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Automated Operational Orbit Determination for the Ice Cloud and Land Elevation Satellite Mission

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Satellite operations depend on the ability to generate accurate predictions of a spacecraft ephemeris in a very short period of time. This operational ephemeris is used by the mission controllers to plan operations such as instrument pointing and orbit adjust maneuvers. This paper examines the methods and parameterizations necessary to achieve an accurate ephemeris quickly in an operational environment. The specific application described is for NASA's Ice Cloud and Land Elevation Satellite mission. The primary tracking data for the Ice Cloud and Land Elevation Satellite are global positioning system pseudorange and carrier phase. Near real time orbit determination accuracy with these observations is better than 2 m root-mean-square over a 24 h solution arc length. Because of stringent pointing requirements it is necessary to predict the satellite ephemeris to an accuracy of better than 400 m in-track after 48 h of prediction. This requirement has been achieved despite the significant drag perturbations on the 600 km altitude orbit. This paper presents the orbit determination and prediction techniques used in the Ice Cloud and Land Elevation Satellite operational system as well as examples of the orbit determination and prediction accuracy achieved.

Introduction

THE Ice Cloud and Land Elevation Satellite (ICESat), which was launched in January 2003, is part of NASA's Earth Observation System (EOS). An illustration of the ICESat spacecraft is shown in Fig. 1 and the orbit characteristics are given in Table 1. ICESat was in an eight nodal day repeat orbit for the calibration/validation period and is currently in a 91 nodal day repeat ground track orbit for mission operations. As seen in Table 1, the A/M (area to mass) ratio differs by a factor of two depending on the configuration in which the spacecraft is flying. The minimum cross-sectional area configuration is referred to as the "sailboat" mode and has the spacecraft flying with the solar panels edge on to the velocity direction, as shown in Fig. 1a. The "airplane" mode, or maximum cross-sectional area configuration, has the solar panels normal to the velocity direction, as shown in Fig. 1b. Hence, perturbations of the orbit due to drag will be much more significant when the satellite flies in the airplane mode.

The major objectives of the ICESat mission are to measure changes in the mass balance of the Greenland and Antarctic ice sheets with sufficient accuracy to assess their impact on global sea level, and to measure seasonal and interannual variability of the ice surface elevation. Another objective is to make topographic measurements of Earth's land surface to provide ground control points for topographic maps and digital elevation models, and to detect topographic change [1].

To meet these scientific objectives, the spacecraft carries the Geoscience Laser Altimeter System (GLAS). The GLAS measures its height above the ice sheet with a precision of <10 cm for 40 HZ data [1]. ICESat also carries two BlackJack global positioning system (GPS) receivers developed at the Jet Propulsion Laboratory (JPL). The BlackJack receiver, as configured for ICESat, is a dual frequency receiver capable of simultaneously tracking a maximum of nine GPS satellites and provides pseudorange and carrier phase data for each. The operational orbit determination (OD) system uses pseudorange and phase data from this receiver to perform the daily OD and orbit prediction for the satellite.

The spacecraft, which was built by Ball Aerospace Technologies Corp., is operated largely with student support by the Laboratory for Atmospheric and Space Physics (LASP) at the University of Colorado at Boulder. The Colorado Center for Astrodynamics Research (CCAR) developed the operational OD software system being operated by LASP. CCAR also developed the software system used by LASP to point the laser at targets of opportunity [2]

To perform the estimation, the spacecraft flight receiver tracking data are processed with International GPS Service (IGS) ground tracking data in a differential mode. Differential mode processing of GPS data helps to remove certain data errors, such as clock drift. These differential data are processed using the MicroCosm® orbit determination software.

Operational Orbit Determination and Prediction Solution Requirements

The primary OD requirements for the ICESat mission are 1) provide orbit fits such that 48 h orbit predictions yield cross-track pointing accurate to 15 m (1σ) on Earth's surface, and 2) estimate the orbit through an orbit adjust maneuver and predict the orbit to the above accuracy. It is also required to control the orbit period so that the ground track repeats to within ± 800 m of a reference track. The prediction accuracy requirement applies to latitudes greater than ± 60 deg and is needed to point the laser at the reference ground track or to illuminate targets of opportunity. This requirement necessitates an accurate determination of spacecraft position, velocity and drag coefficient.

It is required that errors in predicting the ground track of ICESat relative to a target location on Earth's surface be less than 15 m (1σ) cross-track after 48 h at latitudes greater than ± 60 deg. Cross-track pointing errors result from a combination of in-track and cross-track orbit prediction errors. The in-track errors are equivalent to timing errors and are converted into cross-track pointing errors by

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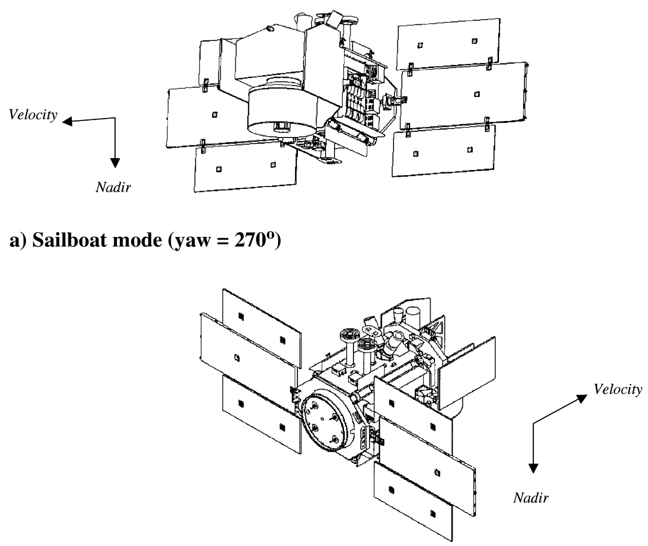

a) Sailboat mode (yaw = 270°)

b) Airplane mode (yaw = 0°)

Fig. 1 ICESat attitude modes (images courtesy of Ball Aerospace).

accounting for Earth rotation, that is,

$$\Delta = \frac{T}{v}\omega_e R_e \cos\phi$$

where T is the in-track orbit error, v is the spacecraft velocity, ω_e is the Earth rotation rate, R_e is the Earth radius, and ϕ is the latitude. The cross-track pointing error (Δ) due to an in-track orbit prediction error is added to the cross-track orbit prediction error to obtain the entire cross-track pointing error. From this equation it is seen that an in-track prediction error of around 400 m results in a 15 m cross-track pointing error at ± 60 deg latitude.

Operational Orbit Determination and Prediction Solution Details

The ICESat OD system consists of an advanced user interface built around the MicroCosm® (MC) orbit determination software system [3]. The automated OD system is designed to handle all tasks required to routinely generate daily satellite ephemerides. MicroCosm® uses a high fidelity dynamic model consisting of the following: 1) EGM96 gravity model complete to degree and order 70, 2) Jacchia-71 atmospheric density model, 3) tabular data consisting of solar flux, geomagnetic data, and Earth orientation parameters (updated on a daily basis), and 4) planetary ephemerides to account for n-body perturbations. This system has been used as the basis for the operational OD system for the Quikscat mission [4] and the Quickbird mission [5].

The only tracking data available from ICESat in near real time are the GPS data. The spacecraft does carry a laser retroreflector but it has only had limited tracking and none of this tracking was performed during the time period included in this paper. The limiting of SLR tracking data is a ICESat mission decision. Consequently, there are no tracking data available to independently quantify absolute orbit accuracy on an operational basis. For the operational system, orbit overlaps are used to assess the precision of the solution in which 27 h solutions are generated starting at 0900 UTC each day. Using a 27 h solution provides a 3 h overlap of consecutive daily orbit determination solutions. The 3 h overlap differences are a measure of orbit precision and are a rough indicator of accuracy. In order to further test accuracy, orbits generated by the Center for Space Research (CSR) at the University of Texas at Austin, using the software system Multi Satellite Orbit Determination Program, are compared with those generated using MC. The CSR orbits are based on double-differenced phase data and are accurate to better than 5 cm 3-D RMS [6]. However, they are not available in real time and can only be used for verification in a postprocessing mode.

Table 1 ICESat orbital and physical characteristics

Parameter	Verification orbit	Mission orbit
Orbit type	Near polar	Near polar
Semimajor axis	6971 km	6970 km
Mean altitude	600 km	599 km
Inclination	94.0 deg	94.0 deg
Eccentricity	0.0013	0.0013
Argument of perigee	90 deg	90 deg
Spacecraft mass	970 kg	970 kg
Cross-sectional area	4.5 m^2 (“sailboat”)	4.5 m^2 (“sailboat”)
	9 m^2 (“airplane”)	9 m^2 (“airplane”)

The GPS data can be used operationally in two modes, single and double-differenced pseudorange. While, in principle, more accurate orbits could be obtained with the phase data, the time needed to process this data type is significantly greater than that of pseudorange because an integer ambiguity or bias must be solved for in each arc of GPS data. Single- and double-differenced GPS measurement formation is described in [7,8].

In order to process the GPS data, the ephemerides of the GPS satellites are needed. The so-called broadcast ephemeris, available with the navigation message, results in ICESat position accuracy of 7–10 m 3-D RMS; which does not meet the ICESat mission requirements. Hence, we use the IGS ultrarapid prediction orbits that are accurate to 25 cm RMS and are available in real time [9]. These orbits are accurate enough to meet operational requirements. IGS rapid and final GPS orbits are accurate to 5 cm but are not available in time to meet ICESat requirements.

As will be shown subsequently, OD accuracy is improved using double-differenced data; however, orbit solutions using single difference data also meet the accuracy requirements for mission support. The single difference method is operationally more reliable because of issues with the availability of ground station data uploads. Consequently, the use of single-differenced GPS—ICESat data is preferred. By comparing results from both single and double-differenced data, it will be shown that requirements can be met with single difference data.

Ionospheric Refraction Error Removal

The Blackjack and all ground receivers considered here are dual frequency; hence, it is possible to remove the ionospheric refraction errors from the GPS data. The method of dual frequency ionospheric refraction error removing is described in [8]. A second method of ionospheric refraction error removal is described in [10]. This second method is based on using single frequency GPS data and is named differenced range vs integrated Doppler (DRVID). A modification of the DRVID method termed “zero bias DRVID” in [11] is compared with results generated with dual frequency data.

Results

Several different sets of solved for parameters were experimented with in order to provide the most accurate orbit during the 27 h solution arc and the most accurate orbit prediction during the 48 h prediction interval. Based on a number of test cases, it was found that the most accurate orbit in the fit interval was obtained by solving for the epoch position and velocity vector, one drag and radiation pressure coefficient (C_d and C_R), a tropospheric scale bias for each pass of double-differenced data, and once per revolution empirical accelerations in the in-track, and cross-track directions every three hours. It was found that the most accurate prediction was accomplished by solving for the epoch position and velocity and one C_d and one C_R for the entire 27 h arc. It also was desired to use single-differenced range measurements rather than double-differenced range measurements because ground station data could be eliminated from the operational system.

Table 2 presents a summary of fit and prediction statistics for five 27 h fits for 2–6 April 2003. Shown are the 3-D RMS differences with the CSR precision solutions for each day. Also shown is the maximum cross-track pointing error above ± 60 deg latitude during

Table 2 Double and single-differenced pseudorange 3-D RMS solution differences with CSR precision solutions and maximum 48 h prediction errors

	With accelerations		Without accelerations			
	Double diff.	Single diff.	Double diff.		Single diff.	
Date	3-D RMS, m	3-D RMS, m	3-D RMS, m	Max 48 h pointing predict error, m	3-D RMS, m	Max 48 h pointing predict error, m
2 April 2003	1.71	2.70	5.55	15.92	5.41	16.86
3 April 2003	2.05	2.86	4.37	11.82	4.37	7.74
4 April 2003	1.94	3.49	6.18	22.34 (with burn)	6.02	23.82 (with burn)
5 April 2003	2.15	3.85	4.98	86.31 (with burn)	5.19	87.82 (with burn)
6 April 2003	3.08	3.31	4.80	13.72	4.66	15.13

Table 3 Double and single-differenced pseudorange using dual frequency, single frequency, and DRVID 3-D RMS solution differences with CSR precision solutions

	Dual freq		Single freq		DRVID	
	Double diff.	Single diff.	Double diff.	Single diff.	Double diff.	Single diff.
Date	3-D RMS, m	3-D RMS, m	3-D RMS, m	3-D RMS, m	3-D RMS, m	3-D RMS, m
22 April 2003	0.79	1.01	2.21	3.17	0.68	0.97
23 April 2003	1.28	1.56	2.96	3.10	1.15	1.63
24 April 2003	0.96	2.09	3.25	3.09	0.85	1.33
25 April 2003	1.00	1.30	2.09	2.97	0.90	1.12
26 April 2003	1.03	1.33	2.79	3.85	1.00	1.39
27 April 2003	0.85	0.96	2.36	3.03	0.93	0.98
28 April 2003	1.27	1.68	4.14	5.20	1.29	1.76

the 48 h prediction for the solutions without 3 h empirical accelerations. As seen from this table the solutions which include the empirical accelerations are more accurate during the fit interval than those without. However, the propagation of these solutions forward over the prediction interval produced solution errors which far exceed ICESat requirements, and thus are not shown or used in the operational procedures.

Table 3 shows a comparison of using different data types, namely dual frequency, single frequency, and DRVID data. Note that the DRVID technique performed slightly better than the dual frequency results. It is believed that this is due to the increased noise on L2, especially at low elevations, that is typical of this receiver.

It is noted that there was an orbit adjust maneuver on 6 April at 10 hrs 19 min. Consequently, the predictions for 4 and 5 April used the design burn in the prediction, whereas the prediction for the 6 April solution used the solved for acceleration. The baseline OD system is not obligated to meet the cross-track prediction requirement in situations where the design burn must be used. Note that the 15 m (1σ) cross-track pointing error requirement is met, except in the two cases where the design burn was used.

The next series of figures presents a typical example of single and double-differenced accuracy results for both fitting and prediction. Figure 2 shows RIC orbit differences between CCAR double and single-differenced pseudorange solutions and CSR precision solutions for 2 April 2003. The CCAR orbits included empirical accelerations in the set of estimated parameters. The 3-D RMS differences are 1.7 and 2.7 m for the double-differenced and single-differenced solutions, respectively. Notice that in this case the difference in 3-D RMS is largely due to the cross-track component. As seen from Table 2, a 3-D RMS difference of 1–3 m is typical for all cases.

Figure 3 shows the same comparisons with CSR orbits for the case where the solved for state vector does not include the 3 h empirical accelerations. Here the 3-D RMS of the orbit differences is 5.5 and 5.4 m for double and single-differenced pseudorange, respectively. In this case, orbit accuracy is the same for single and double-differenced range; however, it is significantly degraded from that obtained by solving for empirical accelerations. This is not surprising because the orbit is perturbed significantly by drag and fewer parameters are being solved for to model drag.

To meet the ICESat requirements, it is necessary to determine how accurately one can predict the ephemeris using the solutions that do not contain the 3 h empirical accelerations. Figure 4 presents a comparison of definitive orbit solutions with 24–48 h predicts

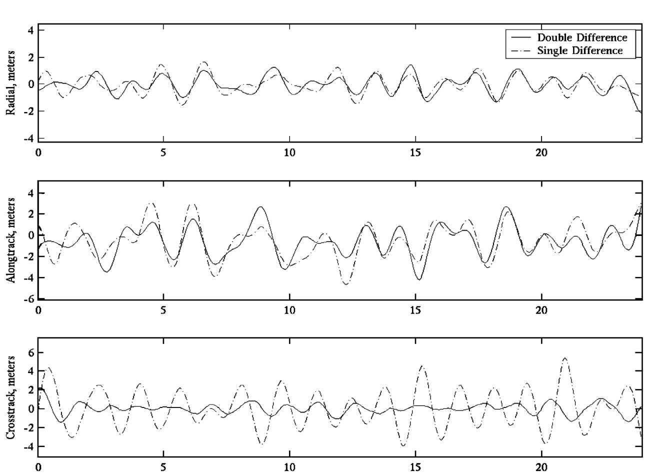

Fig. 2 Double and single-differenced pseudorange solution orbit differences with CSR solutions for 2 April 2003.

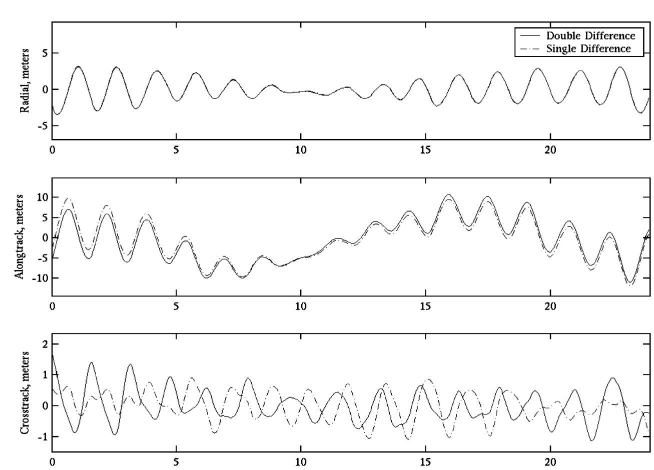

Fig. 3 Double and single-differenced pseudorange solution orbit differences with CSR solutions for 2 April 2003 (no empirical accelerations).

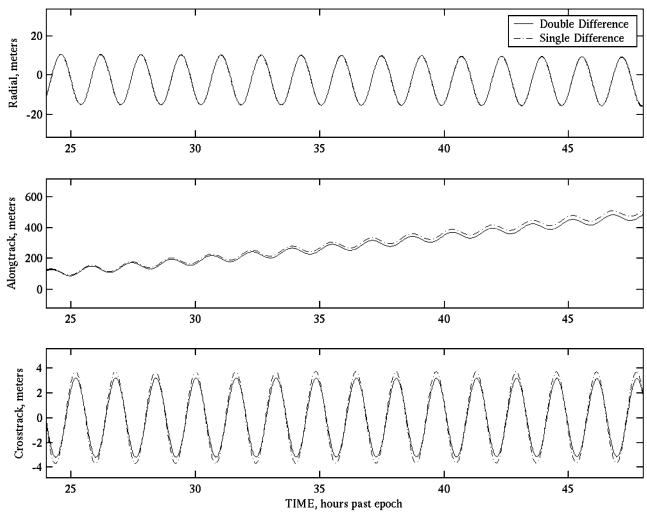

Fig. 4 Orbit prediction error for 24–48 h for double and single-differenced pseudorange solution of 2 April 2003.

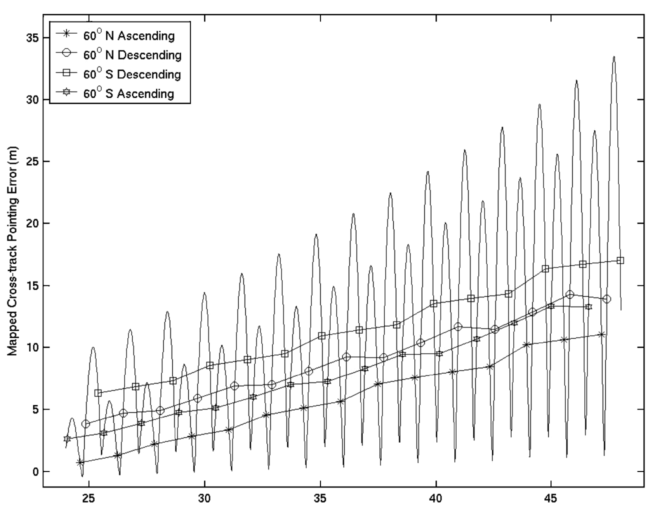

Fig. 5 Cross-track pointing prediction errors from 24–48 h for single difference solution of 2 April 2003.

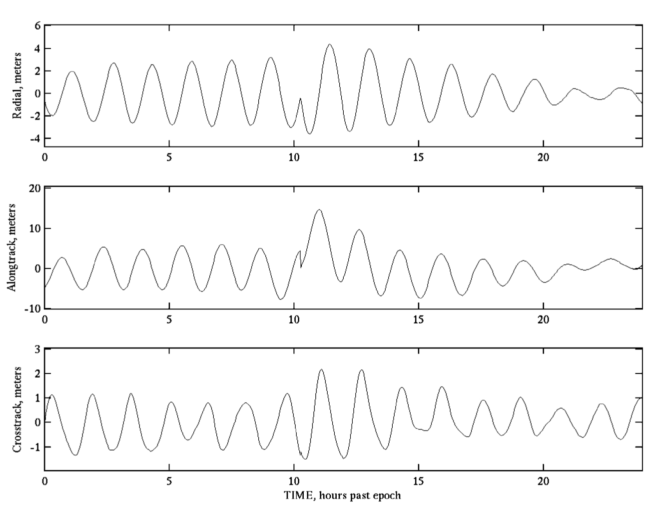

Fig. 6 Single-differenced pseudorange orbit solution overlaps with CSR for 6 April 2003.

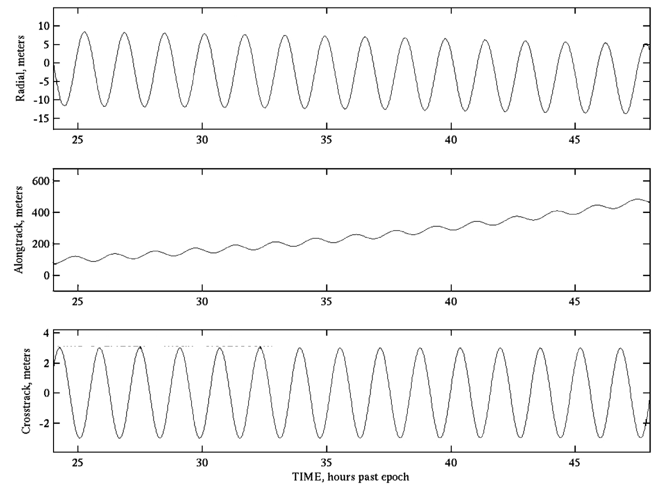

Fig. 7 Orbit prediction error for 24–48 h for the single differences fit of Fig. 6.

propagated from the single and double-differenced solutions. Hence, the differences are largely due to prediction errors. As seen from these figures, the single-differenced data provided predicts which are almost as accurate as the double-differenced data. Furthermore, during April the spacecraft was flying in the airplane configuration with maximum A/M. It will be easier to meet prediction accuracy requirements during the period when the spacecraft is in the sailboat or minimum A/M configuration.

These results are typical of a number of test cases we have analyzed and as a result the recommendation to the operations team is to use the single-differenced pseudorange data for OD solutions. Although results are not shown here, the most precise orbits using empirical accelerations yielded significantly degraded prediction results.

Figure 5 presents a plot of 24–48 h cross-track pointing errors for the case of the single-differenced pseudorange orbit of 2 April. The symbols on this plot represent points on the ground track where the spacecraft crosses 60 deg latitude. Hence, parts of the curve below these lines represent cross-track pointing errors for latitudes greater than ± 60 deg. It is seen that the maximum error is around 15 m after 48 h of prediction for these latitudes. The value at 60 deg *S* descending (16.86 m) corresponds to the number in the last column of line 1 of Table 2.

Orbit Determination and Prediction Through an Orbit Adjust

As stated previously it is required to keep the ICESat ground track within ± 800 m of the reference ground track. Because of the 600 km

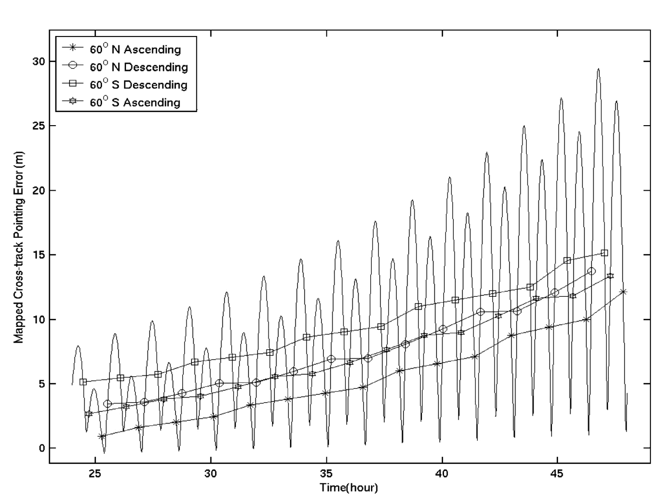

Fig. 8 Cross-track pointing prediction errors from 24–48 h from Fig. 7.

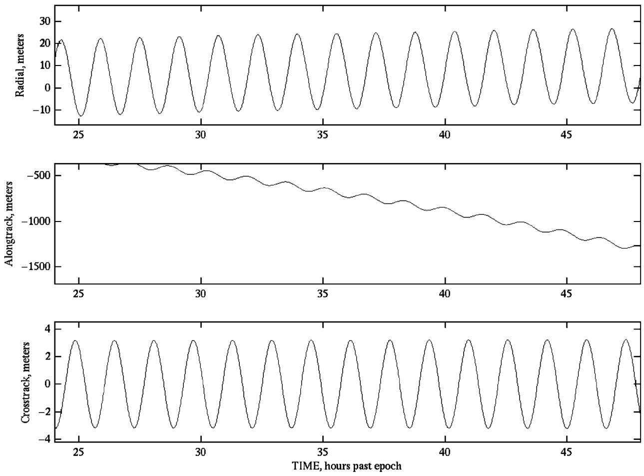

Fig. 9 Orbit prediction errors from 24–48 h for fit on 9 April 2003 with burn at 16 hrs 35 min.

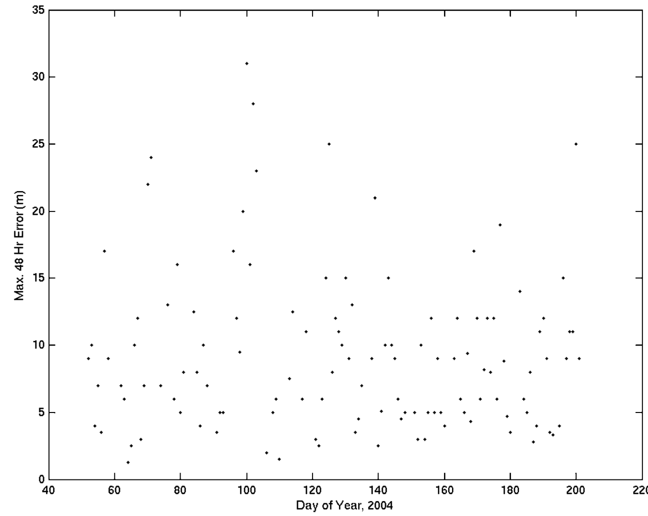

Fig. 11 Maximum 48 h cross-track pointing errors from the operational system.

altitude of the orbit, drag can reduce the semimajor axis by 10–15 m per day. In order to keep the spacecraft within the required ground track boundaries it is necessary to perform an orbit adjust maneuver about once per week. Fitting tracking data through a burn and subsequent prediction of the orbit is difficult but must be done on a weekly basis. The orbit prediction accuracy requirements after an orbit adjust maneuver are the same as those when there is no maneuver.

The orbit adjust maneuvers are small, lasting 10–15 s, and generate a Δv of around 5 cm/s. A constant in-track acceleration over the burn interval is solved for by MC and the resulting Δv is compared with that of the design burn to be sure it is realistic. The equations of motion are then integrated through the burn and the prediction interval.

While the CCAR orbit solutions are generated by fitting data through a burn, the CSR solutions are generated by fitting data on either side of a burn. Figure 6 presents the orbit differences of the CCAR single-differenced pseudorange orbits with the CSR orbits through a burn on 6 April 2003. The burn, which occurred at 10 hrs 19 min into the arc, is evident as a slight discontinuity in the overlap differences. The CCAR orbits were obtained by solving for only one C_d and C_R over the arc. Hence, the 3-D RMS of the overlap differences (4.7 m) is not as small as it could be if one were solving for empirical accelerations and striving for accuracy in the fit interval rather than prediction accuracy. The burn was designed to change the spacecraft velocity by 8.3 cm/s and the solution yielded a Δv of 7.5 cm/s.

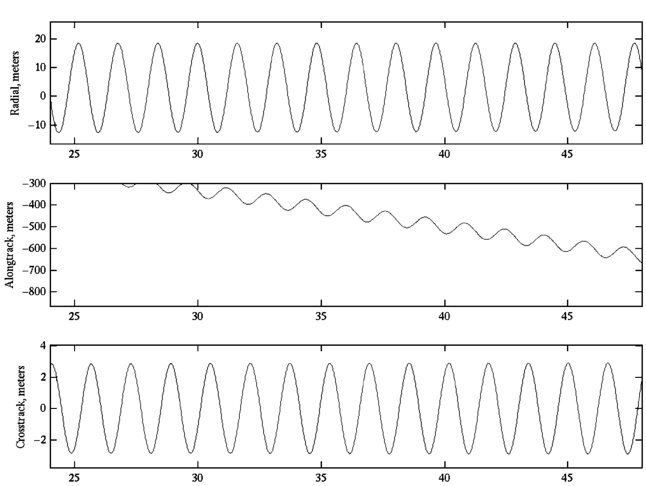

Fig. 10 Orbit prediction errors from 24–48 h for fit on 29 April 2003 with burn at 4 hrs 35 min.

Figure 7 shows the prediction error from 24 to 48 h for the fit through the burn of Fig. 6. The in-track error is about 450 m after 48 h which corresponds to a timing error of about 0.065 sec or about 15 m at 60 deg latitude. Figure 8 presents the cross-track pointing error which is typical of a prediction scenario for a burn in the first half of the arc.

Burns later in the arc are more difficult to resolve because of a lack of tracking data after the burn. These can result in much larger prediction errors. For example, Fig. 9 shows the prediction error from a fit through a burn that occurred at 16 hrs 35 min on 29 April 2003. The prediction error is over 1200 m in-track after 48 h. Figure 10 shows the prediction error for this burn if it were at 4 hrs 35 min into the tracking arc. The in-track error now is around 650 m. If accurate prediction is required using the standard operational OD processing over a burn period, it is recommended to restrict burns to occur in the first half of the day. It should be noted that this was a much larger burn than usual with a Δv of 22 cm/s.

Conclusions

Based on the results presented here, it is concluded that single-differenced pseudorange measurements are adequate to meet the operational OD and prediction accuracy requirements for ICESat. Use of single-differenced pseudorange significantly reduces the time to compute an OD solution over that needed for double-differenced pseudorange and does not require ground station data. To meet the prediction requirements, estimating the epoch position and velocity vector, and one C_d and one C_R for the entire arc was chosen as the best solution. Figure 11 shows the maximum 48 h cross-track error for the first 200 days in 2004. The 1σ dispersion of this data is 11.0 m and demonstrates that the 15 m requirement is being met over a long operational period.

An area of future investigation will be the use of phase data to smooth the pseudorange data. This will reduce the noise in the pseudorange to near the level of phase data and will allow fitting fewer data points. Currently data are being fit on 30 s intervals. With the carrier smoothed pseudorange data it should be able to obtain comparable accuracy with data on 4 or 5 min centers.

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