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ICESat laser altimeter measurement time validation system

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Abstract
NASA launched its Ice, Cloud and Land Elevation Satellite (ICESat) in January 2003. The primary goal of this laser altimeter mission is to provide determination of volumetric changes in the ice sheets, specifically in Antarctica and Greenland. The instrument performance requirements are driven by the scientific goal of determining a change in elevation on the centimetre level over the course of a year's time. One important aspect of the altimeter data is the time of measurement, or bounce time, associated with each laser shot, as it is an important factor that assists in revealing the temporal changes in the surface (land/ice/sea) characteristics. In order to provide verification that the laser bounce time is accurately being determined, a ground-based detector system has been developed. The ground-based system methodology time-tags the arrival of the transmitted photons on the surface of the Earth with an accuracy of 0.1 ms. The timing software and hardware that will be used in the ground-based system has been developed and extensively tested. One particular test utilized an airborne laser equipped to produce a similar signal to that of ICESat. The overflight of the detectors by the aircraft was successful in that the signals were detected by the electro-optical devices and appropriately time-tagged with the timing hardware/software. There are many calibration and validation activities planned with the intention to help resolve the validity of the ICESat data, but pre-launch analysis suggests the ground-based system will provide the most accurate recovery of timing bias.

Keywords: calibration, laser altimetry, sensors

1. Introduction

ICESat, the Ice, Cloud and Land Elevation Satellite, is an Earth Science Enterprise mission that was launched from Vandenberg Air Force Base on 13 January 2003. On board the satellite bus is a unique and sophisticated laser altimeter, the geoscience laser altimeter system (GLAS). GLAS has been designed at NASA Goddard Space Flight Center for the purpose of measuring ice-sheet topography and associated temporal changes, as well as cloud and atmospheric properties. Since the altimeter will operate continuously there will also be secondary scientific investigations associated with land and ocean processes [1]. The scientific investigation will begin in Fall 2003 after a period for spacecraft commissioning and instrument verification. The mission is unique because of the scientific goals of not only mapping the surface of the Earth, but specifically providing an accurate (centimetre level) assessment as to the change in surface elevation, predominantly in the polar regions. Previous Earth orbiting observatories have not been equipped to provide the ICESat level of altimeter accuracy. For example, the cryospheric goal is to support measurements that will determine elevation change with an accuracy of 1.5 cm yr^{-1} over a 10^4 km^2 region where the surface slope is less than 0.6° [1]. The measurements for the cryosphere (and land as well) will be accomplished using the GLAS science mode. In science mode,

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the instrument will measure the distance from the satellite reference point on the optical bench to the surface of the Earth. The echo, or reflection, from the Earth's surface is received by a 1 m diameter telescope. After the telescope receives the signal, the waveform, which is a time history of the backscattered photons, is digitized and stored for downlink to a variety of post-processing centres.

The laser pointing direction is determined by the stellar reference system (startracker and laser reference system). During post-processing the lower level data products, such as the digitized waveform and pointing direction, are used in conjunction with the precision orbit determination (POD) and precision attitude determination (PAD) to infer the geodetic position of the laser surface return. The POD process provides the position of the centre of mass of the spacecraft as a function of time determined from GPS and satellite laser ranging (SLR) tracking data [2]. PAD is the orientation of the optical bench with respect to the celestial reference frame. For each of the laser shots fired at 40 Hz, the position, and ultimately the topography, will be determined. Analysis of repeated topographic profiles will determine temporal variations in the elevation. As one might imagine, determining temporal variations requires that there must be a process of determining the time of measurement within the instrument or implied by timing data products. For GLAS, the time interval between when the laser shot is fired and when the echo signal is received by the telescope will determine the altimeter measurement time, and ultimately the altitude, by multiplying half the photon travel time by the speed of light. The time determination is performed using primary, secondary and tertiary timing elements, but the crux of the system is the on-board global positioning system (GPS) receiver [4]. The timing process in its entirety will be discussed in a subsequent section.

There are several techniques that have been developed to provide verification of data products associated with the altimeter channel. One important technique is the use of direct altimetry over the oceans, also known as ocean sweeps. Ocean sweeps are compositions of roll and pitch manoeuvres where the spacecraft (and thus the laser altimeter beam) is deliberately pointed off-nadir to increase the angular sensitivity, i.e. the lever arm, of the range measurement [2]. The result of this ocean analysis will be a verification of pointing, timing and ranging parameters. A paper by Luthcke [5] presents the models, errors, methodology and specific application to space-borne altimetry. In addition to the ocean, another surface that provides validation of data products is a well characterized flat surface (i.e. White Sands, NM or Bonneville Salt Flats, UT). Flat surfaces can be characterized using kinematic GPS or airborne lidar. By comparing these characterized flat surfaces to GLAS surface characteristics, the laser measured altitude, the laser pointing and bounce time tags can be validated. Further methods for calibration include waveform matching to digital elevation models, SLR, integrated residual analysis and comparison of GLAS-inferred surface elevation/topography to precise surface elevation mapping from NASA's airborne topographic mapper [2].

There are two calibration techniques that will provide *in situ* measurements of the footprint locations on the surface of the Earth. These independent assessments of the laser spot locations will assist in the verification of the spacecraft altitude and the laser pointing direction. Measurements are referred to as independent if there is no required use of GLAS data products for results or data processing. One method utilizes an airborne photography technique that will image the laser photons as they illuminate the surface. The pictures will be taken with several CCD (charged coupled device) cameras on board a small aircraft. Ground fiducial markers will appear in the GLAS spot photograph as well and will provide a known geodetic position within the image so that the footprint location can be relatively identified.

The second *in situ* calibration technique is a ground-based verification method that utilizes many electro-optical detection devices for the acquisition of the laser photons as the satellite passes overhead [3]. This method was developed to provide validation of the laser pointing determination and time of altimeter measurement. The electro-optical devices will be distributed at a validation site near the ICESat ground track and will collaboratively 'capture' the spot on the ground to provide a direct measurement of several spot centroid geolocations. The detector positions will be determined with GPS measurements in the same reference frame as the PAD products. The detectors will not only determine where the laser illuminates the Earth but will also determine the arrival time of the laser footprint on the ground. The position where the laser illuminates the surface is also referred to as the geolocation, meaning a geodetic representation of the spot location. The ground-based timing methodology will supply the most accurate timing verification of the GLAS altimeter time of arrival during the initial calibration phase of the mission, and thus is very crucial to the success of achieving the science requirements of the satellite. The aforementioned ocean scans also provide pointing and timing information: however, the results are based on analysis of the downlinked GLAS data. The *in situ* ground system requires only a laser pulse from GLAS in order to provide an independent laser bounce time for comparison with the satellite timing data. All of the techniques designed for calibration of the GLAS instrument are crucial in the success of the ICESat mission. Verification of the data products is required in order to ensure the validity of the data and identify possible biases in the results that might be mistaken for geophysical artefacts.

2. GLAS timing system

The GLAS timing system has a hierarchy of timing devices and schemes. At the forefront of the system is the GPS time provided by two JPL/SpectrumAstro BlackJack GPS receivers. The BlackJack device provides UTC time accurate to 1 μs. They are configured to supply a 0.1 Hz synchronization pulse to the GLAS main electronics unit and spacecraft control computers. In addition, for each 0.1 Hz pulse there is a correction packet generated that accounts for the offset between the BlackJack receiver time and the GPS system time.

The spacecraft utilizes a 2 GHz stable master oscillator, in the GLAS main electronics unit, for one of the two secondary timescales. The second timescale is provided by a precision external clock located in the spacecraft bus. Both of these systems are implemented using oven controlled quartz oscillators and both systems timestamp the 10 s interval pulse from the BlackJack receivers for an accurate account of GPS time. Lower accuracy times are maintained in the GLAS instrument subsystems, specifically the laser reference system, and the instrument startracker.

The timing system process, in its entirety, uses each of the primary, secondary and tertiary timescales. A brief overview of the system starts with the 0.1 Hz pulse from the BlackJack receivers. This 0.1 Hz signal, as mentioned previously, is routed into the spacecraft bus, specifically the precision external clock, and also the master counter that is driven by the 2 GHz oscillator. The bus time uses the 0.1 Hz pulses from the GPS to produce a data file called the PRAP (position, rate and attitude packet) at 1 Hz intervals. The master counter has multiple requirements. The first requirement is to divide down the 2–1 GHz frequency for the instrument's analogue-to-digital (A/D) converter. The second requirement is to divide down the 2 GHz to a 40 Hz signal. The 40 Hz signal is responsible for the laser triggering, which includes the laser fire acknowledge and the laser profile array system. The 40 Hz frequency is then divided down to a 10 Hz signal and is the synchronization signal for the stellar reference system (i.e. the instrument startracker and laser reference camera).

The data products that are required to achieve the precise altimeter bounce time tag are the Nd:YAG 40 Hz fire command signal and the corresponding digitized return waveform from the A/D converter. A timestamp is latched for both the laser fire command and the laser fire acknowledge using the 15.625 MHz clock. The clock is read on the leading edge of the fire command signal and is read again after a $\sim 200\ \mu$s trigger delay for a timestamp of the fire acknowledge signal. The range gate, an allowable time for receiving the return signal, is set to 4 ms in order to minimize the possible damage to the altimeter detectors. The timestamp associated with the A/D converter's acquisition of the reflected waveform is accomplished with the 1 GHz sampler. The actual surface return, or bounce time, corresponding to each altimetry measurement is calculated by taking the round-trip time of the laser pulse, dividing it in half, adding the value to the laser fire time and multiplying that time by the speed of light. The travel time of the optical energy is the time elapsed between the laser fire time and receipt of the digitized waveform. This bounce time value has an expected accuracy of 0.1 ms which correlates to 70 cm along-track error in spot position on the ground (based on the average 7 km s^{-1} ground speed of ICESat). This laser bounce time tag is precisely the data product that can be empirically determined with the *in situ* data from the ground-based timing verification system.

3. Ground-based timing system hardware

The system designed to perform the independent verification of the time of measurement of the laser altimeter, shown in figure 1, is centred on a National Instrument (NI) PXI (PCI extensions for instrumentation) chassis that harbours all of the components. PXI is a computer-based instrumentation platform based on the cPCI (compact PCI) bus architecture. The chassis contains an internal monitor and keyboard and accommodates up to 8 PXI instrumentation cards including the controller. The ruggedized construction and portability of the system, in addition to the fact that it is self-contained and temperature-controlled, make it suitable for

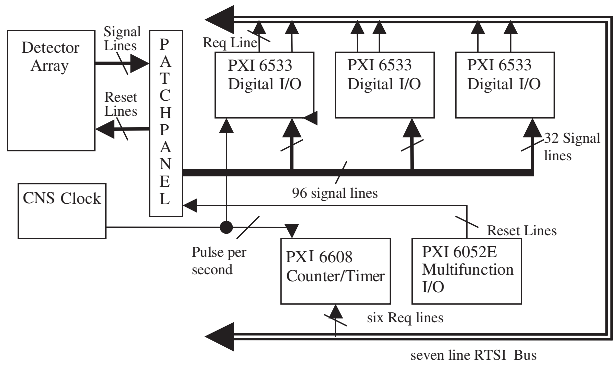

Figure 1. Diagram of the timing system hardware components.

harsh environments. Ultimately, using this particular system expands the potential for timing verification to a variety of locations.

One of the reasons that the National Instruments (NI) products were chosen is the highly accurate NI PXI-6608 counter/timer card. The device has no manual switches or jumpers and its only requirement is software configuration. It can provide accuracies for event detection to better than a microsecond. The PXI-6608 contains a 10 MHz high-stability, oven-controlled crystal oscillator (OCXO), which has a 75 ppb (parts per billion) accuracy. The 75 ppb implies that, for the 10^7 cycles per second, the error per second is no more than 75 ns. The OCXO phase-locks with the 80 MHz time base clock on the board, acquiring the 75 ppb accuracy for that clock as well. The primary interest in the PXI-6608 is its ability to make absolute time measurements upon synchronizing with an external timing source. For the ground-based system, the external time base will be a 1 pulse per second (pps) signal from a high precision GPS receiver.

The GPS receiver to be used for the ground-based timing hardware was carefully selected to ensure that it would be a viable component for integration with the NI system. The receiver that best suited the system was a CNS clock, from Communication Navigation and Surveillance Inc. The CNS clock has 50 ns accuracy in the leading edge pps signal output when operating in timing-only mode. The software, called TAC32, is operable on any computer and has a wide range of features such as self-survey, data logging, 1 pps steering and PC clock synchronization. The PC clock synchronization proved to be vital during the software development phase since the system time is crucial in providing the appropriate time for the detected events. To achieve synchronization with the computer in the PXI chassis and the GPS, the receiver signal is fed into the NI-TIO chip on the PXI-6608. This chip houses, among other components, a real-time clock, or RTC. The RTC is synchronized with the external timing signal from the GPS receiver and uses the 80 MHz clock, mentioned previously, as the time base to provide the counting between 1 s epochs.

The function of the NI PXI-6608 on this board is to timestamp a TTL (transistor–transistor logic) signal that will come from the ground-based electro-optical detectors upon detection of the GLAS laser footprint [3]. However, the PXI-6608 board can only accept signals from a maximum of eight detectors. In order to expand the system to accept signals from significantly more detectors, three NI PXI-6533 digital input/output (DIO) cards were added to the system. These DIO boards receive a signal directly from the detector circuit into the digital input line without any added signal conditioning.

Each DIO card has 32 available input lines, that is, four ports (A, B, C and D) with eight lines each (line 0–7). The card is programmed to monitor the input of each line of each port. If there is a change detected by the monitoring process a signal will be sent out through one of two data request (REQ) lines. REQ 1 reports changes in ports A and B while REQ 2 reports changes in C and D. The DIO port data, read by the system continuously, will indicate that there has been a change in the input pattern. Additionally, the data will include the line number (and thus the corresponding detector) that experienced the change, for example, DIO card 1 A2. Given that the system is comprised of three DIO cards it is capable of handling 96 input lines and will offer signals through one of six REQ lines to show whether or not any of the detectors have been triggered by the ICESat laser footprint.

In addition to the three DIO boards and the NI PXI-6608 counter/timer board a final PXI card was required to complete the timing system. This additional board is needed to provide a signal for resetting the detectors. For this specific purpose a NI multifunction input/output (MIO) board was chosen. The timing system requires a TTL level signal to reset the circuits after event detection, or for the initial reset before testing has begun in the instance of false triggers. The MIO card has eight digital outputs available so only one card is required after consolidating the 96 detector reset lines into groups of 12.

The final hardware requirement was for an interface between the detectors and the PXI chassis. Each card is connected to signals through a shielded cable that is then connected to a 68-pin connector block. The electro-optical detectors, on the other hand, receive and send signals through RJ11 connections (typical phone jack/plug). To accommodate both devices a 96-channel patch panel was selected. The signals are taken from the detectors through category 3 cables into the patch panel. Each of the patch panel's eight 50-pin connector lines are connected to the appropriate DIO input line on the connector block; reset line, power line or ground. There are a few additional connections required between connector blocks, but most of these are made using the internal RTSI (real-time signal input) bus. This configuration is accomplished in software.

4. Ground-based timing system software

The timing program is written in a graphical programming language called LabVIEW. LabVIEW programs are executable algorithms called virtual instruments (VIs). The timing program is best described with a flow chart, but a brief overview will be presented subsequently. Essentially, the goal of the timing program is to timestamp events from an external source relative to an absolute GPS time tag. This time tag will be provided with an accuracy commensurate with the mission requirement of 0.1 ms. The final timing program was produced after many laboratory experiments for the determination of performance of each individual piece of timing equipment as well as the entire collaborative system [3].

In order to obtain maximum accuracy for the timestamping process, each incoming pps leading edge from the CNS clock is timestamped and recorded. This signal is connected to DIO A0. The data, timestamps for each pps, can be used during post-processing to determine the presence of any oscillator drift, delays due to slow initialization of the program in the timing system or any discrepancies with the synchronization of the RTC time to the PC system time.

Each time the program is executed, all detectors connected to the system will reset upon receipt of the signal sent through the designated category 3 line. After initial reset, the detectors are prepared for acquisition of an event. The DIO cards and the counter/timer card are also reset upon initialization. Counter 0 on the NI PXI-6608 card is initialized as RTC 0. The RTC is synchronized with the pps. The RTSI 0 line is configured as the gate input for the RTC. RTSI, incidentally, are lines that can be internally connected to other PXI cards through software configuration and no external hardwire lines are required. There are six RTSI lines available in this system, RTSI 0–RTSI 5. As the program continues to execute the counters are initialized for buffered event counting with the 80 MHz internal oscillator. Six of the counters are configured to count events coming through RTSI 0. Of the remaining two counters, counter 7 is used for initial or epoch time determination, using two-edge separation, and counter 0 will be used to keep track of the counter overflows to guarantee that the program can run for a lengthy ($\sim$h) period of time. The DIO cards are initialized to operate in change detection mode. Upon initialization, each DIO sends a pulse/signal from each of the REQ lines through a RTSI line; each DIO card utilizes two RTSI lines. These signals act as starting points for timing initialization and subsequent event timestamps.

At this juncture, the initialization time is determined in two ways. The first is the time extracted from the PC, which has been synchronized with the RTC, and the second way uses a two-edge separation method between the starting signal and the leading edge of the pps. The two-edge separation time is acquired by starting the measurement after the pulse on RTSI 0 and terminating at the end of the current second (before the next leading edge pps). This 'double' timing method used to find the initialization time (or epoch time, as it can be called) is utilized due to the fact that, although the synchronization between the PC and the RTC provides the fraction of the second (of the initialization time) with an accuracy at the $0.1\ \mu$s level, the actual second integer frequently experiences a 1 s latency. Because of this one second latency, the two-edge separation is required to get the appropriate integer time value. By combining the measurements from the two-edge separation and RTC, the epoch time is the time of the timing program execution in UTC local time to $<1\ \mu$s.

As the program enters the main loop, the REQ lines are scanned by the counters for any changes in input status. A change in input is referred to as an event. Events cause the counter/timer hardware to latch the value of the counter in a buffer. The counter/timer board then requests an interrupt from the computer, which alerts the software to the event. The software reads the port data (patch panel number) and the counter values (time past the recorded initialization time) and logs them. These data are also visible on the computer in real time.

After the program has stopped executing the counts (event occurrences) are converted into seconds and added to the UTC

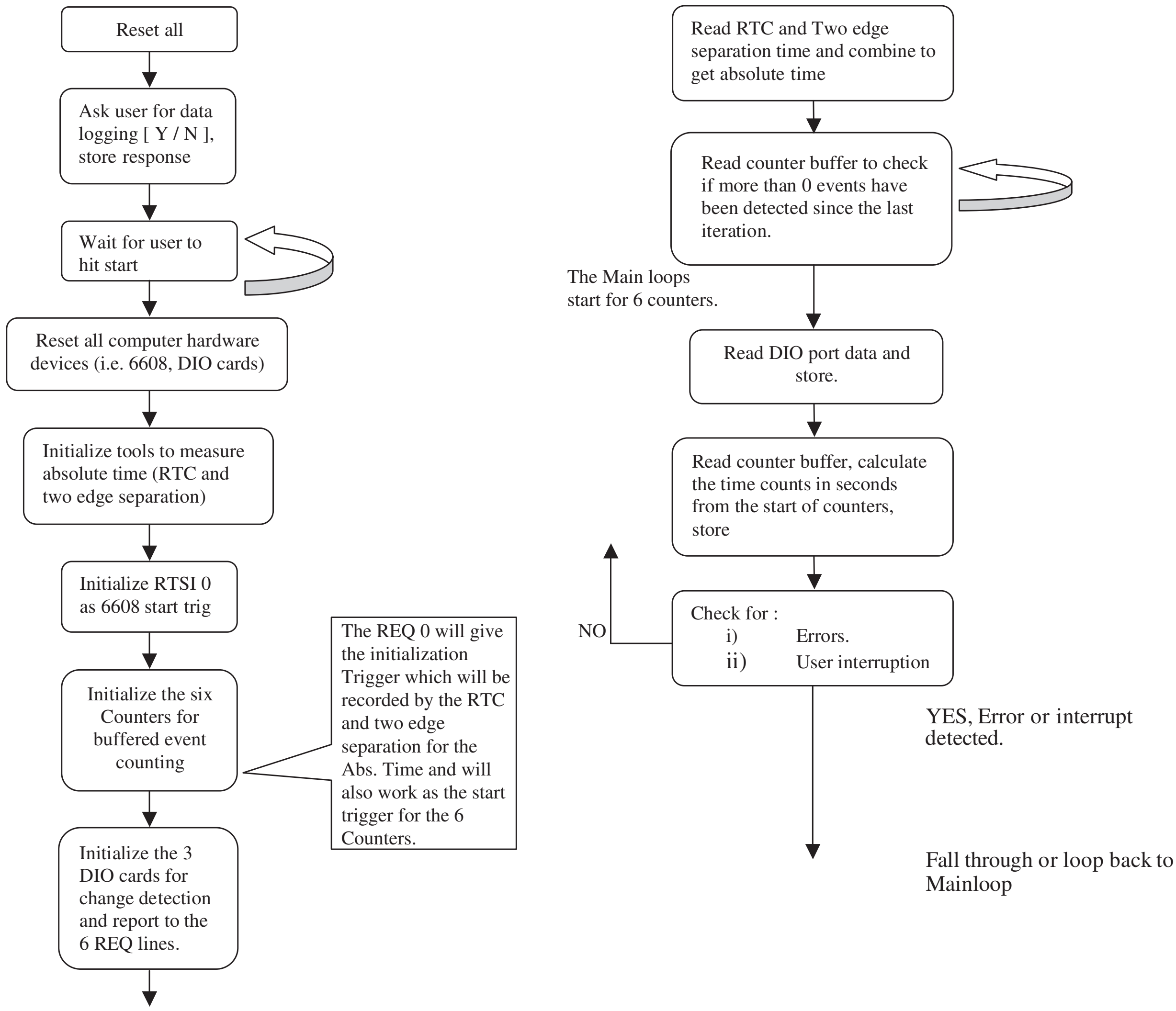

Figure 2. Timing system software flowchart.

Table 1. Complete error analysis for the timestamping procedure.

Error source	Error quantity
TAC[a] GPS receiver	50 ns
NI counter board OCXO[b] drift per sec	75 ns
Cable delay estimation	50 ns
Phase difference between the OCXO and the pps from the TAC	100 ns
Resolution of the DIO[c] scan for events	150 ns
Counter resolution (80 MHz)	12 ns
Total timestamp error	$<1\ \mu$s

[a] Totally accurate clock.
[b] Oven-controlled crystal oscillator in the PXI 6608.
[c] Digital input output PXI 6533.

initialization time (from the RTC/PC synchronization and the two-edge separation). For each detected event there will be an absolute GPS time, and a port number which determines which detector in the field delivered the signal. Each time stamp is adjusted in the post-processing software to accommodate any offset of the pps leading edge and the 1 μs m^{-1} cable delay. All data are logged to a Microsoft Excel file. The flow chart for the program is shown in figure 2.

5. Error analysis

The detectors and the timing system (hardware/software) were extensively tested in the laboratory. These tests included the accuracy of the timestamps, the detectability of the detectors and the delays associated with signal propagation and other items determined through experimental investigation. Additional details regarding the experimental results exist in a previous publication [3]. The error analysis of the timing hardware and software for the timestamping of the system is summarized in table 1.

6. Field tests

The detectors and the timing system, although having been successfully tested and evaluated in the laboratory, had not yet experienced a more realistic environment, that is, similar to the one that it will experience during the calibration/validation phase of the ICESat mission. To test the response and abilities of the detector/timing system in more diverse surroundings, an experiment was designed using an airborne laser.

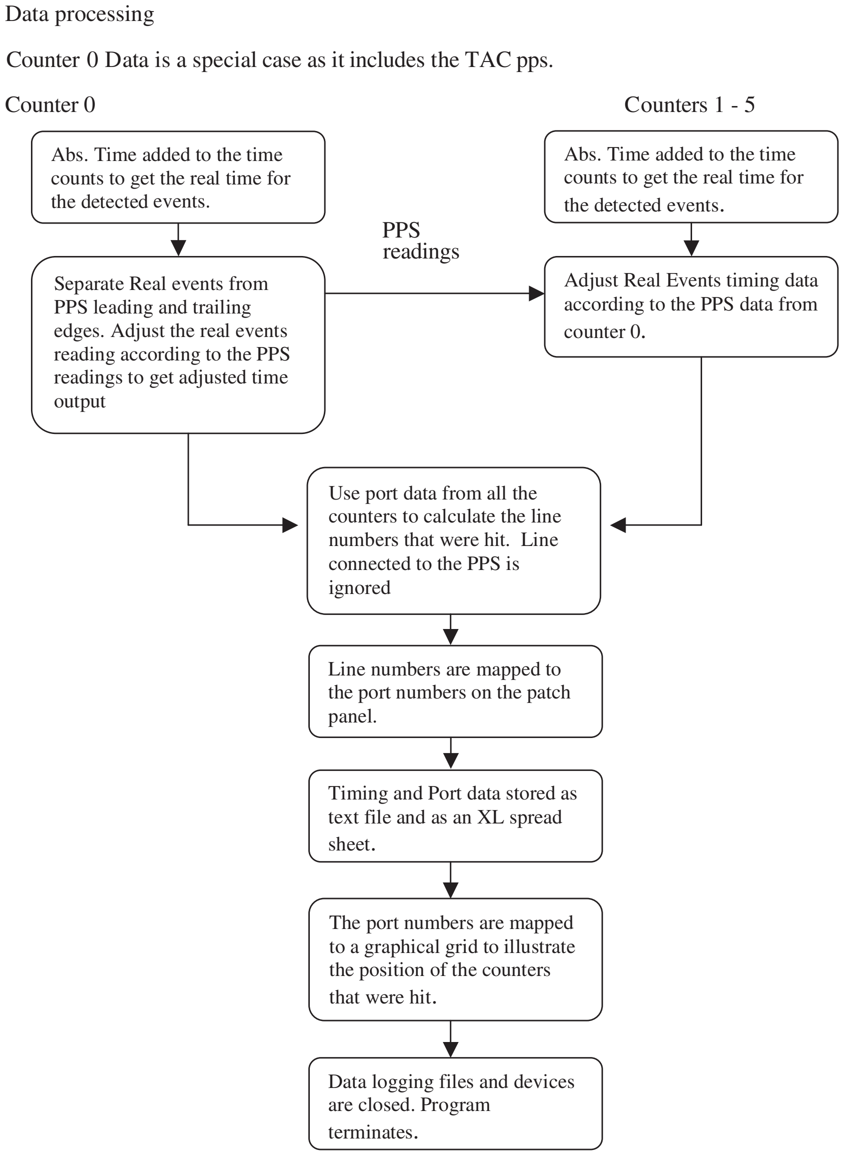

Figure 2. (Continued.)

The experiment was executed in the early morning at the Robert Mueller Airport in Austin, TX. This airport is not active for commercial or private aircraft use, but the runways are still intact and accessible. The timing system, comprising a 96-channel patch panel, a TAC GPS receiver and a National Instruments (NI) PXI chassis (housing all of the PXI components), was centrally located between the 23 detector assemblies. Each detector was wired/connected to the Telco patch panel with category 3 wire and RJ11 connectors. The detector positions were determined prior to the test using a Leica differential GPS and recorded for use in the aircraft navigation software. Each detector was placed in a line with 15 m spacing along the side of the main Mueller runway running southeast to northwest and covering a length of 345 m.

The idea of this experiment was to fire a laser pulse with similar characteristics to the GLAS flight lasers down onto the ground detector line and test the detection abilities of the detectors as well as the timing system software that supplies timestamps associated with arrival of the optical energy to within a microsecond. The conceptual design is shown in figure 3.

Figure 3 gives some specifics as to the signal from the airborne laser and the resulting footprint on the ground surface. In the aircraft was a Big Sky Nd:YAG laser that, at full power, produced a 12.5 mJ/pulse in the infrared. The 2.5 mm laser beam travelled through a 24 mm diverging lens before it left the aircraft through the small opening in the belly of the plane.

The average energy ground level density expected from the GLAS flight lasers is 1.2 nJ cm^{-2}. In order to achieve a comparable energy density the required aircraft altitude was 600 m MSL, given that the divergence of the 24 mm optical lens was experimentally measured at 0.069. In addition, the Big Sky laser had a repetition rate of 2.5 Hz at this altitude so that each footprint would slightly overlap and not give way to the possibility of missing the detector line by a gap between two subsequent signals.

The experiment was performed on 26 July 2002 at 0700. An hour prior to the flyover, the equipment was deployed at

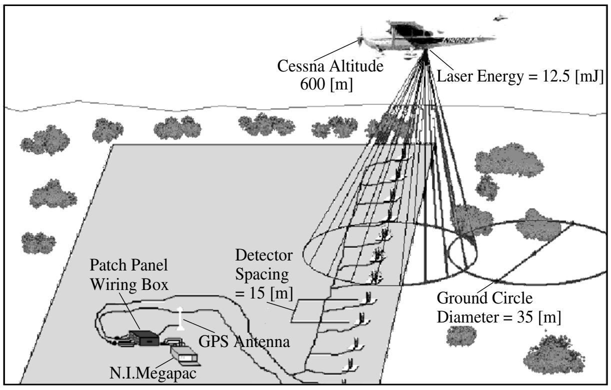

Figure 3. The conceptual design of the airborne laser experiment performed at Robert Mueller Airport in Austin, TX.

Table 2. The results from six passes of the airborne laser over the detector system.

Pass no.	Hit/miss	Altitude (m)	Avg. energy density (nJ cm^{-2})
1	Hit detector 12	434	4.5
2	Miss	437	No laser fire
3	Hit detectors 1, 13	433	4.5
4	Miss	485	3.2
5	Hit detector 15	468	3.5
6	Hit detector 10	464	3.6

the airport. The two wire bundles required for accommodation of 23 detectors were laid out and all of the detectors were assembled in the mounts. One wire bundle (a group of 12 category 3 cables) supplied the connections for detectors no. 1–12. This bundle was laid from the central location to the east while the second bundle, supplying connections to detectors no. 13–23, was laid to the west. Each detector assembly was also carefully levelled using the set screw in the base plate. With the four personnel present at the airport it took approximately 45 min to set up the detectors and timing hardware. The aircraft was able to fly over the detector line six times, each time communicating with the ground personnel using two-way radios. The results of the six aircraft passes over the detector line are shown in table 2, below which are included each corresponding aircraft altitude and the calculated energy density using the separation distance between the detectors and the aircraft for each pass.

Table 2 indicates that, out of the six passes made by the aircraft, four of them were successful (meaning detection of the laser photons by a detector). Table 2 also indicates that the aircraft altitude was slightly lower than the previously stated 600 m, which was caused by the presence of a low cloud ceiling on the morning of the test. At least one of the non-detected passes was due to a malfunction in the laser firing. One speculation as to the cause of the remaining 'miss' could be the airborne laser's lack of pointing control. That is, the laser is pointed nadir through the aircraft but the orientation with respect to the plane is fixed. If the plane rolls even 10°, given the altitude, the laser spot would move 52 m on the ground. This implies that, if the plane was positioned directly over the last two or three detectors in the line and rolled slightly away from the centre of the line, the detectors would not be illuminated by the laser. Furthermore, any roll beyond 10° anywhere within the detector line would not be detected by the system due to limitations of the lens present on the detector's photodiode. Another cause of missing the laser signal could have been the smaller size footprints produced due to the lower altitude. Given the altitudes of 430–90 m, the footprints on the ground ranged in diameter from 18 to 22 m instead of the 36 m diameter originally expected. The smaller size opened up the possibility of a gap between the spots which could have coincided with the location of the detector line.

Table 3. The timestamps with corresponding pass numbers and detector ID.

Detector ID	Timestamp (s)	Pass number	GMT time
23			
22			
21			
20			
19			
18			
17			
16			
15	17 827 228.400 225 352	5	13:00:28
14			
13	17 826 811.400 142 616	3	12:53:31
1	17 826 811.400 142 579	3	12:53:31
2			
3			
4			
5			
6			
7			
8			
9			
10	17 827 426.199 991 682	6	13:03:46
11			
12	17 826 254.800 015 901	1	12:44:15

The timing software supplied a timestamp for each detection of the laser signal. Each timestamp for the four detected cases was a multiple of 400 ms, as would be expected given the 2.5 Hz repetition rate of the laser. The listing of detectors and timestamps are shown in table 3. Each timestamp has the units of seconds and corresponds to Greenwich Mean Time.

Each of the timestamps, or detected events, shown in table 3 is the number of seconds that have passed since 0 h 1 January 2002 UTC time (adjusted from Greenwich UTC to local time). The adjustments for the delay time associated per length of cable have also been figured into the time values.

The navigation software onboard the Cessna was designed to record the GPS coordinates of the aircraft every second for the duration of the flight. Therefore, the position and timing from the plane could be compared to the data from the ground-based system.

The tests were a major success for the detection and timing system. The 'failure' on pass 4 of the aircraft is yet to be determined, but could be due to a variety of causes primarily associated with the airborne laser or aircraft attitude. The timing appears to be operating within the 0.1 ms accuracy requirements as far as supplying a timestamp. This timing confidence is based on the fact that all of the timestamps acquired were multiples of 400 ms, which corresponds to the 2.5 Hz laser repetition rate. The timestamps cannot be compared to the aircraft navigation times to the 0.1 ms level due to the accuracy limitations of the aircraft, but the results do show that there are no gross systematic offsets.

7. Conclusions

In order to verify the accuracy of the time of measurement associated with the ICESat altimeter data, a ground-based timing system was developed and tested. The goal of the timing system is to provide an independent measurement of the absolute time of arrival of the laser footprint on the surface of the Earth. The ground-based detectors, which are electro-optical devices, are used to detect the presence of the infrared light and send a signal to the timing system central control unit. The central control unit is a PXI chassis that holds the DIO cards and the counter/timer card. The software for the central unit was specifically designed to provide the time tag for incoming signal detection. After laboratory testing the system proved itself and exceeded the 0.1 ms accuracy requirement by supplying the absolute event time to within a microsecond. The system was tested further outside of the laboratory using an airborne laser. This test concluded that the devices could detect an ICESat-like signal in a non-laboratory environment and that it could provide an accurate time tag for the arrival of the signal.

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