ON ORBIT RECEIVER PERFORMANCE ASSESSMENT OF THE GEOSCIENCE LASER ALTIMETER SYSTEM (GLAS) ON ICESAT

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ABSTRACT

The GLAS instrument on the NASA's ICESat mission has provided over a billion measurements of the Earth surface elevation and atmosphere backscattering at both 532 and 1064-nm wavelengths. The receiver performance has stayed nearly unchanged since ICESat launch in January 2003. The altimeter receiver has achieved a less than 3-cm ranging accuracy when excluding the effects of the laser beam pointing angle determination uncertainties. The receiver can also detect surface echoes through clouds of one-way transmission as low as 5%. The 532-nm atmosphere backscattering receiver can measure aerosol and clouds with cross section as low as 1e-7/m·sr with a 1 second integration time and molecular backscattering from upper atmosphere with a 60 second integration time. The 1064-nm atmosphere backscattering receiver can measure aerosol and clouds with a cross section as low as 4e-6/m·sr. This paper gives a detailed assessment of the GLAS receiver performance based on the in-orbit calibration tests.

1. INTRODUCTION

The Geoscience Laser Altimeter System (GLAS) was developed at NASA Goddard Space Flight Center for the Ice, Cloud, and land Elevation Satellite (ICESat) mission [1-2]. It measures both the Earth surface topography and atmosphere backscattering profiles from a 600 km near polar circular orbit. It uses diode-pumped Q-switched Nd:YAG laser with 1064 and 532-nm dual wavelength outputs. The laser pulse energy at launch was about 75 mJ at 1064 nm and 35 mJ at 532 nm. The laser pulse width is 5 to 6 ns and the pulse rate is 40 Hz. The laser footprint diameter on ground track is about 70 m. There are three receiver channels: (1) the surface elevation measurement channel at 1064-nm wavelength with a 100-MHz electrical bandwidth detector and 1-Gs/s pulse waveform sample rate; (2) the 1064-nm cloud backscattering measurement channel with a 2 Ms/s sample rate; (3) the 532-nm aerosol and cloud backscattering measurement channel with a set of single photon counting detectors and 75-m vertical range bins. GLAS also has a stellar reference system (SRS) that relates the laser pointing angle to the star field and hence the initial space. An on board GPS receiver provides the spacecraft position and time information.

The initial GLAS in-orbit measurement performance has been reported in [3]. A detailed description of the laser design and on-orbit performance can be found in [3-4]. The SRS design and performance has been reported in [5]. This paper gives a detailed description of the ranging and atmosphere backscattering receiver performance based on the in-orbit calibration tests and comparison with other independent measurements.

2. GLAS SURFACE ELEVATION MEASUREMENT PERFORMANCE

The GLAS surface elevation measurement channel consists of a 1-meter telescope, an aft optics assembly, a 0.75-nm bandpass filter, a Si avalanche photodiode (APD), post amplifiers, and an 8-bit 1Gs/s waveform digitizer. An on board software algorithm automatically detects the surface echo from the recorded waveform via a modified maximum likelihood detection technique, that uses a bank of six digital matched filters, a peak detector, and decision process to let surface echoes out weigh cloud echoes when both are present. The on board algorithm also autonomously adjusts the detection threshold and the post amplifier gain setting to maximize the receiver sensitivity and dynamic range.

The performance of the GLAS surface elevation measurement receiver is calibrated periodically using the on board optical test source (OTS). The OTS consists of a laser diode that can simulate the transmitted and the echo laser pulse pairs with a preprogrammed delay and pulse amplitude. The GLAS measurements of these simulated transmitted and the echo pulse pairs demonstrated a <3 cm ranging standard deviation and ~5% pulse amplitude measurement error. Fig. 1 shows an example of the OTS test data. The results from all other OTS tests since ICESat launch have been consistent without any measurable degradation.

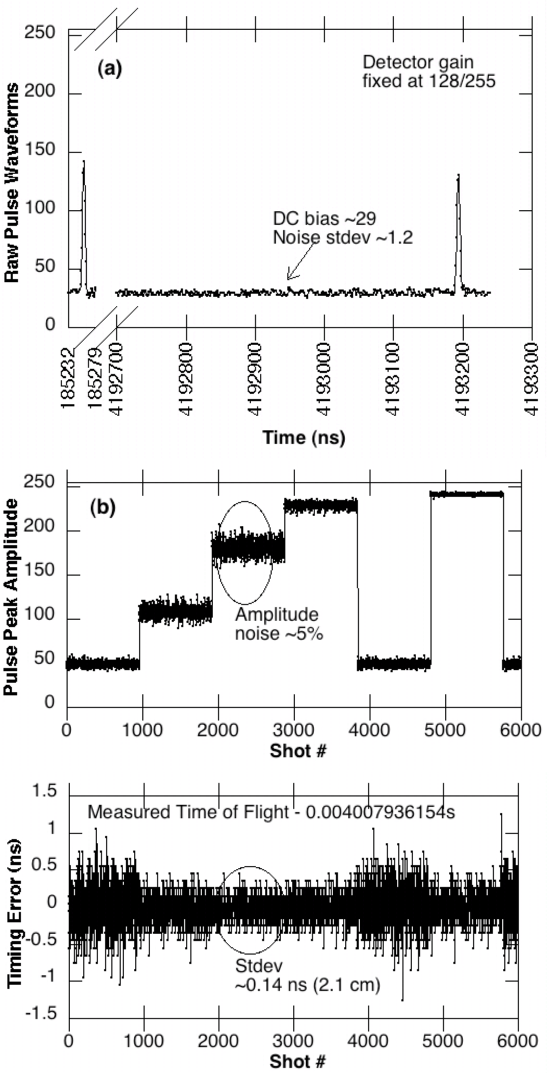

Fig. 1. Sample OTS test results on May 8, 2006: (a) Sample transmitted and echo pulse waveforms simulated by the OTS; (b) Measured pulse amplitude as the OTS stepping through four preprogrammed levels; (c) Time of flight measurement error as OTS stepped through different signal levels.

The on-orbit range measurement of Lake Vostok in Antarctic accuracy, a flat and relatively smooth surface area, showed a ranging precision of 2-3 cm, which agreed with the above OTS test results. The on-orbit range measurement at another calibration site, salar de Uyuni in Bolivia, also showed a 2-3 cm ranging precision when compared to the independent survey results using the Global Position System (GPS) receivers [6].

The time stamp accuracy of each laser pulse has been verified to be within 3 μs using an array of photodetectors and GPS based timers at the White Sand Space Harbor in Texas [7]. The surface echo detection algorithm performed well despite of the fast varying surface reflectance, slope, and atmosphere conditions. The algorithm reliably detects weak surface echoes in the mist of cloud echoes under most of circumstances. The false detection rate has been kept to below 1% in all the measurements. The automatic gain control algorithm keeps the echo pulse amplitude to within 50% to 80% of the full scale of the waveform digitizer regardless of the surface reflectance and slope. The detector gain control loop response time is about 0.1 s (5 laser shots) with little overshoot in response to a sudden change in the received signal pulse amplitude.

The photodetector responsifvity is monitored through the detector shot noise level in response to the background light from the sunlit Earth. The detector dark noise is also monitored when ICESat is on the dark side of the Earth. Fig. 2 shows a typical plot of the detector noise over an entire ICESat orbit. The detector responsivity and dark noise have been stable since launch and no measurable degradation has been observed except for a known temperature and Sun angle effect.

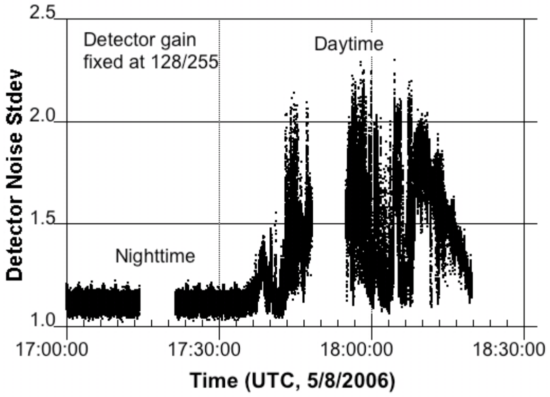

Fig. 2. Detector noise standard deviation (stdev) calculated from the digitized waveform over an orbit.

It was also found that the received signals from ice and snow surfaced over Antarctic continent are several times stronger than we had expected. The atmosphere transmission appeared to be nearly 90% most of the time when clouds were not present. The ice and snow surface appeared to have a nearly 100% Lambertian equivalent reflectance due to the opposition effect and partial specular reflection. As a result, a significant amount of the received pulse waveforms were saturated. To correct for the range walk due to the saturation, a series of laboratory experiments were conducted using a flight spare detector assembly. It was found that although the pulse shape was severely distorted under saturation, the pulse area under the waveform still follows a definitive relationship to the actual laser echo pulse energy. One could then infer the input pulse energy from the detected pulse area. For flat areas with slope <0.5 degrees, the received pulse width can be assumed to be the same as the transmitted ones. Therefore one could estimate the pulse centroid time from the leading edge time and the pulse area. The saturation correction algorithm has been shown to reduce the range error to less than 5 cm in range bias and ~3 cm in standard deviation [6,8] over flat areas.

The minimum detectable surface echo signal from Antarctic is about 0.05 fJ/pulse, which is about 1/400 the signal level under clear sky conditions. Therefore, GLAS can range through clouds of opacity as high as 3 (5% one-way transmission) over Antarctic, including all high altitude clouds and some mid to low level clouds along the coastal regions.

3. GLAS 1064-NM CLOUD BACKSCATTERING MEASUREMENT PERFORMANCE

The 1064-nm cloud backscattering measurement channel shares the same Si APD detector with the surface elevation measurement channel. However, it uses a different set of detector post amplifiers, an anti-aliasing lowpass filter, and a separate waveform digitizer with 0.5 μs sampling interval (75-m vertical range bin). The overall receiver noise level is about 3 times as those shown in Fig. 2 considering the differences in the amplifier gain and bandwidth. The nighttime noise standard deviation is about 4 in the digitizer output unit, which is equivalent to the backscattered signal pulse amplitude from clouds of cross section of 5e-6/m-sr. The maximum input signal before saturation corresponds to a cloud cross section of 4.0e-4/m-sr. The entire a receiver linear dynamic range covers from planetary boundary layer aerosol to all but dense cumulus clouds. Signals from these dense clouds have similar pulse waveforms as surface echoes and they are often recorded by the surface elevation measurement channel. All of these have been verified by the airborne lidar measurements under flying ICESat [9].

The AC coupling between the photodetector and the amplifiers mandated by the surface elevation measurement channel causes a droop in the received waveform after a strong cloud echo and the effects can last as long as 100 μs. A novel digital filter is devised to compensate for the pulse waveform distortion in the ground data processing. The filter consists of a cascade of two boxcar integrators with their scaling factors matching the time constants of the AC coupling circuits.

4. GLAS 532-NM CLOUD BACKSCATTERING MEASUREMENT PERFORMANCE

The 532-nm cloud and aerosol backscattering measurement channel uses a set of Si single photon counting models (SPCM) as the detectors. It measures the atmosphere backscattering profiles up to 40-km altitude at a 75-m vertical resolution. The background photons are sampled before and after each 40-km backscattering profile. The bandpass filter assembly in front of the detectors consists of a 0.28-Å bandwidth temperature-tuned Etalon and a 3.5-Å blocking filter. The center wavelength of the Etalon is automatically tuned to the average laser wavelength via a software feed back control loop. A pointing mechanism is used to center the 0.17 mrad receiver field of view onto the laser footprint. An on board test source, a green light emitting diode (LED), is used to verify the detector performance and the receiver functionality.

The SPCM photon counter performance is monitored from dark count rate and the responses to the sunlit Earth. Fig. 3 shows an example of the SPCM house keeping data, consisting of counts from each individual SPCMs over a 10 μs time interval after the laser pulse emission but before it reached Earth atmosphere. The peak value gives an indication of the SPCM photon counting efficiency illuminated by the sunlit Earth, which can be considered as constant light source when averaged over a large area and over a long time.

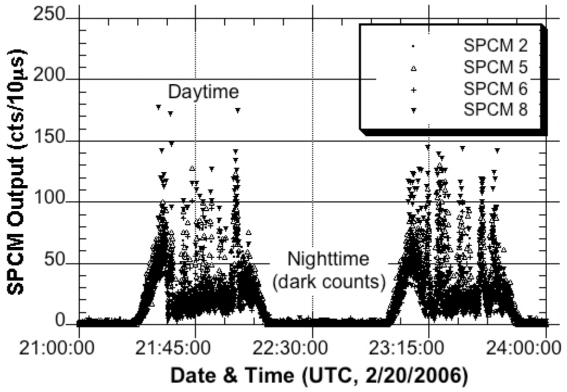

Fig. 3. Sample instantaneous SPCM output count rate over two ICESat orbits.

All the SPCM house keeping data are similar to those shown in Fig. 3 and there has been no measurable degradation in photon counting efficiency.

Fig. 4 shows the average SPCM dark count rate over the past three years since ICESat launch. The dark count rate has been increasing steadily at about 60 counts/s per day per SPCM due to space radiation damage. Although the SPCM dark count rates have risen significantly since launch, they are still much lower than the signal backscattered from clouds and aerosol. More details on the SPCMs can be found in [10]. To date, these SPCMs have been in orbit for more than three years. The accumulated operating time has reached 290 days (7000 hours).

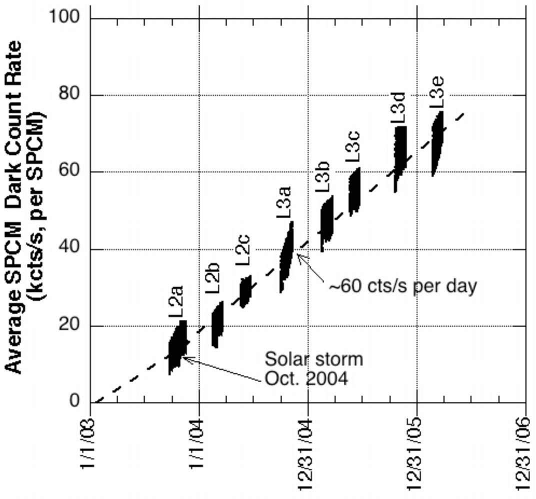

Fig. 4. SPCM dark count rate and radiation damage since ICESat launch (Jan. 12, 2006).

The Etalon bandpass filter also functioned well in orbit, which enables GLAS to measure atmosphere backscattering against the brightest background light at daytime. The Etalon temperature control loop keeps the etalon center wavelength to the laser center wavelength. The control loop has a time constant of about 7 minutes, which is fast enough to track out the orbit variation (90 minutes period) but long enough to average out the laser wavelength fluctuation. The laser is mostly single mode on each shot but can hop among 2 to 3 longitudinal modes, 0.02-0.03 Å apart, from shot to shot. Occasionally, the laser can have 2 to 3 modes simultaneously on a single shot. A software algorithm is used to estimate the laser center wavelength and to reject outliers before feeding back to the control loop. The Etalon filter and the control loop not only serve to minimize the background light onto the detectors, but also provide a direct measurement of the laser spectral characteristics.

Comparison between the GLAS measurements and the near real time airborne lidar measurements shows that the GLAS 532-nm receiver can detect signals from atmosphere with cross section as low as 1e-7/m-sr with an 1 s integration time. The maximum dynamic range is about 5e-5/m-sr. The receiver can also detect molecular scattering at 30 km altitude with a 60 s integration time [9].

5. CONCLUSION

All three GLAS receiver channels performed well in orbit and meet and exceed the science measurement requirements. The surface elevation measurement channel achieved 2-3 cm range measurement accuracy. The 1064-nm cloud backscattering measurement channel is capable of detecting aerosol with cross section of 5e-6/m-sr. The 532-nm aerosol and cloud backscattering measurement channel is about 50 times more sensitive and capable of detecting molecular backscattering in upper atmosphere.

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