLR data played a very important role in calibrating the Jason-1 GPS measurement model. In order to fully exploit the reduced dynamic solution technique, measurement modeling errors must be reduced. During the initial Jason-1 POD analysis of the GPS data we determined that there was a significant difference in the z-component (zenith) of the Jason-1 GPS antenna phase center offset from the *a priori* value (z-component delta). Further complicating the situation, the z-component delta exhibited a marked difference in magnitude between spacecraft attitude modes: approximately -4 cm in fixed yaw and about -6 cm in sinusoidal yaw. At JPL and then at GSFC we estimated an Antenna Phase Center map (APC map) from the GPS DDLC observations themselves [*Luthcke et al.*, 2003]. The GSFC map was developed by estimating parameters that describe the correction at each point on a 5x5 degree grid in antenna frame azimuth and elevation. The solution was determined using data from only twelve 30-hour arcs carefully selected to sample all attitude regimes from over 170 days worth of data. The new APC map makes a significant improvement in the overall accuracy of the GPS-based orbits and eliminates the need for an attitude-dependent average antenna offset correction. The new APC map is an important part of the Jason-1 POD process. The SLR data provided an invaluable independent metric for the calibration of this GPS APC map. Figure 1 shows the improvement in independent SLR residuals (all residuals, not just those acquired at high elevation) obtained using the GSFC APC map. The independent SLR residuals in Figure 1 have been confronted to GPS reduced dynamic solutions using the GSFC APC map and no map using the varying offset correction. The SLR residuals clearly demonstrate improvement over the entire time series with dramatic improvement in the fixed yaw attitude regimes. Table 1 shows the improvement in performance obtained by the calibration of the APC map and highlights the sensitivity and importance of the SLR data to provide an independent unambiguous assessment of POD accuracy.

Table 1. Jason-1 APC Map performance in GPS RD solutions:
residual summary for cycles 8-24.

APC Map	GPS DDLC RMS (cm)	Independent SLR RMS (cm)	Independent Xover RMS (cm)
No APC Map	0.942	2.308	5.843
GSFC APC Map	0.752	1.701	5.766

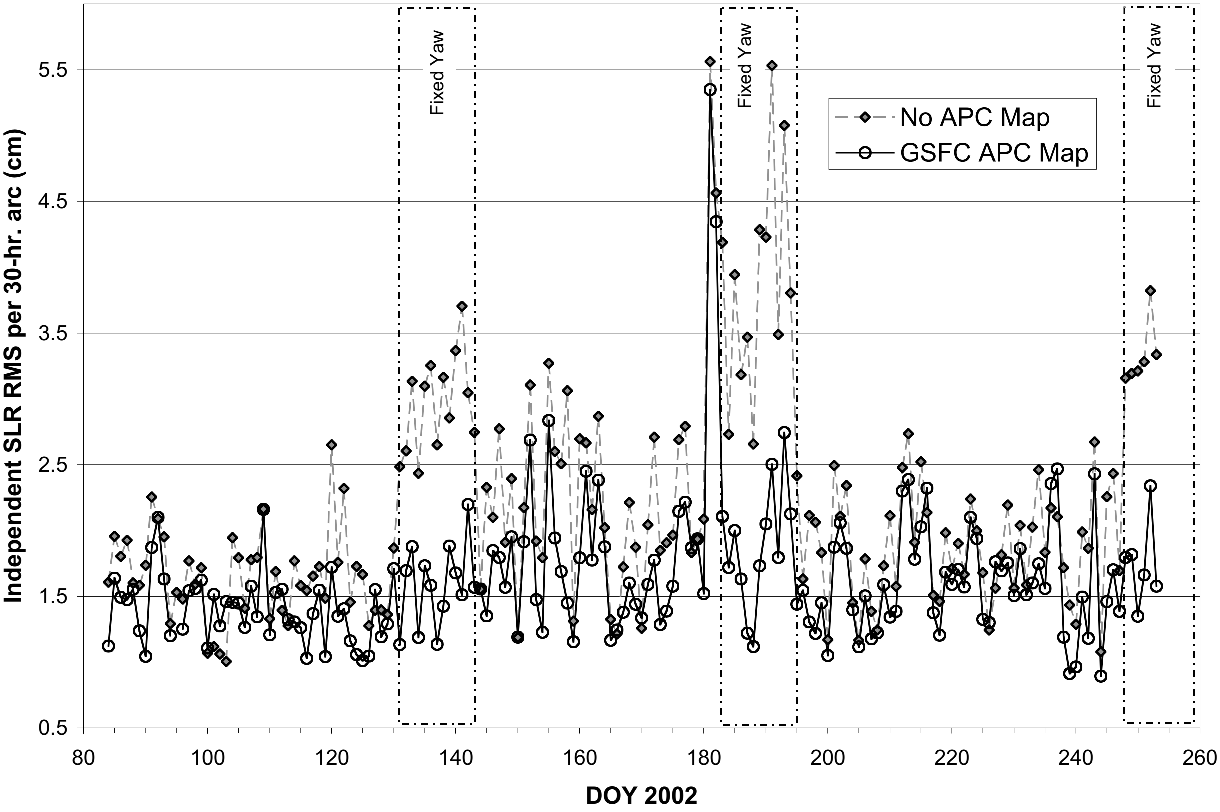

Figure 1. Jason-1 GPS APC map calibration – Independent SLR performance [*Luthcke et al.*, 2003]. Accurate modeling of the GPS antenna phase center is required for POD. The time series of independent SLR residuals RMS / 30-hour arc, cycles 8-24, show the benefit of using the GSFC APC map correction and highlight the importance of the SLR data in calibrating the GPS measurement model.

SLR as a Validation Tool

The Jason-1 radial orbit accuracy goal of 1 cm has been shown to be achievable using GPS-based solutions and the reduced dynamic technique [*Luthcke et al.*, 2003]. Much of the challenge of achieving the 1-cm radial orbit accuracy goal is validating the 1-cm orbit. Towards this end the SLR data have proved to be invaluable. In the previous section we demonstrated the importance of the SLR tracking data in calibrating the GPS-based solution reduced dynamic parameterization and measurement models. The SLR data was shown to be an important independent performance discriminator between candidate solutions. Similarly, it naturally follows that the SLR data provide a valuable and unique validation tool. Orbit overlap and GPS residuals do not measure radial orbit accuracy. In the case of Jason-1, the residuals formed from the DORIS data also do not directly measure radial orbit accuracy. Altimeter crossover residuals, given the 5-cm level oceanographic contamination of the orbit signal arising from mismodeled tides and mesoscale phenomena, limit the ability of these measures to isolate the orbit error. Nevertheless, crossovers can be employed as a relative measure and be used to infer radial orbit accuracy improvement or degradation between solutions, but not the absolute orbit accuracy being achieved. The SLR data provide a high-accuracy, direct and unambiguous observation of the orbit error. In particular, high-elevation SLR observations are the only independent measure of radial orbit accuracy which is capable of cm-level validation.

To compute an estimate of the radial orbit accuracy from high-elevation SLR residuals, a pass bias is estimated for independent SLR data that exceeds 60 degrees in elevation. Only the data from historically well performing SLR stations that have acquired at least ten high-elevation passes during our study period were used. The RMS of the pass biases and an overall RMS is computed for each of the selected stations. Figure 2 presents the independent high-elevation SLR pass bias RMS for each station post-fit to our Jason-1 GPS reduced dynamic solutions. While this is our only direct means of assessing radial orbit accuracy, it is still not a perfect test and contains error sources other than radial orbit error (e.g., station position, Jason-1 LRA offset, and a small horizontal orbit error component). Still, the high-elevation SLR analysis is the best source of information for validating our Jason-1 GPS reduced dynamic orbits and these other contributing errors makes the RMS-of-fit to the high elevation SLR data the upper bound for the absolute radial error being achieved. On this basis, we are achieving centimeter-level (< 1.3 cm) radial orbit accuracy.

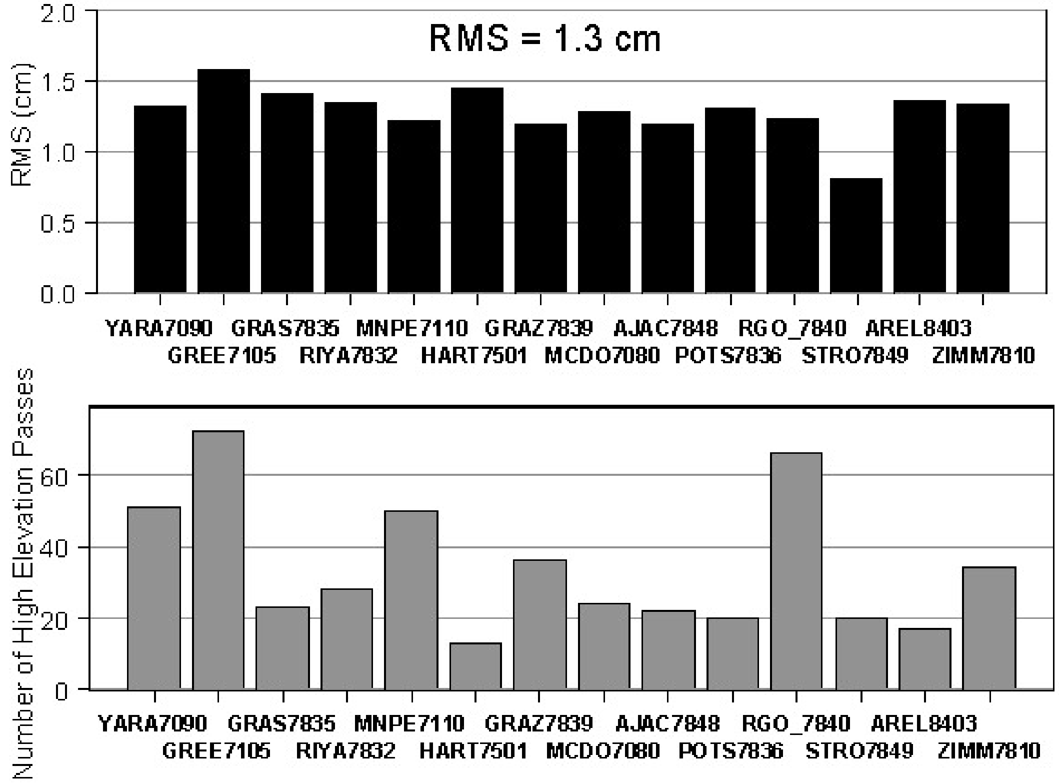

Figure 2. Jason-1 Independent SLR High Elevation performance from the GPS reduced dynamic solutions [*Luthcke et al.*, 2003]. Measurement biases estimated from high elevation pass SLR residuals offer the only direct measure of radial orbit accuracy. The RMS of the estimated biases indicates orbit error does not exceed 1.3 cm. The actual radial error is less because the statistic contains other error sources in addition to the radial orbit error. SLR data above 60 degrees are selected for the high elevation test.

Using SLR to improve GPS-based POD

While the previous two discussions have demonstrated the significance of SLR tracking in GPS-based POD, the orbit accuracies achieved are still the result of the GPS data. The question arises: can SLR be used to improve upon the POD and not just provide the important role of calibration and validation data? To answer this question we combined the SLR and GPS data into 30-hour orbit solutions much like our GPS-only solutions. Again, the reduced dynamic technique was employed and the parameterization was "tuned". The results are detailed in *Luthcke et al.,* [2003], and show that an improvement in orbit performance is observed for orbit solutions ranging from repeat cycle 8 through 24. Specifically the altimeter crossover residuals can be used as an independent measure of radial orbit improvement. Figure 3 shows the crossover discrepancy RMS computed per 10-day Jason-1 repeat cycle for both the GPS and GPS+SLR reduced dynamic orbit solutions over a 170-day period. An overall improvement is observed when the SLR data is combined with the GPS data in the POD solutions. The overall crossover RMS improved from 5.766 cm in the case of the GPS-only solutions to 5.752 cm in the case of GPS+SLR solutions. This represents a significant 4-mm improvement in radial orbit accuracy where the 4 mm magnitude is also observed in the RMS difference between the GPS and GPS+SLR solutions over the 170-day study period. Therefore, this analysis demonstrates that SLR data can still directly contribute to the overall POD accuracy even in the wake of the excellent orbit performance achieved from GPS-only solutions.

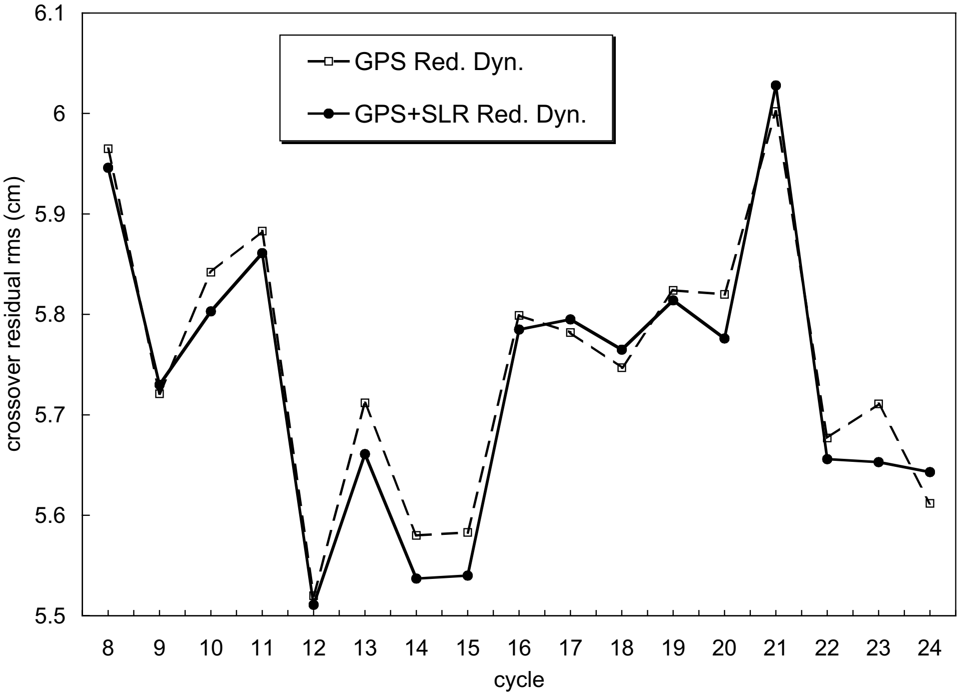

Figure 3. Jason-1 crossover RMS per 10-day repeat cycle for both GPS and GPS+SLR reduced dynamic solutions. The results demonstrate the SLR data can improve radial orbit accuracy when properly combined with GPS data.

Conclusions

The new era of geodetic satellites all carry aboard a state-of-the-art GPS receiver to provide the primary tracking data to meet their stringent POD accuracy goals. While the orbit accuracy goals cannot be met without the temporal and geometric strength of the GPS data, the SLR data still serve an important and invaluable role. The GPS tracking is an indirect ambiguous observation of the orbit. This can be problematic, especially when fine-tuning the large GPS POD solution parameter set, and when sorting out systematic errors. The SLR tracking data provide the highly accurate, direct and unambiguous observation of the orbit necessary for the calibration and validation of the GPS-based POD solutions. We have used nearly one half of a year's worth of data to demonstrate the worth of the SLR data in these roles. Additionally, we have shown the SLR data can contribute to the further improvement of orbit accuracy when combined with the GPS data. Further enhancements in the SLR network to improve temporal/spatial coverage of LEO geodetic satellites will serve to further improve POD for these vital missions and therefore improve their science return.

Acknowledgments

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