

# GPS-based Precision Orbit Determination for a New Era of Altimeter Satellites: Jason-1 and ICESat

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## ABSTRACT

Accurate positioning of the satellite center of mass is necessary in meeting an altimeter mission's science goals. The fundamental science observation is an altimetric derived topographic height. Errors in positioning the satellite's center of mass directly impact this fundamental observation. Therefore, orbit error is a critical component in the error budget of altimeter satellites. With the launch of the Jason-1 radar altimeter (Dec. 2001) and the ICESat laser altimeter (Jan. 2003) a new era of satellite altimetry has begun. Both missions pose several challenges for precision orbit determination (POD). The Jason-1 radial orbit accuracy goal is 1 cm, while ICESat (600 km) at a much lower altitude than Jason-1 (1300 km), has a radial orbit accuracy requirement of less than 5 cm. Fortunately, Jason-1 and ICESat POD can rely on near continuous tracking data from the dual frequency codeless BlackJack GPS receiver and Satellite Laser Ranging. Analysis of current GPS-based solution performance indicates the 1-cm radial orbit accuracy goal is being met for Jason-1, while radial orbit accuracy for ICESat is well below the 5-cm mission requirement. A brief overview of the GPS precision orbit determination methodology and results for both Jason-1 and ICESat are presented.

## INTRODUCTION

On December 7, 2001 the joint US/French Jason-1 satellite radar altimeter was launched as the follow-on to the highly successful TOPEX/Poseidon (T/P) mission. As the successor to T/P, Jason-1 will continue, and improve upon, the time series of centimeter level ocean topography observations obtained over two decades of satellite radar altimetry.<sup>1</sup> On January 12, 2003 NASA's Geosciences Laser Altimeter System (GLAS), carried aboard the Ice, Cloud and land Elevation Satellite (ICESat), was successfully placed into orbit. The GLAS instrument consists of three near-infrared lasers that will be operated sequentially over the life of the mission. Altimeter derived surface elevations are obtained from the 1064 nm near-infrared channel, while cloud and aerosol elevations are derived from the 532 nm channel. The ICESat's surface elevation observations collected over the life of the mission will enable the determination of ice sheet mass balance, the study of associations between observed ice changes and polar climate, and the estimation of the present and future contributions of the ice sheets to global sea level rise.<sup>2</sup> These two missions usher in a new era in satellite radar altimetry with a state-of-the-art radar altimeter and a dedicated Earth observing laser altimeter.

The accurate knowledge of the history of the spacecraft center of mass location (the orbit) is critical to the overall success of satellite altimeter missions. Radial orbit errors directly map into the fundamental science observations, namely the altimeter derived topographic height. Radial orbit error is a major component in the overall error budget of satellite altimeter missions, and Jason-1 and ICESat are no exception with both having stringent accuracy requirements for their particular orbit configuration. The radial orbit accuracy requirement for Jason-1 is 2.5 cm with a goal of 1 cm, while the accuracy requirement for ICESat is 5 cm. The orbit configuration for these two missions is very different. Jason-1 orbits the Earth in a ~1335 km altitude near-circular orbit with 66.03° inclination, while ICESat orbits the Earth in a ~600 km altitude near-circular orbit with a 94° inclination. The much higher altitude of Jason-1 is more favorable for precision orbit determination (POD), significantly reducing the drag perturbations on the satellite. However, due to instrument design constraints the laser altimeter must orbit at a much lower altitude.

Fortunately, the POD for these two missions can rely on the near continuous tracking data from the dual frequency codeless BlackJack GPS receiver. The BlackJack GPS receiver is capable of acquiring carrier phase and pseudorange observations at both L1 and L2 frequencies from up to 12 simultaneous GPS spacecraft regardless of antispoofing (AS).<sup>3</sup> In addition to the GPS observations, each of these missions also has available Satellite Laser

Ranging (SLR) to a nine corner cube hemispherical Laser Retroreflector Array (LRA). In the case of Jason-1 Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) tracking are also available. Additionally, the altimeter observations themselves can be used as tracking data processed as altimeter crossover discrepancies.

A detailed analysis of Jason-1 POD method and performance can be found in Luthcke et al. 2003.<sup>4</sup> In this analysis Jason-1 radar altimeter crossover data provides an excellent discriminator of radial orbit accuracy. While not providing an absolute orbit accuracy estimate, the crossovers are invaluable in discriminating between orbit solutions and assessing orbit centering. The results from this crossover analysis and additional analysis presented in Luthcke et al., 2003 clearly show the GPS-based orbits are superior in overall radial orbit accuracy and in reducing geographically correlated radial orbit error. The analysis demonstrates the Jason-1 GPS-based orbit solutions are successfully achieving the 1 cm radial orbit accuracy goal and are superior to orbit solutions based on SLR, DORIS and altimetry. The GPS-based POD strategy is now being applied to ICESat. This paper provides an overview of our GPS-based POD methodology and summarizes and compares the Jason-1 POD performance with that obtained from a preliminary ICESat analysis from early mission data. The results provide a range of POD performance for vastly different satellite altimeter orbit configurations.

## **POD METHODOLOGY OVERVIEW**

At the heart of our POD capability is NASA Goddard Space Flight Center's (GSFC) GEODYN precision orbit determination and geophysical parameter estimation software. GEODYN can simultaneously process a myriad of tracking data including: GPS, SLR, DORIS, crossover and direct altimetry derived from both radar and laser altimeter ranging. Double Differenced LC (DDL) phase observations are used as the fundamental GPS observations in our GPS POD analysis. These observations have cycle slips detected and corrected while phase ambiguities are estimated per DDL pass. Our analysis uses a consistent set of ITRF2000 GPS and SLR station positions with few modifications and corrections.<sup>5</sup> The GPS station complement (approximately 33 stations) is selected based on International GPS Service (IGS) reported performance and their global distribution. For each of the stations phase center offsets are modeled and a tropospheric scale factor is estimated every 60 minutes. Our GPS solutions use IGS final orbits along with GPS satellite attitude and phase center models for the GPS satellite tracking point offsets. However, we perform an editing procedure to eliminate any problem GPS satellite orbits.<sup>4</sup> Jason-1 and ICESat tracking point offsets are modeled using spacecraft telemetered attitude quaternions along with modeling GPS antenna boresite and dipole directions and correcting for phase windup. We have developed both a Jason-1 and preliminary ICESat antenna phase center correction map ( $5^{\circ} \times 5^{\circ}$  in antenna frame azimuth and elevation) to account for the variation of the GPS antenna phase center as a function of signal antenna incidence.<sup>4</sup>

Surface forces (solar radiation, drag and earth radiation) are modeled using a "macro-model" multi-flat-plate representation of the spacecraft and the telemetered attitude data for orientation.<sup>6</sup> Atmospheric density is computed using the MSIS-86 model.<sup>7</sup> The JGM3<sup>8</sup> gravity model is used for Jason-1 while the GGM01C<sup>9</sup> model is used for ICESat along with the application of solid Earth and ocean tide perturbations. Force modeling errors are minimized through the application of a reduced dynamic technique, where time correlated empirical accelerations are estimated at a high rate.<sup>4</sup> For Jason-1 we estimate a set of along and cross track 1-cycle-per-revolution (1CPR) empirical accelerations every 30 min. with a 60 min. correlation time and a  $1.e-9 \text{ m/s}^2$  correlation sigma.<sup>4</sup> For ICESat we estimate a set of along and cross track 1CPR empirical accelerations every 20 min. with a 40 min. correlation time and a  $1.e-7 \text{ m/s}^2$  correlation sigma. For both Jason-1 and ICESat we estimate the initial state (position and velocity) and a coefficient of drag per arc. Our nominal GPS solutions are computed in 30-hr arcs with 6-hr. overlapping time periods. A long arc that covers a complete repeat cycle of the altimeter satellite orbit (10 days for Jason-1 and 8 days for ICESat) is constructed by "blending": together the center 24-hrs. from each 30-hr. arc solution.

## **POD PERFORMANCE**

For our POD performance assessment presented here we have analyzed 170 30-hr. Jason-1 arcs ranging from day of year (DOY) 84 – 254 of 2002, and for ICESat we have analyzed 29 30-hr arcs ranging from DOY 51-86 of

2003. Due to laser altimeter safety considerations there is very little SLR tracking of ICESat. Therefore the SLR data is withheld from the POD and used as an independent tracking data type for orbit performance assessment. By contrast Jason-1 has a relatively dense amount of SLR tracking and this tracking data was both withheld from the solution as an independent performance metric and included in the orbit determination solution itself. The analysis in Luthcke et al., 2003 demonstrates a slight improvement in orbit accuracy is achieved by solutions that include both the GPS and SLR data. However, for the purposes of comparing Jason-1 and ICESat orbit performance in this paper, we will summarize the performance of orbit solutions determined solely from GPS tracking data.

Unfortunately, no direct measure of orbit error exists. Therefore, we must use several different performance tests to help us gauge and understand the remaining errors in our POD solutions. Tracking data post-fit residual performance is an important performance metric. Both dependent (used in the orbit solution) and independent (withheld from the orbit solution) data residual performance are assessed. The independent data residuals are an important discriminator of solution performance, and in the case of the SLR, are an important measure of orbit accuracy. 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 direct measure of radial orbit accuracy. Another useful means of estimating orbit error is to compare ephemerides computed from independent tracking data, solution techniques and/or orbit determination algorithms and software. Orbit overlap tests (consistency of two adjacent arcs in a common time interval) are used to assess the orbit solution precision. As mentioned above the detailed analysis of altimeter crossover residuals is another important tool for characterizing orbit error. Although, this analysis was invaluable in Jason-1 orbit error characterization and orbit performance discrimination as outlined in Luthcke et al., 2003, due to such factors as the present level of laser altimeter crossover discrepancies (contain much larger errors from sources other than the orbit), we are currently not using this analysis for ICESat orbit performance assessment. Therefore, it will not be summarized and compared below. Only those performance metrics from which we have results for both ICESat and Jason-1 are summarized here.

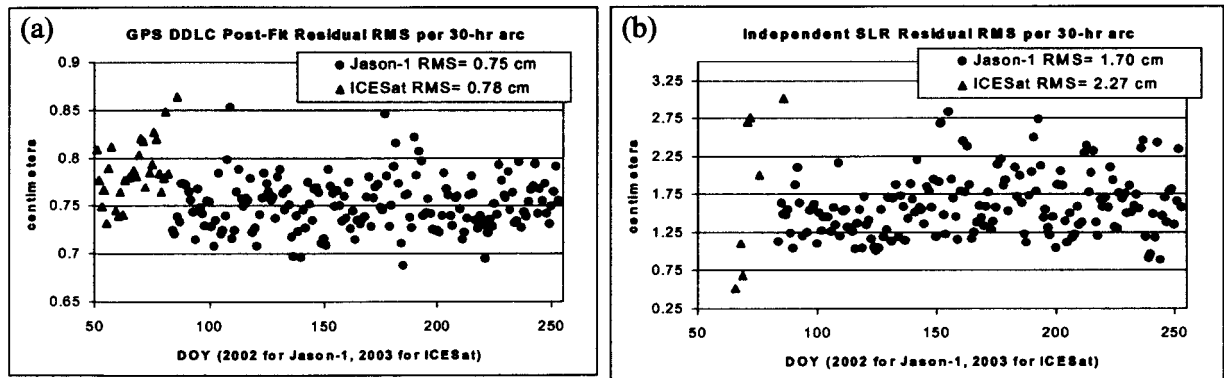
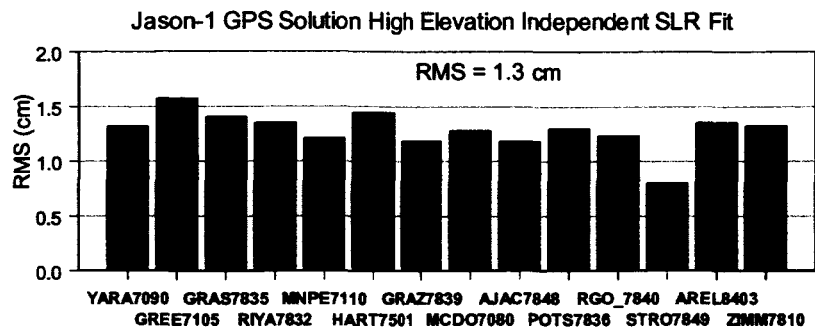


Figure 1. Jason-1 (blue-dot) and ICESat (red-triangle) tracking data fit. (a) GPS DDLC Post-fit residual RMS per 30-hr arc, (b) Independent (withheld from solution) SLR residual RMS per 30 hr. arc.

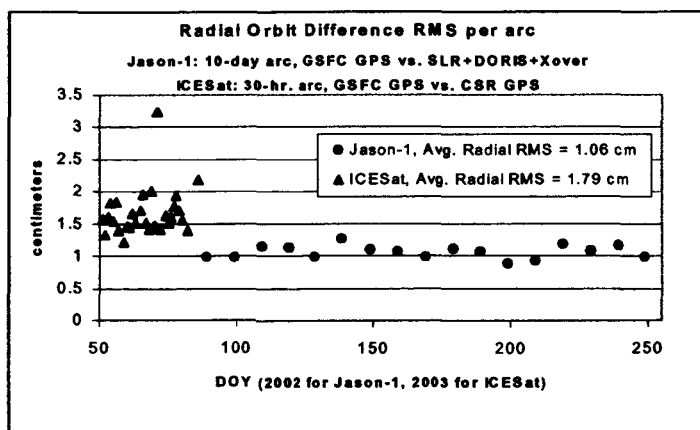
Figure 1 presents the tracking data residual performance statistics accumulated over our Jason-1 and ICESat test arcs. Figure 1a shows the GPS DDLC post-fit residual root-mean-square (RMS) per 30-hr arc. Figure 1b presents the independent (withheld from the solution) SLR residual RMS per 30-hr. arc. The results demonstrate the Jason-1 orbit performance is superior to that being obtained for ICESat as is expected due to the much lower altitude and impact of mis-modeled forces (e.g. drag) on ICESat. The most direct measurement of radial orbit accuracy is obtained from high elevation SLR pass biases. A pass bias is estimated for independent SLR data that exceeds 60° in elevation. The data from historically well performing SLR stations that have acquired at least 10 high elevation passes were used. For each of these stations the RMS of the pass biases is computed and an overall RMS is also computed. Figure 2 shows the independent high elevation SLR pass bias RMS for each station resulting from the Jason-1 GPS orbit solutions. It is important to note that while this is one of the most direct means for measuring radial orbit accuracy, it is not a perfect test and contains error sources other than radial orbit error (e.g. station position, LRA offset, and a small horizontal orbit error component). Therefore, the Jason-1 high elevation independent SLR analysis indicates the Jason-1 GPS solutions have a radial orbit accuracy better than 1.3 cm.

Unfortunately, due to the ICESat SLR tracking scenario there were no high elevation passes to generate this statistic for ICESat. However, Figure 1b suggests ICESat radial orbit accuracy is likely to be better than ~2.0 cm, although more data and further analysis is needed to lend confidence to this estimate.



**Figure 2.** Jason-1 independent SLR high elevation performance from the GPS reduced dynamic solutions. Measurement biases estimated from high elevation pass SLR residuals offer the best single metric to gauge 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 as well. SLR data above 60 degrees are selected for the high elevation test.

As mentioned above, another important means of characterizing orbit error is to compare ephemerides computed from independent tracking, solution techniques or software and algorithms. Figure 3 presents our independent solution orbit difference analysis. For the Jason-1 analysis we compared our (GSFC) orbits computed with GPS tracking data to our orbits computed using SLR, DORIS and altimeter crossover data. Figure 3 shows the RMS computed from each 10-day radial orbit comparison. The results demonstrate 1 cm radial RMS agreement between solutions computed from two independent sets of tracking data, further supporting the assessment that the GPS-based Jason-1 orbit solutions have achieved the 1 cm radial accuracy goal. In the case of ICESat, only the GPS tracking and very limited SLR tracking are available. Therefore, we compared our GPS-based ICESat orbit solutions to the “mission” orbit solutions used in the production of ICESat level 1a and 1b products. These mission orbits are computed at the Center for Space Research (CSR) at the University of Texas. While the orbits are not computed from independent tracking data, they are computed using independent methods, algorithms and software. Figure 3 presents the RMS from each 30-hr. ICESat radial orbit comparison. The results show radial orbit



**Figure 3.** Jason-1 (blue-dot) radial RMS orbit difference per 10-day arc between GSFC GPS orbit solutions and GSFC orbit solutions computed from SLR, DORIS and altimeter crossovers. ICESat (red-triangle) radial RMS orbit difference per 30-hr arc between GSFC GPS orbits and ICESat mission GPS orbits computed at CSR.

agreement at the level of 1.8 cm is currently being achieved. These results and the tracking data analysis results presented in Figure 1 indicate an ICESat radial orbit accuracy of ~2 cm is currently being achieved. These ICESat results are preliminary from the early stages of the mission and further analysis is required. Orbit accuracy can only be as good as orbit solution precision. Orbit overlap tests are used to estimate orbit solution precision. Figure 4 presents the RMS radial orbit difference computed for each 6-hr. overlap time period from the 30-hr GPS orbit solutions. The results show radial orbit precision of less than 5 mm for both Jason-1 and ICESat.

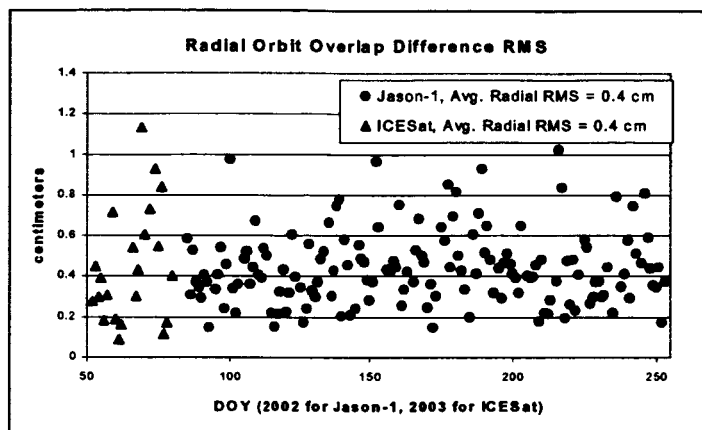


Figure 4. Jason-1 (blue-dot) and ICESat (red-triangle) radial orbit overlap difference RMS per 30-hr. arc 6-hr. overlapping time period.

## CONCLUSIONS

Orbit accuracy is an important component to the overall success of satellite altimeter missions. Jason-1 and ICESat are no exception and these new missions have very stringent radial orbit accuracy goals. The analysis presented in this paper has demonstrated the radial orbit accuracy goals of 1 cm for Jason-1 and 5 cm for ICESat are currently being achieved, and in the case of ICESat is likely being far exceeded (~2 cm). In order to achieve these goals, near continuous GPS tracking data, from the BlackJack receiver carried aboard each satellite, has been processed in a reduced dynamic solution with state-of-the art force and measurement models. Each of these missions also carries a SLR LRA. The SLR data has been shown to be invaluable in both the calibration and validation of the GPS-based orbit solutions. In fact, the SLR data is the only independent, direct and unambiguous measure of orbit accuracy. Additionally, in the case of Jason-1 further orbit accuracy has been achieved by combining the SLR data with the GPS tracking in the orbit solution. While a detailed analysis of the Jason-1 orbit error characteristics has been performed (Luthcke et al. 2003), only the preliminary analysis presented here has been completed for ICESat. Further analysis of ICESat orbit error characteristics including the processing of significantly more arcs will need to be done before a definitive ICESat orbit accuracy assessment can be completed.

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