Precision Orbit Determination, Validation and Orbit Prediction for ICESat

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CONFERENCE PAPER

The ICESat orbit has been determined using one of two BlackJack GPS receivers. The accuracy of the radial orbit component has been validated using ground-based Satellite Laser Ranging to an accuracy of 1-2 cm, which exceeds the pre-launch requirement of 5 cm.. Other measures of precision, such as “orbit overlaps,” yield better than 1 cm precision.. Although ICESat does not have stringent prediction requirements, the 600 km altitude makes it a suitable object for prediction experiments. As expected, atmospheric density variability is the dominant, and significant, source of prediction error.

1. INTRODUCTION

The NASA Ice, Clound and land Elevation Satellite (ICESat) was launched 13 January 2003 00:45 UTC into a 600 km altitude, 94° inclination, frozen orbit. The primary payload was the Geoscience Laser Altimeter System (GLAS), an instrument intended to detect changes in the polar ice sheets and built at NASA Goddard Space Flight Center. Change detection is based on the determination of the GLAS illuminated spot coordinates on the Earth’s surface, a process referred to as spot geolocation, which requires determination of both the spatial position and the orientation of the GLAS instrument in space [1, 2, 3].

After about 30days of on-orbit laser operation, Laser #1 failed and a review board was convened to investigate the anomaly. The review board made recommendations for operation of the remaining two lasers, which were followed in the following operation periods. To support the science requirement for ice sheet change detection, an operation scenario was adopted in which a laser was operated for approximately 30 day periods, two or three times per year. These operation periods, or campaigns, are summarized in Table 1. The next campaign, known as 3k, is scheduled to begin October 4, 2008. As described in the following discussion, surface change detection is based on analysis of the derived surface elevation (or geodetic height above the Earth reference ellipsoid) and this elevation requires accurate knowledge of the GLAS instrument in space and the laser pointing direction. ICESat is equipped with GPS receivers and a passive array for ground-based satellite laser ranging (SLR).

In Fig. 1, two GPS choke-ring antennas are visible in the zenith view, mounted on the spacecraft bus (built by Ball Aerospace). Each antenna is attached to a JPL BlackJack GPS receiver and only one antenna/receiver set can be operated at a time. Since launch, the same antenna/receiver set has been used (the left-most antenna shown in the zenith view). A passive laser retroreflector array (LRA) mounted on the spacecraft bus (shown in the nadir view) supports SLR.

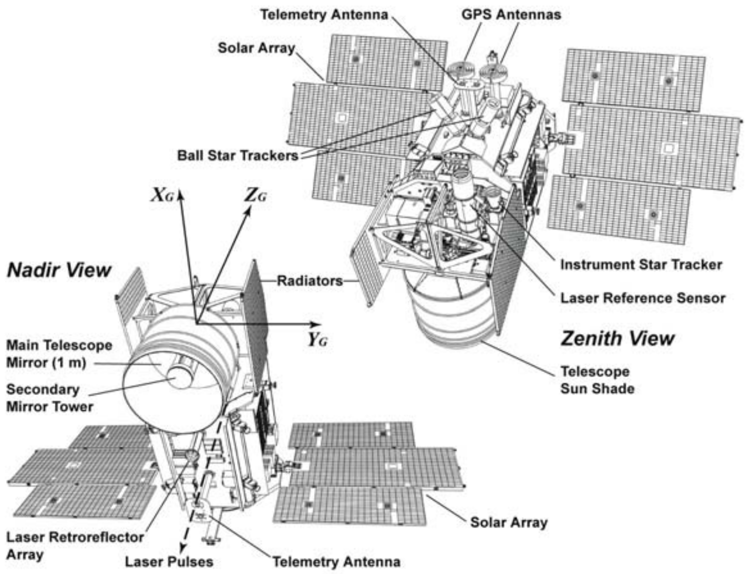

Fig. 1: Nadir and zenith views of ICESat

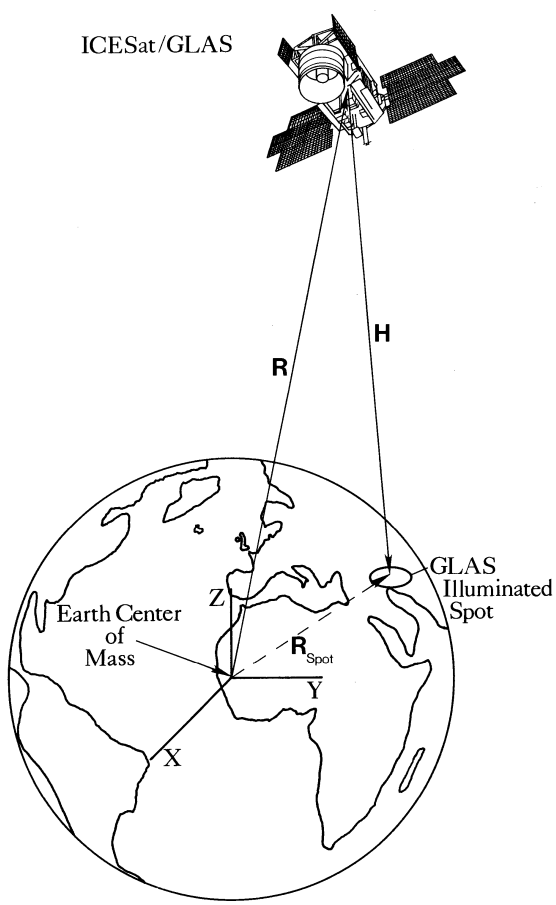

Fig. 2: Determination of laser illuminated spot coordinates

The geolocation of the spot on the Earth's surface, as illuminated by GLAS, is based on the determination of two vectors shown in Fig. 2: the position vector (**R)** that gives the spatial position of a reference point in GLAS, and the altitude vector (**H**) from GLAS to the illuminated spot. The determination of **R** is obtained from the process known as Precision Orbit Determination (POD) and the determination of **H** is obtained from the laser pulse round-trip travel time and directional information obtained, in part, from the process known as Precision Attitude Determination (PAD). This paper focuses on POD.

2. ICESat POD

ICESat Precision Orbit Determination (POD) is based on the GPS pseudo-range and carrier phase measurements acquired by the operating BlackJack (BJ) receiver and a batch processing methodology [4]. The BJ measurements are double-differenced with measurements acquired by the International GNSS Service (IGS) network of global receivers. The POD team at CSR has generated POD solutions over the periods when the GLAS laser altimeter was active. Thirteen such laser campaigns, each of 33 days or more, have been conducted (the fourteenth campaign begins October 4, 2008). "Rapid" POD products are generated with about 3-day latency using the IGS Rapid products (IGR), while "Final" POD products are generated with about three week latency based on the final IGS ephemeris products (known as IGS).

A common method for evaluating the POD precision is to compare ephemerides that are adjacent in time and overlap. For ICESat POD, a 30-hour arc is processed, where the middle 24-hour is the daily POD product and the additional 6-hours overlaps with the independently determined adjacent arcs. Orbit comparison in the overlapping region provides a measure of precision. Such a measure, while somewhat representative of the orbit accuracy, usually provides an optimistic estimate. The ground-based laser ranging measurements provide an independent tool to assess the accuracy of ICESat POD. By withholding the SLR data from the POD solution, range residuals can be formed using the adopted tracking station coordinate and the GPS-determined ICESat ephemeris.

The ICESat orbit modeling includes a GRACE-derived model of the gravitational field of the Earth [5], an extensive solid Earth and ocean tide model, third-body effects and models representing nongravitational forces, such as atmospheric drag and radiation pressure. The daily POD estimated parameters include the ICESat state, empirical once per orbital revolution parameters and GPS double difference ambiguity parameters.

3. GPS Data

ICESat carries two JPL Blackjack GPS receivers (one receiver operates at a time) to collect high precision GPS data to support POD activities. The GPS receiver #1 was powered up January 17, 2003 at about 15:15 UTC and has remained on. Performance of the receiver has been comparable to pre-launch testing in signal simulators. POD team at CSR has generated POD solutions over the periods when the laser altimeter was turned on. Table 1 summarizes the ICESat Laser Campaigns conducted so far. Each campaign lasted about 35 days in duration.

Table 1. ICESat Laser Campaigns

Campaign	Year	DOY	Calendar Date	Duration (days)
L1	2003	051–088	02/20–03/29	38
L2a	2003	268–322	09/25–11/18	55
L2b	2004	048–081	02/17–03/21	34
L2c	2004	139–173	05/18–06/21	35
L3a	2004	277–313	10/03–11/08	37
L3b	2005	048–083	02/17–03/24	36
L3c	2005	140–174	05/20–06/23	35
L3d	2005	294–328	10/21–11/24	35
L3e	2006	053–087	02/22–03/28	35
L3f	2006	144–177	05/24–06/26	34
L3g	2006	298–331	10/25–11/27	34
L3h	2007	071–104	03/12–04/14	34
L3i	2007	275–309	10/02–11/05	35

“Rapid” POD products are generated using rapid IGS GPS ephemerides, and rapid solar flux and geomagnetic indices.

Figure 4 shows the number of tracked GPS satellites for each campaign. Note that the maximum number of GPS satellites to be tracked by the on-board GPS receiver was set to be eight. Figure 2 shows the number of GPS receiver resets each day for each campaign. The number of resets reduced significantly after the first two campaigns. The resets are related to the use of an early version of BlackJack software.

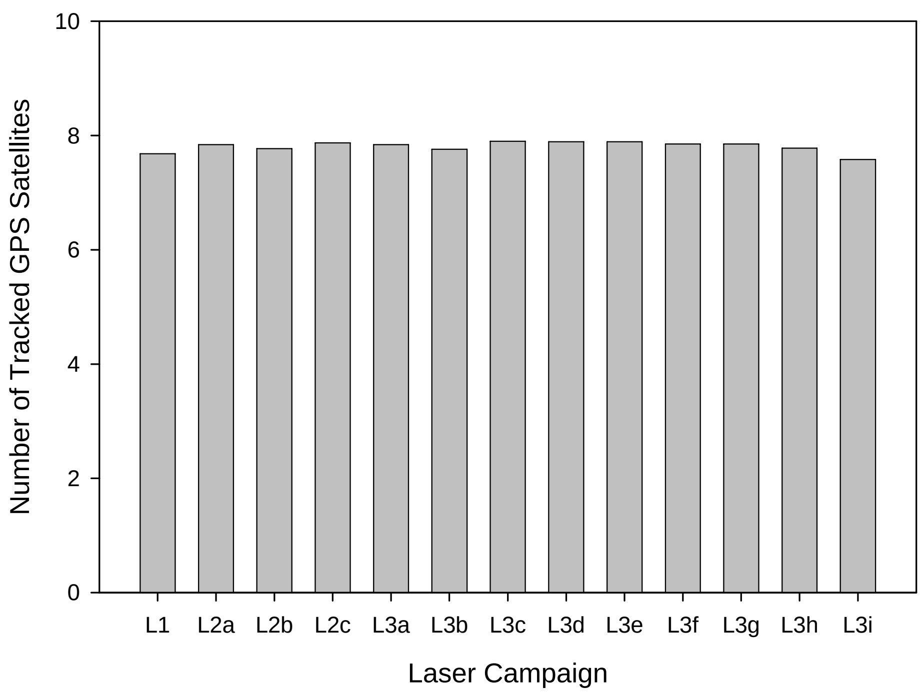

Fig. 3. Average Number of Tracked GPS Satellites

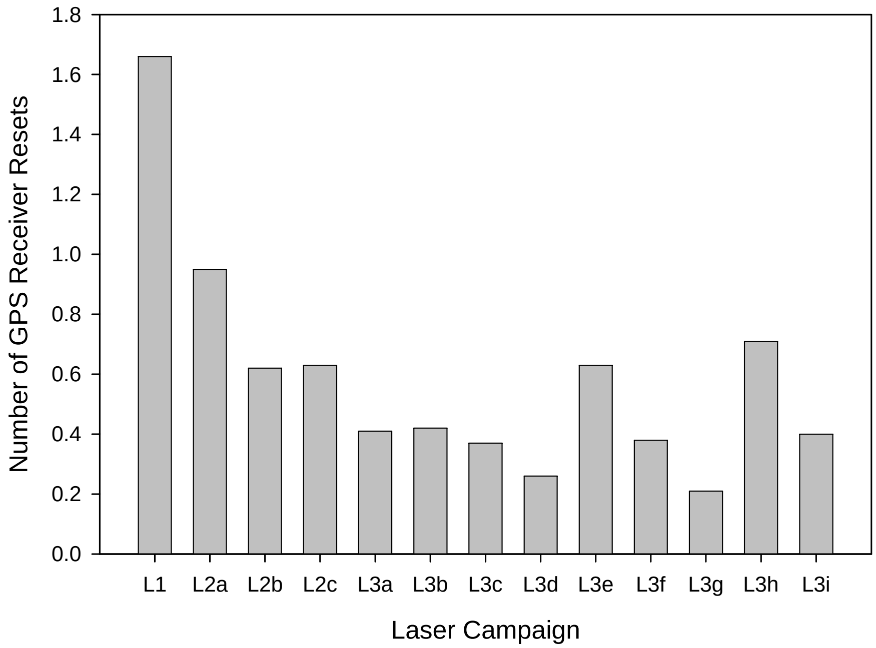

Fig. 4. GPS Receiver Resets per Day

4. SOLUTION STRATEGIES

Typical arc length is 30-hours with 6-hour overlaps. Double-differenced carrier phase measurements using about 40 ground stations were generated with 30 second sampling. Using a preprocessing software called TEXGAP (university of TEXas Gps Analysis Program), the time tags are corrected using the pseudorange measurements, L1 and L2 phase measurements are combined to remove the first-order ionospheric effects, the outliers are edited, and cycle-slips are fixed. For ICESat orbit determination, fully dynamic approach with high parameterization was employed using MSODP (Multi-Satellite Orbit Determination Program).

ICESat POD models consist of reference frame related models, force models, and measurement models. IERS 1996 and 2003 standards were adopted for this POD analysis. GGM01 was used as the geopotential model. Solid earth tides and Ocean tides (CSR TOPEX_4.0) were modeled. Rotational deformation and relativity effects were modeled. JPL's DE405 was used as the planetary ephemerides for N-body perturbations. Solar and Earth radiation pressure forces were modeled using a macro model, and the atmospheric drag was modeled using MSIS model.

Tropospheric effects were modeled using MTT mapping function and surface meteorological data from ground stations. We applied 15° elevation cutoff for ground GPS stations, while 0° elevation cutoff was applied for ICESat GPS receiver. Station coordinates were fixed to ITRF2005 solutions, and the GPS orbits were fixed to IGS orbits.

ICESat attitude was determined using the Instrument Star Tracker (IST), and the on-board solar array orientation information was used to provide appropriate solar array orientation. The PAD was used in the POD process.

Estimated parameters in orbit determination process include ICESat initial conditions., once per revolution Cd, one per revolution one-cycle-per-revolution (1-cpr) along-track and cross-track parameters, double-differenced ambiguity parameters, 2.5-hour zenith delay parameters for ground stations, and the radial-component of center-of-mass offset correction parameter for ICESat GPS antenna.

5. POD VALIDATION

A common method for evaluating the POD precision is to compare ephemerides that are adjacent in time and overlap. For ICESat POD, a 30-hour arc is processed, where the middle 24-hour is the daily POD product and the additional 6-hours overlaps with the independently determined adjacent arcs. Orbit comparison in the overlapping region provides a measure of precision. Such a measure, while somewhat representative of the orbit accuracy, usually provides an optimistic estimate.

Table 2 summarizes the mean double-differenced RMS for both Rapid and Final POD solutions. The double-differenced RMS for all solutions is about 1 cm.

Table 2. Mean DD-RMS
(All units are in cm)

Campaign	Rapid POD	Final POD
L1	1.03	1.01
L2a	1.07	1.02
L2b	1.04	1.01
L2c	1.06	1.04
L3a	1.00	1.00
L3b	1.01	1.00
L3c	1.02	1.01
L3d	1.03	1.02
L3e	1.01	1.01
L3f	1.07	1.07
L3g	1.02	1.02
L3h	1.04	1.03
L3i	1.04	1.03
Mean	1.03	1.02

Table 3. Mean Overlap Statistics (All units are in cm)

Campaign	Rapid POD				Final POD			
	R	T	N	3D RSS	R	T	N	3D RSS
L1	0.70	1.16	0.73	1.56	0.63	1.03	0.68	1.42
L2a	0.82	1.26	0.75	1.72	0.79	1.36	0.67	1.77
L2b	0.80	1.27	0.80	1.74	0.71	1.01	0.69	1.46
L2c	0.71	1.08	0.72	1.50	0.63	1.01	0.70	1.41
L3a	0.68	1.06	0.69	1.47	0.63	1.02	0.69	1.41
L3b	0.60	0.96	0.81	1.42	0.54	0.89	0.76	1.32
L3c	0.74	0.94	0.49	1.32	0.74	0.94	0.48	1.32
L3d	0.60	0.96	0.56	1.28	0.59	0.96	0.57	1.29
L3e	0.59	0.93	0.54	1.24	0.59	0.89	0.54	1.21
L3f	0.67	1.16	0.77	1.57	0.66	1.11	0.78	1.53
L3g	0.52	0.82	0.60	1.16	0.53	0.85	0.60	1.19
L3h	0.56	0.88	0.69	1.28	0.55	0.88	0.73	1.29
L3i	0.66	0.93	0.55	1.29	0.64	0.90	0.54	1.24
Mean	0.67	1.03	0.67	1.43	0.63	0.99	0.65	1.37

Table 3 shows the mean orbit overlap statistics for each campaign. The mean of the mean radial orbit overlap for all campaigns is less than 7 mm for both Rapid and Final POD solutions, and the mean of 3D RSS is less than 1.5 cm. Note that there is slight improvement in DD-RMS and orbit overlaps in the Final solutions comparing with the Rapid solutions.

The ground-based laser ranging measurements provide an independent tool to assess the accuracy of ICESat POD. By withholding the SLR data from the POD solution, range residuals can be formed using the adopted tracking station coordinate and the GPS-determined ICESat ephemeris. Ten SLR stations participate in the ranging to ICESat. Those are Zimmerwald, McDonald Observatory, Yarragadee, Greenbelt, Monument Peak, Maui, Graz, Rgo, Arequipa, and Hartebeesthoek. To assure the safety of the detector in GLAS instrument, a 70-degree maximum elevation pointing restriction has been imposed on those ground stations participating in the ranging. This precludes illumination during nadir and all nominal off-nadir operations.

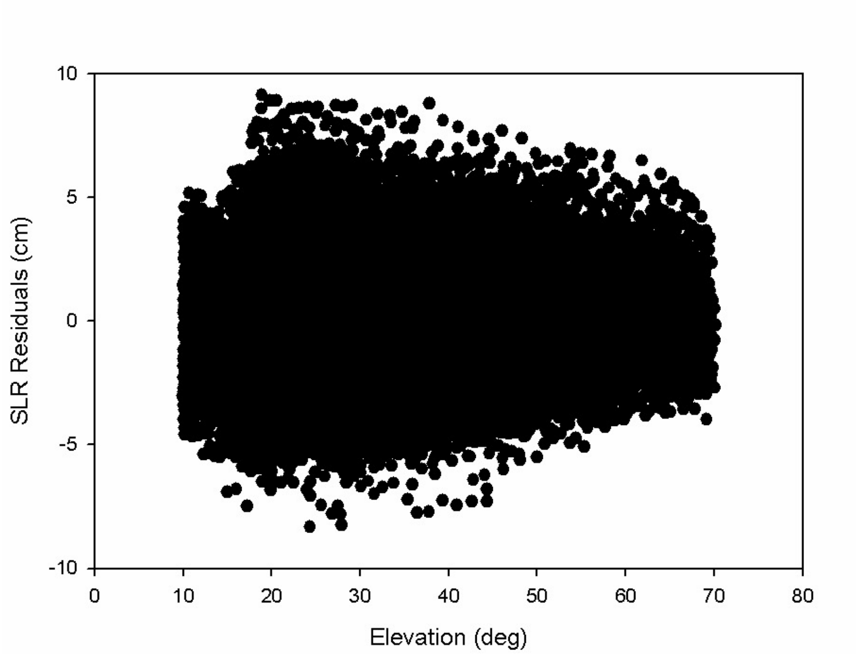

Fig. 5. SLR Residuals as function of elevation angle.

Figure 5 shows the SLR residuals by the elevation angle. Note that the SLR residuals decrease as the tracking elevation increases. SLR residuals reflect not only the radial component of orbit errors, but also a part of the horizontal component. Usually, the high elevation residuals represent more of the radial component of the orbit accuracy, but unfortunately, we don't have tracking over 70-degree due to the restriction mentioned above. To quantify the contribution of the radial orbit errors to the SLR residuals, a "radial" RMS was calculated based on the tracking geometry. Also, high elevation residuals are computed using SLR data above 60 degree elevation. Two SLR station coordinate systems were used for this analysis. One is the ITRF-2000, and the other is the ITRF-2005.

Table 4 summarizes the SLR residual statistics for the Final POD. Note that the tracking from the participating stations was increased substantially, and about 6.6 passes were tracked per day for the recent four campaigns. The overall RMS was 2.27 cm and 2.08 cm for ITRF-2000 and ITRF-2005 case, respectively. There was about 2 mm improvement in overall RMS for using ITRF-2005 coordinate system. The "radial" RMS was 1.41 cm and 1.31 cm, and the high elevation (above 60 degree) RMS was 1.80 cm and 1.89 cm for ITRF-2000 and ITRF-2005 case, respectively.

Table 4. ICESat SLR Residuals for Final POD (All units are in cm)

Campaign	Pass	# Data	ITRF-2000			ITRF-2005		
			RMS	Radial	RMS > 60°	RMS	Radial	RMS > 60°
L1	22	330	1.51	0.91	n/a	1.35	0.83	n/a
L2a	8	272	1.79	1.09	1.60	1.78	1.11	1.77
L2b	3	37	1.83	0.98	n/a	1.68	0.91	n/a
L2c	22	243	2.55	1.68	1.15	1.84	1.15	1.43
L3a	6	48	2.25	1.42	n/a	1.49	0.92	n/a
L3b	37	999	1.81	1.04	0.95	1.77	1.04	1.61
L3c	68	1860	2.00	1.23	1.53	1.88	1.16	1.42
L3d	191	6278	2.42	1.45	2.01	2.07	1.22	1.55
L3e	84	3147	2.16	1.31	1.76	1.75	1.08	1.81
L3f	216	7741	2.49	1.57	1.93	2.16	1.38	1.79
L3g	241	8866	2.45	1.54	2.04	2.55	1.63	2.49
L3h	221	8509	2.03	1.25	1.50	1.82	1.16	1.80
L3i	235	8271	2.18	1.34	1.53	1.96	1.23	1.47
Total	1355	46601	2.27	1.41	1.80	2.08	1.31	1.89

Table 5 summarizes the SLR residual statistics by the tracking stations for the Final POD. Zimmerwald tracks with two laser frequencies, one for infrared (I), and the other for violet (V). McDonald Observatory has two detectors, one for testing (1). Yarragadee has the best tracking with 342 passes total. Hartebeesthoek generated the worst RMS of about 3.6 cm for both ITRF-2000 and ITRF-2005 cases. Yarragadee and Greenbelt have the least RMS of about 2 cm for ITRF-2000, and better than 2 cm for ITRF-2005 case. These stations generate the least “radial” RMS of about 1.2 cm for ITRF-2000, and about 1 cm for ITRF-2005 case. There are some stations which have mean value of more than 1 cm, such as McDonald (1), Maui, Graz, and Hartebeesthoek for ITRF-2000, and McDonald (1), Maui, and Hartebeesthoek for ITRF-2005 case. There might be some biases, such as station bias, station coordinate errors, that contribute to these large mean. Among all stations, Yarragadee performed the best with 1.54 cm RMS, 0.93 cm “radial” RMS, and 1.45 cm for high elevation RMS using ITRF-2005 coordinate system. Based on the SLR residual analysis, it can be concluded that ICESat POD has exceeded the pre-launch accuracy requirement of 5 cm.

Table 5. ICESat SLR Residuals for Final POD
(All units are in cm)

Station	Pass	# Data	ITRF-2000				ITRF-2005			
			Mean	RMS	Radial	RMS > 60°	Mean	RMS	Radial	RMS > 60°
Zimmerwald-I	205	5612	-0.81	2.58	1.60	1.89	0.46	2.44	1.55	2.14
Zimmerwald-	209	6269	-0.33	2.43	1.51	1.72	0.88	2.53	1.64	2.66
V	7	159	-2.97	3.34	1.89	n/a	-2.80	3.02	1.72	n/a
McDonald (1)	73	981	0.46	2.30	1.37	n/a	-0.04	1.95	1.17	n/a
McDonald (2)	342	14860	-0.31	2.02	1.21	1.64	-0.56	1.54	0.93	1.45
Yarragadee	80	3205	-0.21	1.98	1.14	1.68	0.14	1.90	1.12	1.80
Greenbelt	109	3782	-0.95	2.10	1.36	1.98	-0.73	1.92	1.25	1.78
Monument	12	433	1.25	2.45	1.53	3.46	1.25	2.45	1.53	3.46
Peak	156	6138	-1.29	2.25	1.33	2.01	-0.82	2.02	1.17	1.56
Maui	107	3743	-0.76	2.22	1.57	1.69	-0.59	2.16	1.53	1.68
Graz	13	183	0.33	2.43	1.67	2.29	0.31	2.44	1.67	2.31
Rgo	42	1236	0.99	3.65	2.32	2.36	1.12	3.62	2.28	2.15
Arequipa										
Hartebeesthoek										
Total	1355	46601	-0.52	2.27	1.41	1.80	-0.18	2.08	1.31	1.89

6. PREDICTION EXPERIMENTS

A near-real-time prediction is required for aspects of ICESat operation in the ground data system; hence, daily experience with predictions has been acquired. However, the accuracy requirements for this operation are not stringent. For this aspect, the BJ receiver derived navigation solution is used as the observation set for an orbit determination processing in which epoch state, radiation pressure and drag coefficients are estimated, as well as coefficients of an empirical once per orbital revolution along-track and cross-track variation. These estimated parameters are used in a one-day prediction. In late 2003 (days 301-303) during a period of solar storm activity, the prediction accuracies were as much as 2 km; however during a period of low solar activity in 2008 (days 075-078), the prediction accuracies were less than 50 m.

In special prediction experiments that used the estimated parameters from the POD process for the same time interval used in the preceding paragraph, the high solar activity predictions exhibited about 2 km error, but the low solar activity case was better than 20 m.

7. CONCLUSIONS

The POD analysis, based on thirteen ICESat Laser Campaigns of GPS data spanning more than 450 days over 5 years, has been shown to provide less than 1 cm radial precision and the SLR residual analysis has provided a measure of the radial accuracy of 1-2 cm to support determination of the data products. Regular orbit predictions and orbit prediction experiments show the expected high correlation with solar activity, but the POD methodology shows no significant degradation with solar activity.

8. REFERENCES

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