Pre-Launch Testing of GPS Receivers for Geodetic Space Missions

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Biography

Dr. George Davis received his Ph.D. in Aerospace Engineering from the University of Texas in 1996. His dissertation research focused on GPS-based precision orbit determination for low altitude geodetic satellites. Following the completion of his degree, he joined the University of Colorado Center for Astrodynamics Research as postdoctoral research associate and managed the development of an automated orbit determination system for a commercial imaging satellite. In 1997, Dr. Davis joined the Orbital Sciences Corp. to support the NASA Goddard Space Flight Center in the research, development, and testing of spaceborne GPS technologies and applications.

Edward Davis received his BS degree in Mathematics from Salisbury State University in 1985. His recent positions include that of the Goddard GPS Test Facility (GGTF) manager, SpaceHab Universal Communications GPS lead engineer, and the Amateur Radio Satellite (AMSAT), GPS experiment lead engineer. Mr. Davis built the GPS simulator test scenarios, and assisted in the VCL and ICESat test plan development efforts.

Scott Luthcke received his BS degree in Physics from the University of Maryland in 1988 and an MS degree in Applied Physics from the Johns Hopkins University in 1994. He is currently employed by the Raytheon ITSS and resides at the Space Geodesy Branch of the Goddard Space Flight Center. His research focuses on precision orbit determination and altimeter data analysis for planetary research applications. He is currently a mission Co-Investigator and science team member for the NASA ESSP Vegetation Canopy Lidar mission and is a member of the TOPEX/Poseidon precision orbit determination and Shuttle Laser Altimeter teams.

Kimberly Hawkins received her BS degree in Physics from the James Madison University in 1983. Ms. Hawkins is currently responsible for verifying that the JPL Blackjack GPS receivers meet the ICESat Mission requirements.

Abstract

The methodology used and the results obtained in the pre-flight testing of the Blackjack GPS space receiver for the VCL and ICESat spacecraft is described. Both real and simulated signals were used to: (1) assess the accuracy and coverage of the navigation solutions, (2) assess the accuracy and stability of the 1-PPS timing signal, (3) assess the precision of the carrier phase observable, and (4) measure the cold-start time to first fix. In addition, an anechoic chamber was used to measure the antenna phase centers with mm-level precision. While the test results have generally been excellent and are discussed in this paper, emphasis is placed on describing the test methodology. It is anticipated that future geodetic satellite missions using GPS for navigation, timing, and POD can employ the same tests for pre-launch performance assessment of their particular receiver.

1.0 INTRODUCTION

Geodetic space missions such as VCL and ICESat place stringent demands upon the use of GPS receivers for navigation, timing, and precise orbit determination (POD). For example, such receivers must continuously track all viewable GPS satellites and must provide navigation solutions with at least the level of accuracy specified in the GPS ICD-200 (100 m, 1-σ). This requirement is typically linked to the use of the real-time position information to range gate science instruments such as lidars and altimeters. Such receivers must also output a 1-pulse-per-second (1-PPS) timing signal accurate to 1 microsecond or better. This requirement is typically linked to the use of the timing signal to synchronize the spacecraft and instrument clocks to GPS time, an increasingly important function of spaceborne GPS. The carrier phase data generated by such receivers must also have millimeter precision to support few-centimeter to few-decimeter POD. Finally, it is desired that the receiver be capable of cold-start acquisition (no host vehicle ephemeris or GPS almanac required) in less than 30 minutes to avoid significant losses of science data when resets due to single event upsets or latch-ups occur.

In this paper, the methods for testing the GPS space receivers for the VCL and ICESat spacecraft at the NASA Goddard Space Flight Center (GSFC) are described. Both real and simulated signals were used to: (1) assess the accuracy and coverage of the navigation solutions, (2) assess the accuracy and stability of the 1-PPS timing signal, (3) assess the precision of the carrier phase observable, and (4) measure the cold-start time to first fix. In addition, an anechoic chamber was used to measure the antenna phase centers with mm-level precision. It is anticipated that future geodetic satellite missions using GPS for navigation, timing, and POD can employ the same tests for pre-launch performance assessment of their receiver.

2.0 VCL AND ICESAT MISSION OVERVIEW

The Vegetation Canopy Lidar (VCL) spacecraft is part of the Earth System Science Pathfinder (ESSP) program [1]. With a nominal mission length of 18 months, VCL will characterize the three-dimensional structure of the Earth's land cover and solid surface by making global measurements of vegetation height, vegetation vertical structure, and surface elevation with a spaceborne multi-beam laser altimeter. ICESat is part of the Earth Observing System (EOS) program to acquire data for the long-term study of the Earth's global processes and systems [2]. With a nominal mission length of 3 years, ICESat will retrieve globally distributed cryosphere, atmosphere and land topography altimeter and lidar data. The baseline orbit parameters for VCL and ICESat are summarized in Table 1.

Table 1. VCL and ICESat Orbit Parameters

	VCL	ICESat
altitude	400 km	600 km
eccentricity	0.001	0.0013
inclination	67 deg	94 deg

The GPS receiver requirements to support the VCL and ICESat missions are summarized in Table 2. The accuracy of the 1-PPS timing pulse and the accuracy of the real-time navigation solutions are driven by the use of the GPS receiver for real-time range gating of the instruments. The requirements on the number of dual-frequency channels and on the precision of the observables are driven by the POD requirements. Note that the ICESat POD requirements are more stringent than that of VCL. The ICESat mission includes the need for precisely repeating ground tracks from season to season to measure elevation changes in local ice sheets, thus placing more exacting demands on the receiver.

Table 2. VCL and ICESat GPS Requirements

	VCL	ICESat
1-PPS Timing Accuracy	10 μsec	1 μsec
Number of Dual-Frequency Channels	≥8	≥9
Data Noise:		
Pseudorange	100 cm (1-σ)	30 cm (1-σ)
Carrier Phase	3 cm (1-σ)	0.1 cm (1-σ)
Real-time Navigation:		
Position	100 m (1-σ)	100 m (1-σ)
Velocity	2 m/sec (1-σ)	1 m/sec (1-σ)
POD Accuracy:		
Radial	30 cm RMS	5 cm RMS
Horizontal	100 cm RMS	20 cm RMS
Antenna Phase Center Location:	1.5 cm (1σ)	5 mm (3σ)

3.0 GPS SPACE RECEIVER

Both VCL and ICESat will fly the BlackJack GPS receiver being developed by the NASA Jet Propulsion Laboratory for geodetic and atmospheric satellite science missions. The BlackJack is a state-of-the-art, 48-channel, L1/L2 Y-codeless GPS space receiver. Three channels per GPS satellite are used for C/A-code tracking of the L1 carrier and codeless tracking of the L1 and L2 carriers, so it is capable of codeless tracking of up to 16 GPS satellites.

For VCL and ICESat, the BlackJack is part of a GPS system that is comprised of a receiver, a dual-frequency patch antenna, and a radio frequency (RF) cable. The receiver, built by Spectrum Astro, Inc., includes a low noise amplifier to boost the power of the receiver GPS signals. The antenna is a stacked dual-element passive patch antenna developed by Sensor Systems, Inc. for aviation applications. The cable is a low loss Gore-Tex RF cable.

4.0 TEST FACILITIES AND EQUIPMENT

The pre-flight testing of the BlackJack was conducted at the Goddard GPS Test Facility (GGTF) and at the Goddard Geophysical and Astronomical Observatory (GGAO. The GGTF, a world-class facility for GPS receiver test and development, was used to assess the BlackJack acquisition and tracking performance in a simulated orbital environment.

The GGTF houses GSSI. STR 2760 GPS signal simulator, and a GSSI STR 4760 GPS signal simulator, for both ground and space receiver testing. The STR 2760 is a dual-frequency, 40-channel, 4-antenna output simulator that can simulate both the C/A-code and P-code on the L1 carrier and the P-code on the L2 carrier for up to 10 GPS satellites on each of four RF outputs. The STR 4760 has the same features as the 2760, but has 64 versus 40 channels to simulate up to 16 channels per output. The GGTF will also house a second STR 4760 in the near future. Navigation message data superimposed on the L-band carriers along with the codes can be obtained from an actual GPS almanac, or can be specified by the user. The user can also control the power levels of the signals being generated, as well as introduce clock, ionosphere, troposphere, and navigation data errors.

For "live sky" testing, the GGTF provides several roof-top antennas with line-loss compensated cables to supply real GPS signals in a laboratory environment. A roof-top radome is also available for testing GPS equipment outdoors without exposing receivers, antennas, computers, etc. to rain or snow..

The GGAO consists of a radio telescope for very-long baseline interferometry (VLBI), several telescopes for satellite laser ranging (SLR), a GPS timing and development lab, meteorological sensors, and a hydrogen maser clock. The long history of VLBI and SLR positing has made the GGAO an important fiducial site for the International GPS Service (IGS). The GGAO operates several IGS receivers, with GODE being perhaps the most important. The GGAO was used in zero-baseline testing of the BlackJack to assess the data precision and timing accuracy.

5.0 PERFORMANCE TESTS

A summary of the tests performed is provided in Table 3. As previously discussed, these tests were carried out with a test load of the BlackJack software, not the expected flight load.

Table 3. Summary of Performance Tests

Case	Description
1	The BlackJack flight system was tested inside the GGTF rooftop radome to ensure that the receiver, cable, and antenna obtained acceptable signal levels from real sky signals.
2.1	The Case 1 SNR data were used to calibrate the output power of the GPS signal simulator for all simulated orbital tests.
2.2	The BlackJack was tested using the GPS signal simulator in the orbital mode for time-to-first-fix.
2.3	The BlackJack was tested for navigation performance using the GPS signal simulator in the orbital mode for 24 hours.
2.4	The accuracy and stability of the BlackJack 1-PPS timing pulse was assessed with a digital oscilloscope.
3	The BlackJack receiver was tested to verify the accuracy of the 1-PPS timing pulse.

The Case 1 testing used real sky GPS signals with the GPS flight system. The purpose of this test was to demonstrate that the insertion loss due to the RF cable would not cause unacceptably low signal levels. The signal-to-noise (SNR) ratio data obtained in this test was used to calibrate the output power of the GPS signal simulator in the Case 2 tests. The test configuration is shown in Fig. 1.

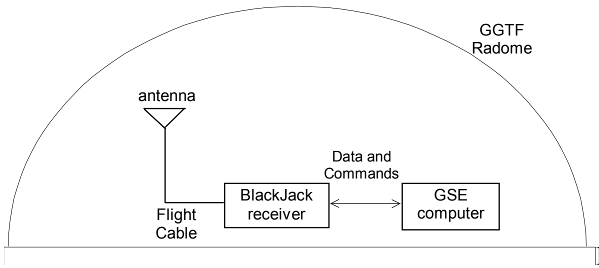

Figure 1. Case 1 Test Configuration

Case 2 testing used simulated GPS signals obtained from the STR 2760 GPS signal simulator. The simulated signals were fed directly into the BlackJack antenna port. The Case 1 SNR data were used to calibrate the output power of the GPS signal simulator. The purpose of the Case 2 tests was to demonstrate the ability of the BlackJack to acquire signals and to navigate in an orbiting environment. It was also used to characterize the 1-PPS timing signal with a digital oscilloscope. The test configuration is shown in Fig. 2.

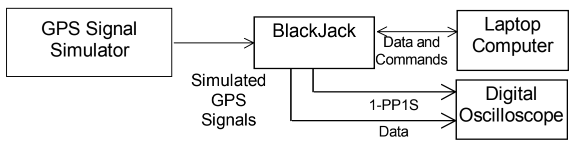

Figure 2. Case 2 Test Configuration

Case 3 testing used real sky GPS signals obtained from the GGAO choke ring antenna. A multi-port RF splitter was used to provide the BlackJack the same GPS signals being provided to the GGAO's TurboRogue-12 (TR-12) and Totally Accurate Clock (TAC) receivers. The TR-12 is a dual-frequency geodetic receiver and the TAC is a single-frequency timing receiver. Both use a hydrogen maser as an external oscillator. Since the TR-12 has been tracking continuously for several years, it provides a reference against which the navigation performance of the BlackJack can be compared. The TAC is known to provide UTC time accurate to within 20 nanoseconds, so it provides a reference against which the BLACKJACK timing performance can be compared.

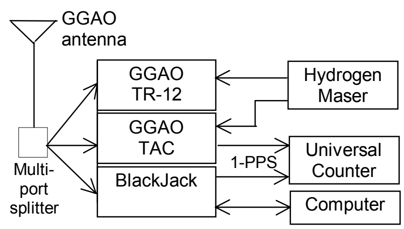

Figure 3. Case 3 Test Configuration

4.1 CASE 1 RESULTS

In the Case 1 test, the BlackJack flight system (receiver, antenna, and cable) was used to track real GPS signals inside the GGTF rooftop radome. The radome material is specified by the manufacturer to attenuate L-band RF signals by no more 0.3 dB, so the effect on the SNRs is negligible. The purpose of this test was to demonstrate that the insertion loss due to the flight cable would not prevent the receiver from acquiring and tracking real sky signals. Such a test is necessary because GPS receivers are generally tested with roof-top antennas that have large amplifiers to overcome power losses due to long cable runs. In addition, the SNR data obtained from this test was needed to calibrate the GPS signal simulator used in the Case 2 tests.

An example of the C/A, P1, and P2 SNR data for one of the PRNs tracked over the 30-minute session is shown in Fig. 4. It can be seen that the C/A SNR was in the 400-600 volts/volt range, which is considered acceptable for the BlackJack.

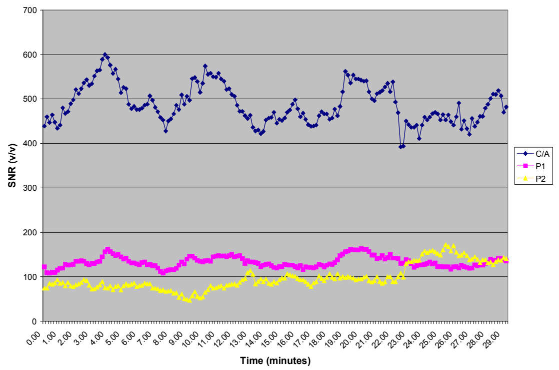

Figure 4. Case 1 SNR Data for PRN 15

The Case 1 BlackJack position data were averaged over the 90-minute tracking session to provide a reference position for comparison with the positions at each data epoch. The true position was not available for comparison because the flight antenna was used to obtain the GPS signals, not one with a surveyed position. The reference position obtained in this manner contains biases due to Selective Availability (SA) since the 90-minute data interval does not provide adequate time for averaging out its effect. The position variations with respect to the reference therefore do not reflect the expected navigation performance that will be obtained on-orbit with the BlackJack flight system. They do, however, demonstrate that the BlackJack flight system tracks real GPS satellites and generates navigation and observable data.

The variation of the Case 1 real-time positions from the reference position is shown in Fig. 5.

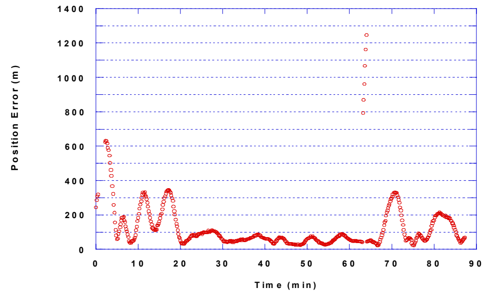

Figure 5. Case 1 Real-Time Position Variation vs. Time

As expected, the real-time positions exhibit the sinusoidal-like variations associated with SA. The large variations observed over the first 20 minutes and again at around 65 minutes, however, are due to the clock errors associated with start-up of the BlackJack. The BlackJack employs clock steering to keep its internal time reference close to that of GPS time, but does so only when tracking 5 or more GPS satellites. As a result, the oscillator drifts rapidly immediately after start-up, after a reset, or whenever tracking falls below 5 satellites.

The unusually large position variations seen in Fig. 5 are due to BlackJack software errors that can result in the incorrect computation of the GPS orbits from the GPS broadcast ephemeris. Such GPS position errors can corrupt the navigation solutions at the km-level, as is demonstrated by the large excursion in Fig. 5. To gain insight on this error, the pseudorange data were post-processed with GPS broadcast ephemerides obtained from the IGS. The post-processed solutions were then averaged over the 90-minute data interval to provide a reference position, and the variations with respect to this reference are shown in Fig. 6. It can be seen that the variation of the post-processed position solutions exhibits the same signature as that of the real-time position solutions, but with smaller magnitude.

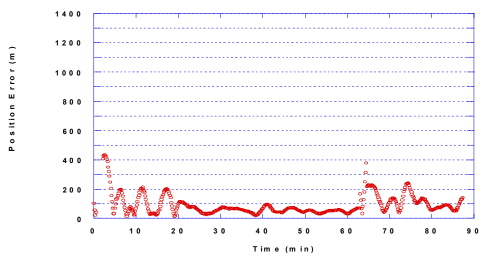

Figure 6. Static, Live Sky Post-Processed Position Variation vs. Time

The real-time solutions were then subtracted from the post-processed solutions at each epoch. The resulting differences are shown in Fig. 7. It can be seen that the real-time and post-processed navigation solutions differ by 100-200 m. These differences should be due solely to the incorrect computation of the GPS spacecraft positions by the BlackJack software since all other common error sources such as SA cancel out.

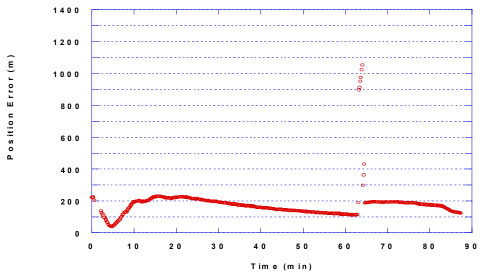

Figure 7. Difference between Real-Time and Post-Processed Position Solutions vs. Time

Since the time these tests were performed, most of the navigation errors in the BlackJack software have been identified and fixed. The use of the GPS signal simulator was very helpful in identifying those errors and demonstrates the importance of such testing for development receivers such as the BlackJack.

4.2 CASE 2 RESULTS

In the Case 2 tests, GPS signals obtained from the STR 2760 simulator were fed directly into the antenna port of the BlackJack. The simulator generated error dual-frequency P-code signals free from measurement errors such as SA and ionosphere delay. These tests were used to establish ranges for the TTFF in the VCL orbit and to assess the navigation accuracy in the orbiting mode.

4.2.1 CASE 2.1 RESULTS

The Case 2.1 test was used to calibrate the output power of the STR 2760 for the orbital simulations using the SNR data collected in the Case 1 test. A static scenario was therefore used to generate GPS signals for a ground-based receiver.

During the Case 2.1 simulation, the gain setting used to boost the GPS signal power above the GPS ICD-200 specification was varied until the SNRs observed from the BlackJack approximately matched those obtained in the Case 1 test. A sample of the SNR data for PRN 15 is summarized in Table 4. Comparing these values to the Case 1 SNR data shown in Fig. 4 suggest that the simulator gain setting should be 11 dB for the orbital tests. It is noted, however, that such an approach to setting the simulator gain is empirical and may require further testing before the optimal gain setting is established.

Table 4. Case 2.1 SNR Data for PRN 15

Simulator Gain (dB)	C/A SNR	P1 SNR	P2 SNR
13	683	371	285
12.1	632	322	241
11.0	568	260	191
10.6	548	245	179
10.0	516	219	144
9.6	493	201	128
11.5	600	293	219
11.0	571	263	195

The BlackJack three-dimensional (3D) position error obtained from the Case 2.1 simulation is shown in Fig. 8. The 3D position error is computed as the root-sum-square of the X, Y, and Z position errors obtained by subtracting the position solutions from the truth position. It can be seen that the position error asymptotically decreases from about 200 m to about 100 m over the data span. This error is due solely to the BlackJack software errors since SA was not simulated.

The BlackJack time bias obtained from the Case 2.1 simulation is shown in Fig. 9. The clock steering employed by the receiver is evident. It is seen that the clock bias was initially –3.5 microseconds and was driven toward zero as the receiver continued to track GPS satellites. The final value for the clock bias was -0.0578 microseconds. Inspection of Figs. 8 and 9 suggest that upon start-up, the large time bias causes large position errors, exceeding those due to the navigation software error.

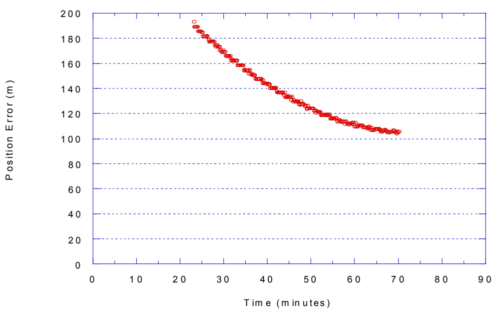

Figure 8. Case 2.1 Position Error vs. Time

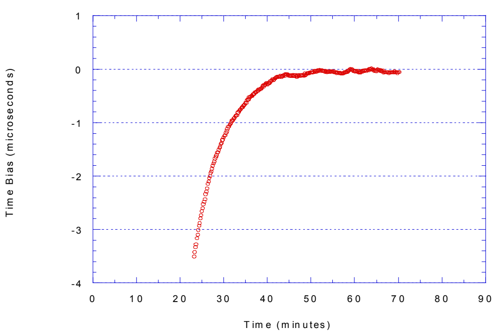

Figure 9. Case 2.1 Time Bias vs. Time

4.2.2 CASE 2.2 RESULTS

To establish the range of Time To First Fix (TTFF) for the BlackJack in the nominal VCL orbit, the initial mean anomaly of the BlackJack was varied from 0 to 315 degrees in increments of 45 degrees. In each case, the BlackJack was allowed to acquire satellites until the first navigation solution was obtained. The TTFF results are shown in Table 6.

Table 6. Time to First Fix in VCL Orbit

Mean Anomaly (deg)	TTFF (min)
0	7
45	9
90	8
135	5
180	5
225	4
270	3
315	5

The BlackJack TTFF in the VCL orbit ranged from 3 to 9 minutes. This variation is due mainly to the sequential search algorithm employed the BlackJack GPS space receiver. Since the BlackJack searches for PRNs sequentially from 1 to 32, it quickly locks on to 4 satellites when the visible PRNs at the time of start up consist mainly of the lower numbered PRN take slightly longer to lock on.

4.2.3 CASE 2.3 RESULTS

The purpose of the Case 2.3 test was to obtain a significant amount of navigation data in the orbital mode so that the BlackJack navigation accuracy could be assessed. It was also desired if receiver resets occurred over a 24-hour period.

The BlackJack 3D position and velocity error obtained from the Case 2.3 simulation, after applying a 1 km edit criterion to the position error, are shown in Figs. 10 and 11, respectively. As shown in Table 7, the post-edit root-mean-square (RMS) radial orbit error obtained from the Case 2.3 simulation, which did not include SA, was 146.7 m, which exceeded the VCL and ICESat requirements.

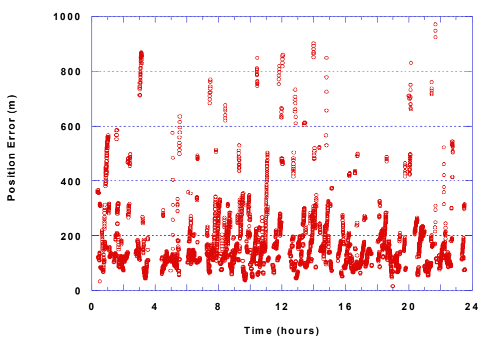

Figure 10. Case 2.3 BlackJack Position Error vs. Time

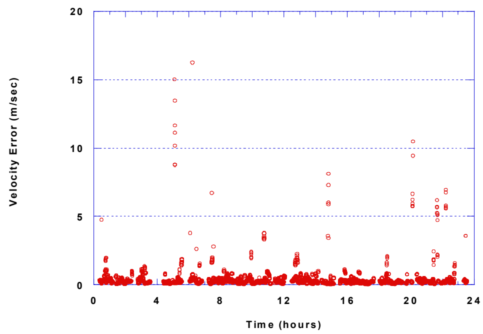

Figure 11. Case 2.3 BlackJack Velocity Error vs. Time

Table 7. Case 2.3 Edited Orbit Error Statistics

	Max	Min	Mean	RMS
X	827.7	-697.2	5.0	111.9
Y	809.6	-680.4	-1.3	123.1
Z	795.9	-751.2	-3.7	105.5
V_X	10.40	-2.52	0.02	0.36
V_Y	1.69	-14.04	-0.01	0.36
V_Z	14.95	-8.11	0.02	0.46
R	781.1	-872.5	4.5	146.5
I	624.8	-632.2	-35.7	92.7
C	611.1	-433.4	0.1	86.51
V_R	6.34	-12.06	-0.06	0.53
V_I	5.95	-3.91	-0.04	0.29
V_C	15.25	-6.73	-0.01	0.31

- position error in m, velocity error in m/sec

4.2.4 CASE 2.4 RESULTS

The Case 2.4 test was used to characterize the 1-PPS timing pulse and data throughput. The output from the 1-PPS timing port and the data port were fed into a calibrated digital oscilloscope, while the output from the beep port was fed into the GSE.

The BlackJack 1-PPS timing pulse is shown in Fig. 12. Each division on the x-axis of the oscilloscope display is 500 nanoseconds, so the width of the timing pulse is approximately 1.7 microseconds wide. This compares well to the 1.8 microsecond specification.

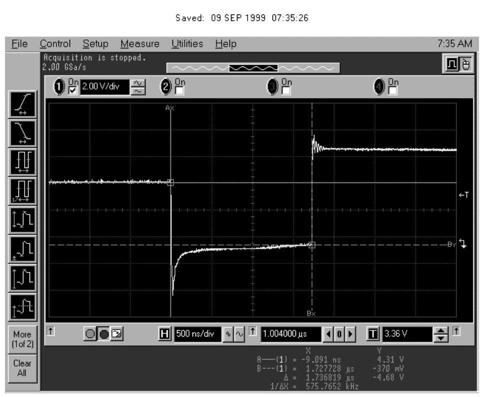

Figure 12. BlackJack 1-PPS Timing Pulse

The data bursts resulting from the output of the timing, navigation, and observable packets over 10 seconds are shown in Fig. 13. The width of these bursts can be very important because of on-board data storage requirements. It can therefore be very important to estimate data buffering needs as a function of time.

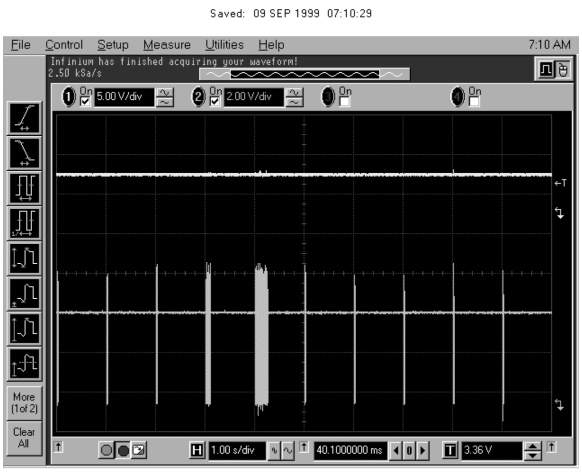

Figure 13. Data Bursts from Time, Navigation, and Observable Packets over 10 Seconds

6.3 CASE 3 RESULTS

In the Case 3 test, the GGAO choke ring antenna and RF splitter were used to provide GPS signals to the BlackJack, the TR-12, the TAC, and to the ICESat BlackJack engineering model (ICESat EM). A sample of the SNRs obtained for the BlackJack, the ICESat EM, and the TR-12 is shown in Table 8. In general, the BlackJack SNR was slightly better or comparable to that of the ICESat EM and the TR-12. Note that both the P2 SNR obtained from the BlackJack and ICESat EM were twice that of the TR-12.

Table 8. Sample of Case 3 SNR Data

		PRN	
		9	29
BlackJack	C/A	505	502
	P1	221	203
	P2	201	221
ICESat EM	C/A	482	462
	P1	207	181
	P2	205	226
GGAO TR-12	C/A	518	497
	P1	110	100
	P2	110	119

In the timing accuracy test, the VCL BlackJack and TAC 1-PPS timing signals were fed into a calibrated universal counter. The BlackJack timing pulse was used to start the counter and the TAC was used to the stop it. The TAC timing signal is known to be accurate to around 20 nanoseconds with respect to UTC as kept by the U.S. Naval Observatory. The TAC timing signal was intentionally delayed 10 microseconds to provide an adequate interval for counting. Consequently, the error in the BlackJack time tag is the sum of the absolute value of the BlackJack timing bias and the count interval minus the 10 microsecond bias.

Samples of the BlackJack time bias were visually obtained every 10 seconds from the GSE screen at three times after power on. The count intervals were also recorded. The time tag accuracy results are summarized in Table 9. It is observed that soon after power up, the BlackJack time tag is in error at the 200 microsecond level. However, after the receiver reaches steady state 30 minutes later, the timing error is on the order of 200 nanoseconds. Another 30 minutes later, the error has increased slightly, but it is still well below the VCL requirement of 10 microseconds.

The Case 3 positioning error is shown in Fig. 14 and the time bias is shown in Fig. 15. The Case 3 positioning error is larger than that obtained in the Case 2.1 ground-based simulation because the real data have SA-induced range errors. Note that upon power up, the time bias increases up to 85 microseconds and then is steered back toward zero once 5 GPS satellites have been tracked for a while. Over this time, the position errors reach 700 m, which is due mainly to the poor PDOP associated with the tracking of only 4 GPS satellites. From about 40 minutes to about 90 minutes into the tracking session, the clock bias is on the order of 0.1 microseconds. The BlackJack then drops to 4 GPS satellites and the time bias begins to grow as clock steering is turned off. During this time, the position error approaches 400 m, again due to poor PDOP. At about 120 minutes past the initial epoch, the BlackJack resumes the tracking of 5 or more GPS satellites and the time bias is again steered toward zero. At about 160 minutes past the initial epoch, the BlackJack again briefly drops to 4 GPS satellites, causing the time bias to drift again until another GPS satellite is picked up.

To see the level of real-time positioning error that should be expected from the BlackJack once the navigation software has been fixed, post-processed position solutions were obtained from the TR-12 pseudorange data. The resulting positioning errors are shown in Fig. 16. Only occasionally does the SA-corrupted positioning error exceed 100 m.

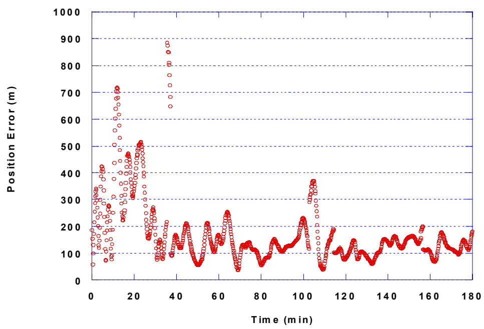

Figure 14. Case 3 BlackJack Position Error vs. Time

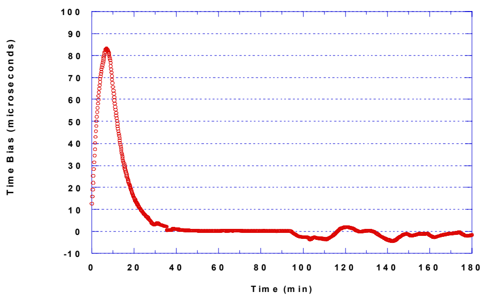

Figure 15. Case 3 BlackJack Time Bias vs. Time

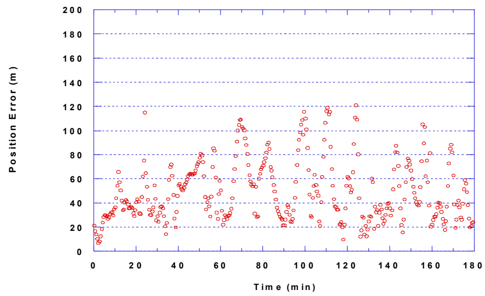

Figure 16. Case 3 TR-12 Position Error vs. Time

The BlackJack carrier phase precision was ascertained in a zero-baseline test. The carrier phase data from Case 1 and Case 3 were processed as double-differenced one-way range observables constructed from the BlackJack carrier phase data and the carrier phase data from the following IGS sites: GODE, ALGO, BRMU, SCH2, SOL1, STJO, USNA, USNO and WES2. The data were processed with GEODYN, a batch filter used in high precision ground- and space-based geodesy applications. In each case, a time tag correction was computed for every observation epoch without application of the receiver computed time bias.

The residuals obtained from the BlackJack-GODE baseline are plotted in Fig. 17.

Table 9. Case 3 Timing Test Results

	ΔT = 9 min			ΔT = 32 min			ΔT = 67 min		
No.	Time Bias	Count Interval	Timing Error	Time Bias	Count Interval	Timing Error	Time Bias	Count Interval	Timing Error
1	-127.46	118.54	236.00	-2.21	7.69	-0.10	+0.18	10.44	0.62
2	-130.07	120.32	240.39	-2.10	7.71	-0.19	+0.18	10.52	0.70
3	-132.09	121.96	244.05	-1.98	7.68	-0.34	+0.18	10.52	0.70
4	-132.86	122.83	245.69	-1.90	7.67	-0.43	+0.16	10.53	0.69
5	-133.54	123.26	246.80	-1.79	7.70	-0.51	+0.16	10.53	0.69
6	-134.07	123.68	247.75	-1.69	7.90	-0.41	+0.12	10.38	0.50
7	-134.66	124.13	248.79	-1.61	7.93	-0.46	+0.12	10.32	0.44
8	-134.76	124.16	248.92	-1.56	8.14	-0.30	+0.13	10.30	0.43
9	-134.72	124.06	248.78	-1.48	8.30	-0.22	+0.12	10.29	0.41
10	-134.47	123.44	247.91	-1.34	8.65	-0.01	+0.09	10.21	0.30
11	-133.82	122.63	246.45	-1.28	8.81	0.09	+0.09	10.26	0.35
12	-133.05	121.96	245.01	-1.23	8.96	0.19	+0.09	10.28	0.37
13	-132.12	120.83	242.95	-1.10	9.13	0.23	+0.11	10.31	0.42
14	-131.08	119.92	241.00	-1.02	9.23	0.25	+0.13	10.38	0.51
15	-129.89	118.04	237.93	-0.95	9.27	0.22	+0.10	10.36	0.46

- times in microseconds

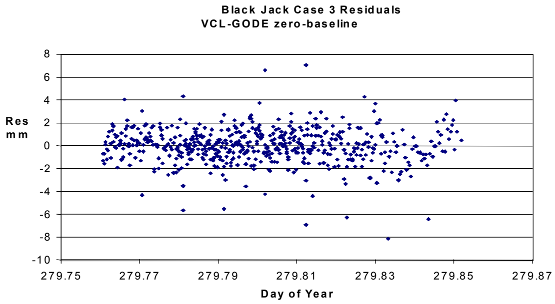

Figure 17. Case 3 TR-12 Position Error vs. Time

The RMS of these residuals is 1.5 mm. The RMS of the residuals obtained from all BlackJack-IGS site baselines is 11.6 mm. Inspection of these residuals, however, showed that the structure was dominated by systematic error sources, such as multipath and residual troposphere delay, and that the scatter of the residuals was actually sub-cm.

When the Case 1 double-differenced data were analyzed, the RMS of the BlackJack-IGS site baselines was 20.1 mm. This analysis required estimation of the flight antenna coordinates, since they were not tied to any kind of survey. Again, inspection of the residuals showed that the structure was dominated by systematic error sources and that the scatter was sub-cm. An important conclusion of this test was that no significant degradation in the residuals was observed when using the flight antenna. Unlike ICESat, the VCL BlackJack will not use a choke-ring to reduce the impact of multipath. The multipath environment of the radome is considered to be much worse that that of the spacecraft itself.

8.0 ANTENNA PHASE CENTER MEASUREMENT

For geodetic missions that require cm-level POD to fully exploit the precision of their instruments, the accuracy of the antenna phase center location is an important component of the overall POD error budget. The spacecraft equation of motions used in the POD filters are based on the motion of the spaceraft center of mass, while the GPS receiver reports positions and measures data relative to the antenna phase center. To use such data in the POD filter, it is necessary to correct for the offset betweem the spacecraft center of mass and the antenna phase center, which can often be on the order of a meter or more. It is therefore necessary to make precise measurements of the antenna phase center.

The antenna phase center measurements for both VCL and ICESat were made at the GSFC Electromagnetic Anechoic Chamber. Figure 18 shows the VCL antenna mounted on a mock-up of its surroundings on the spacecraft, which in turn is mounted on the chamber test fixture. The antenna is the white circular object mounted on the gold-colored backplane in the upper left quadrant of the simulated spacecraft surface.

In Fig. 18, the antenna is seen approximately from the direction of the source test signal. From this viewpoint, the x-axis of the chamber is horizontal and points to the right; the y-axis, also horizontal, points into the paper, parallel to the incident test signal; and the z-axis points up. The azimuth axis is the test fixture's vertical rotation axis, and the head-angle axis is its horizontal rotation axis, which is visible near the center of the figure and nominally intersects the azimuth axis. The azimuth angle of the test antenna is defined by the projection of the head-angle axis onto the x−y plane: zero when the projection parallels the −y-axis of the chamber, as it does in the figure, and increasing toward the −x-axis.

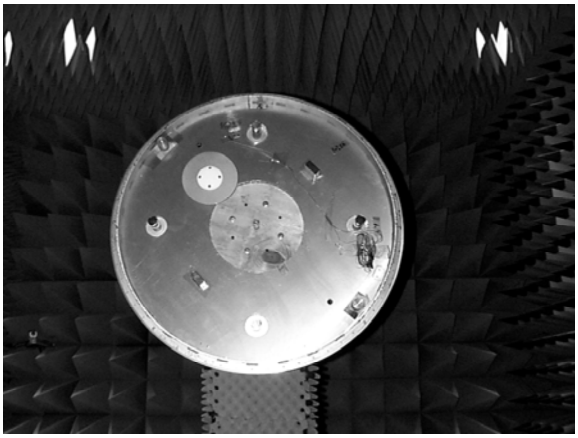

Figure 18. VCL Antenna and Spacecraft Mockup Mounted on Test Fixture

Various mechanical measurements were made to determine the geographic origin of the x-y plane, as well as tilt biases in the x-y, x-z, and y-z planes. Such biases must be removed from the electrical measurements of the phase center, which were made by sending L1 and L2 source signals through the antenna while varying the elevation and azimuth angles of the test fixture.

Table 10 gives the results of the five-parameter fit to the location of the phase center for each frequency, except for a constant phase offset, which is a "nuisance parameter". The data were weighted "sinusoidally" so that equal solid angles in the pattern would have equal influence. Also, only measurements with azimuth angles of ±75° were used in the fit. Here, d is the distance from azimuth axis to phase center, ϕ is the azimuth of phase center at azimuth axis, r is the distance from h-a axis to phase center, and θ is the azimuth of phase center at head-angle axis. The residual RMS is that of the measurements with respect to the model and provides a measure of the uncertainty in the fit, but does not take into account the uncertainty in the mechanical measurements.

Table 10. Locations of the L1 and L2 Phase Centers

Parameter	Value At L1	Value At L2
d	85.47 ± 0.821 mm	89.22 ± 0.610 mm
ϕ	1.34 ± 0.370 deg.	–0.95 ± 0.263 deg.
r	224.07 ± 0.550 mm	224.03 ± 0.404 mm
θ	–134.31 ± 0.166 deg.	–135.11 ± 0.124 deg.
Residual RMS	5.71 mm	4.24 mm

8.0 CONCLUSIONS

Pre-flight testing of the VCL and ICESat GPS space receiver was conducted that the GGTF and at the GGAO. The GGTF was used for testing the BlackJack acquisition and tracking performance using real and simulated GPS signals. The latter were used to test the BlackJack in a simulated orbit environment. The GGAO was used for testing the BlackJack timing accuracy and carrier phase precision.

The tests illustrated what must be done to characterize the performance of a geodetic-quality GPS space receiver before flight. In particular, the tests illustrated the value of comprehensive testing in identifying and fixing software errors that could compromise flight performance. For example, the navigation performance testing was particularly helpful in determining the nature of the GPS ephemeris computation error. It is anticipated that other geodetic satellite missions utilizing GPS for navigation, timing, and POD could perform the same types of test for pre-flight qualification of their receivers.

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