SHUTTLE LASER ALTIMETER

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Mission Results & Pathfinder Accomplishments

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INTRODUCTION

The Shuttle Laser Altimeter (SLA) is a Hitchhiker experiment that has flown twice; first on STS-72 in January 1996 and then on STS-85 in August 1997 [1]. Both missions produced successful laser altimetry and surface lidar data products from approximately 80 hours per mission of SLA data operations. A total of four Shuttle missions are planned for the SLA series. This paper documents SLA mission results and explains SLA pathfinder accomplishments at the mid-point in this series of Hitchhiker missions.

The overall objective of the SLA mission series is the transition of the Goddard Space Flight Center airborne laser altimeter and lidar technology [2, 3] to low Earth orbit as a pathfinder for NASA operational space-based laser remote sensing devices. Future laser altimeter sensors will utilize systems and approaches being tested with SLA, including the Multi-Beam Laser Altimeter (MBLA) and the Geoscience Laser Altimeter System (GLAS). MBLA is the land and vegetation laser sensor for the NASA Earth System Sciences Pathfinder Vegetation Canopy Lidar (VCL) Mission, and GLAS is the Earth Observing System facility instrument on the Ice, Cloud, and Land Elevation Satellite (ICESat). The Mars Orbiting Laser Altimeter, now well into a multi-year mapping mission at the red planet [4], is also directly benefiting from SLA data analysis methods, just as SLA benefited from MOLA spare parts and instrument technology experience [5] during SLA construction in the early 1990s.

The SLA instrument measures distance by timing the two-way propagation of short (~ 10 nsec) laser pulses over the roundtrip path between the Space Shuttle and the Earth's surface. Laser pulses at 1064 nm wavelength are generated in the SLA laser transmitter and are detected by a telescope equipped with a silicon avalanche photodiode detector. Both transmitter and receiver are located in one Hitchhiker canister referred to as the Laser Altimeter Canister (LAC). They view the Earth through a large 0.38 m diameter window that is located in the upper-end plate of the LAC. The laser transmits through a 40 mm hole in the periphery of the telescope mirror. The LAC sensor is protected in non-operating times by a motorized door assembly that is part of the Hitchhiker canister. The SLA instrument computer and all the command and telemetry interfaces to Hitchhiker are located in a second canister referred to as the Altimeter Support Canister (ASC). The SLA data system makes the pulse time interval measurement to a precision of 10 nsec and also records the temporal shape of the laser echo (i.e., waveform) from the Earth's surface enabling interpretation of the surface height distribution within the 100 m diameter laser footprint. The operational concept of SLA, its implementation as a dual-canister Hitchhiker bridge-mounted payload, and details of its instrument configuration were presented at the 1995 Shuttle Small Payloads Symposium [6]. SLA sensor parameters are summarized here and illustrations of its implementation as a Hitchhiker payload are presented.

The SLA pathfinder contributions presented in this paper are grouped into 3 main areas: (1) laser altimetry measurements from Earth orbit; (2) space-based laser altimeter data processing; and (3) surface lidar. The SLA-01 and SLA-02 mission operations and subsequent data analysis resulted in significant pathfinder accomplishments in each of these three areas. Sensor performance on orbit ran close to predicted in terms of successful acquisition of Earth surface pulse echoes. Statistics are given and explained as are example records of pulse echoes. A major effort was expended and is still continuing to obtain the maximum science benefit from the SLA data. This involves computations of range, waveform, orbit, and pointing angles applicable to each pulse and georeferencing which incorporates all the measurements into a computation of surface elevation and location for each laser footprint. Data sets from both missions are now available on the World Wide Web at the address given below. As we look forward to SLA-03 and SLA-04 missions which are intended to complete the SLA pathfinder objective, we envision a transition to smaller laser footprints on the Earth's surface, higher pulse-rates and thus higher-resolution data sets, scanning laser sensors, and extended periods of observation leading to eventual operation of SLA on the International Space Station.

INSTRUMENT DESCRIPTION

A detailed description of the SLA instrument and its Hitchhiker interface are reported in our pre-flight paper [6]. The SLA works by generation of short laser pulses at 1064 nm optical wavelength on the Space Shuttle and reception of the weak backscattered laser radiation from the Earth. The pulsed laser source is a solid-state, diode-pumped, Nd:YAG device that pulses at a fixed, continuous rate of 10 pps. The optical receiver of SLA collects the near-infrared (i.e. 1064 nm) pulse backscatter from the Earth's surface and converts it to an electronic pulse that traces the time-history, or echo, of the optical reflection from the 100 m diameter laser footprint. Analog electronic signals (i.e. pulse waveforms) from the START and STOP detectors of the LAC are presented to the SLA data system for digital measurements of the START-to-STOP time interval, yielding the range to the first surface intercepted (cloud top, ocean surface, vegetation canopy top, or bare ground). Furthermore, the shape of the pulse echo is converted into digital samples with a resolution of 2 to 10 nsec. Digitizer sampling rate and averaging are parameters that can be commanded in flight to optimize waveform resolution. Digital timing and waveform data are formatted into packets on-board SLA in the ASC flight computer and are sent by Hitchhiker low and medium rate telemetry to the HH Payloads Operations Center at GSFC as well as recorded on board SLA in hard drives.

The as-flown configuration of SLA is illustrated in Figure 1 in block diagram form. Note that the START signal is generated from a small optical sample of the output laser beam. The nominal duration of the START pulse and the impulse response of the STOP pulse circuitry was found by pre-launch measurements to be approximately 15 to 20 nsec nsec full-width-at-half-maximum. A 15 nsec pulsewidth is nominal when the laser transmitter is operating at full power and has an optimum temperature interface of approximately 0 to 10 C. The pulse broadens to about 20 nsec as the laser pump-diodes heat up in the Nd:YAG laser head to 25 to 35 C. There is a corresponding reduction in pulse energy from a maximum of about 35 mJ per pulse at the lower

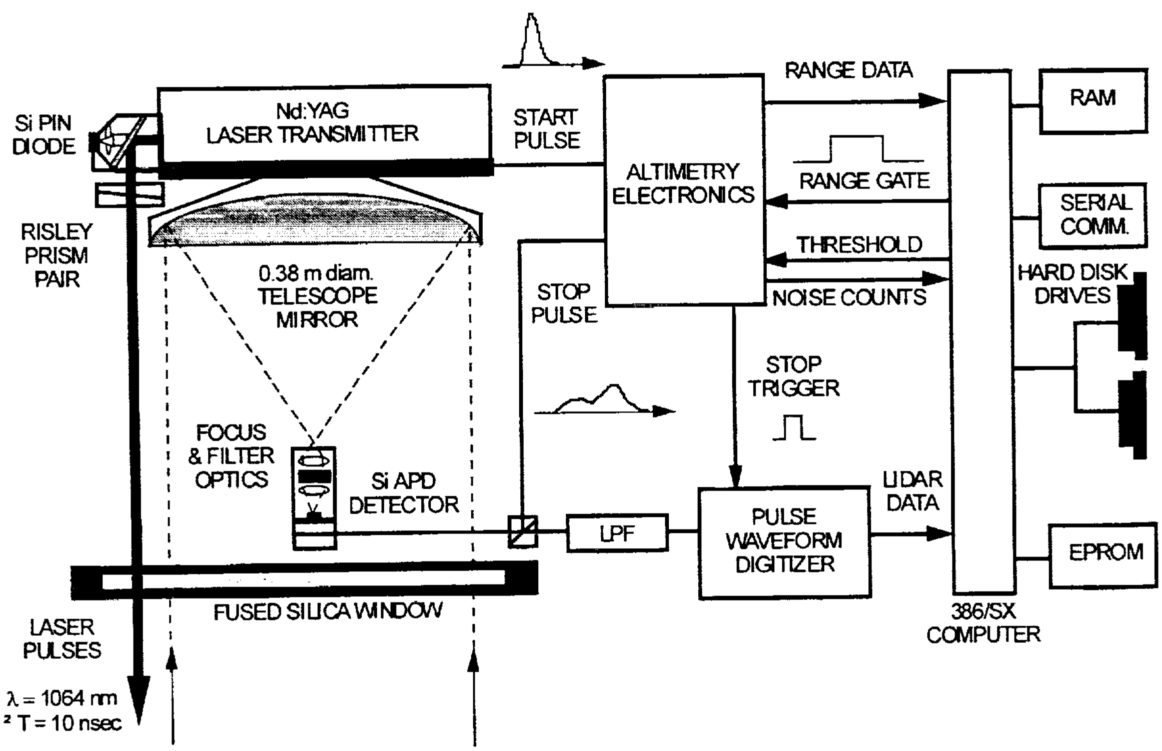

Figure 1. Instrument configuration of the Shuttle Laser Altimeter for the SLA-01 and SLA-02 Missions

temperatures to about 20 mJ at the higher temperatures. These and other as-flown sensor parameters for SLA are documented in quantitative form in Table 1. The STOP signal, broadened and distorted in time by interaction with the reflecting surface, appears as a single- or multi-peaked waveform that typically extends several tens to hundreds of nsec. There is an autonomous digital tracking loop in the SLA data system that facilitates data acquisition by adjusting an electronic threshold based on number of noise counts that appear over a 1 sec average of the detector noise level. This compensates for changes in background noise counts from the detector-noise-limited operations at night to the solar-backscatter-limited operations during daytime. The purpose of this loop is maintenance of the lowest-possible electronic threshold for detection of weak pulse echoes for a given false-alarm ratio of about 1 part in 10^5. The serial communication port for the SLA 386SX computer that is illustrated in Figure 1 is for RS-422 up-link commands and down-link telemetry as relayed by the HH ACCESS payload control system. We also store all data on board on the dual hard drives for post- mission retrieval of a complete flight data record.

SLA INSTRUMENT SPECIFICATION	Minimum	Maximum
SENSOR:		
energy per pulse (mJoule)	20	40
pulse width (nsec, full-width-at-half-maximum)	10 minimum at 40mJ (0-10C) 20 maximum at 20mJ (25-35C)	
pulse repetition rate (pps)	10	
beam divergence (mrad, $1/e^2$)	0.35	
beam far field pattern	multi-mode	
receiver throughput (%)	50	60
bandpass filter width (nm)	2	2.2
detector field-of-view (mrad)	0.75	
detection sensitivity (nWatt)	0.5	2
ALTIMETRY ELECTRONICS:		
time interval range (counts)	0	65536
time interval resolution (nsec/count)	10 with interpolation bit to 5	
clock timebase (MHz)	100	
matched filter bandwidths (MHz)	16.6, 5.5, 1.8, 0.6	32, 16.6, 5.5
noise counter range (counts/sec)	1	16384
threshold setting range (mV)	10	2550
post-detection gain		
system impulse response (nsec, 1 sigma)	20, 60, 180, 540	10, 20, 60
false alarm ratio	$1x10^{-5}$	$1x10^{-4}$
PULSE DIGITIZER:		
digitizer input low pass filter (MHz)	15	32
sampling rate range (Megasamples/sec)	100	500
waveform amplitude resolution (bits)	8	
number of waveform samples per pulse	100	120
COMPUTER:		
clock frequency (MHz)	25	
random access memory (Mbyte)	1	
Erasable-prog.-read-only-memory (Kbyte)	256	
flight software size (Kbyte)	150	180
hard drive storage volume (Mbyte)	340	540
downlink data rates (kbps)		
low-rate / medium rate	0.12 / 19.2	

Table 1. Shuttle Laser Altimeter Instrument specifications for the SLA-01 and SLA-02 Missions

Photographs of the completed LAC and ASC payload components of SLA-01 prior to their insertion in the HH canisters are shown in Figures 2 and 3. In the LAC photograph the diode-pumped, Nd:YAG laser transmitter can be seen mounted above the receiver telescope on a circular interface plate. The cylindrical section below the laser with the three reinforcing rings is the telescope tube. The 0.38 m diameter mirror and silicon APD are packaged on the centerline inside that tube. The LAC is mounted to an annular ring (bottom of the photograph) which bolts to the upper end plate of the HH canister. Refer to [6] for more details and a three-dimensional view of the LAC and ASC. In the ASC photograph of Figure 3 it is possible to see the space-frame construction of vertical supports (2) and cross-braces that hold the electronic boxes of power supplies, computer, digitizer, and timing circuits. The hard drives are mounted at the base of the ASC on a thin plate that mounts to the upper end plate of the HH canister. The SLA payload computer is mounted in a tray that also serves as the lower cross-brace. The computer cover is removed in this photograph revealing the copper heat sinks for computer chips.

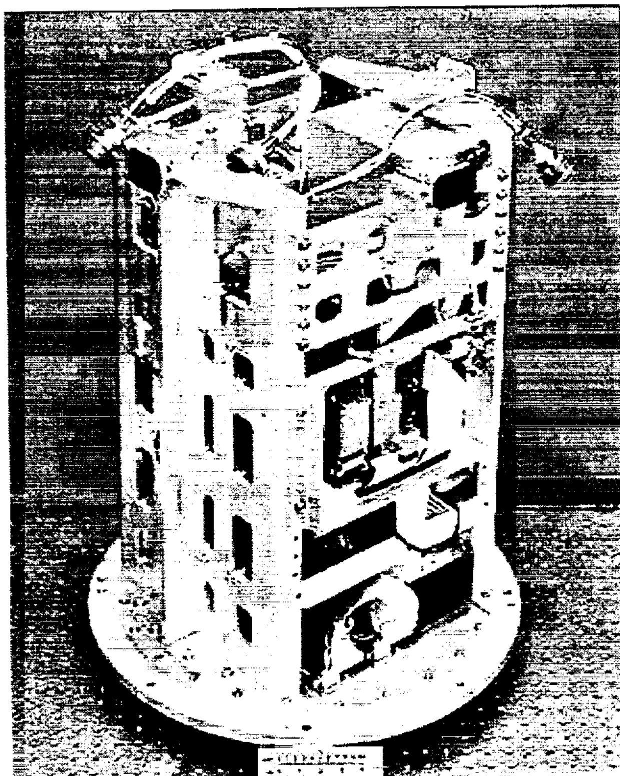

Figure 2. Laser Altimeter Canister (LAC)

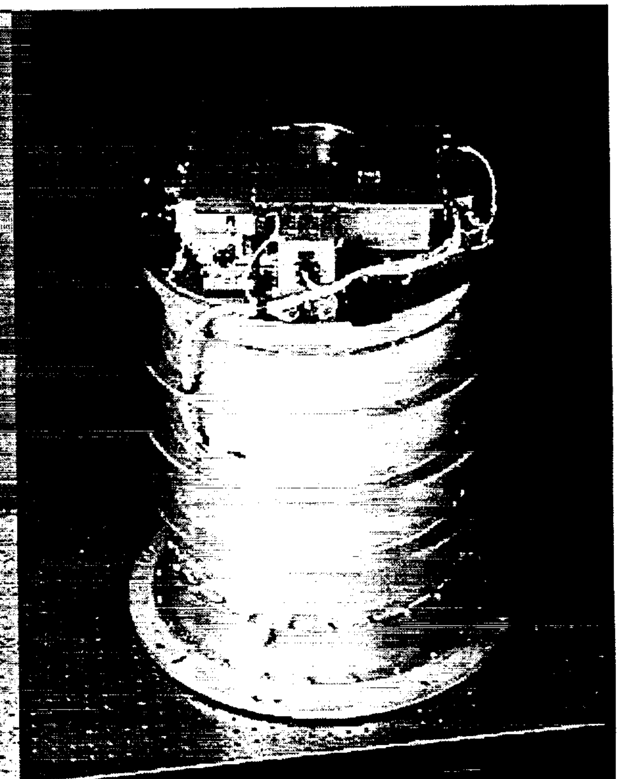

Figure 3. Altimeter Support Canister (ASC)

SLA ON-ORBIT OPERATIONS

Both SLA-01 and SLA-02 payload operations followed the same general scenario summarized as follows. Prior to activation of the SLA payload Hitchhiker power is applied to the LAC and ASC only for purposes of replacement heater operation. This permits both canisters to achieve their operational temperture set points between 5 and 20 C. The first step in activation occurs when the ASC canister is powered on and two-way communication (i.e. telemetry & command) is established with the ASC payload computer. After the laser power is enabled and switched on by the crew (using the Standard Switch Panel) the LAC is ready for activation. At this point, the Hitchhiker motorized door assembly (HMDA) for the Laser Altimeter Canister (LAC) is opened. Then, the power-on (activation) command is sent to the LAC in order to initiate SLA operation. Separate commands are used to activate the ASC, activate the LAC, and control laser transmitter operation inside the LAC. Laser activation is a potential eye safety hazard to crew operations, thus the LAC is deactivated and the HMDA door closed during all periods of EVA. Furthermore, SLA operations require that the Shuttle Z axis be controlled to within ± 1° of nadir in an Earth-viewing orientation (-ZLV). Activation of the LAC canister is permitted only when the HMDA is fully open and is controlled by the following: (1) an electrical interlock on the HMDA door; (2) computer commands sent from the ground; and (3) crew procedures.

All ASC and LAC payload operations commence on receipt of uplink commands to the ASC. During operations the laser transmitter pulses at 10 pps, pulse data from laser radiation backscattered by the Earth's surface are collected and processed, and the altimetry and housekeeping data are formatted and recorded. The ASC payload data system computer program operates the laser altimeter instrument in the LAC continuously until the standby or power-off commands are issued. Laser altimeter data are acquired and stored on the hard disk drives and a summary of laser altimeter ranging data and housekeeping data are sent over the HH 1200 baud low rate telemetry channel. The complete data set recorded on the twin hard drives is sent via the HH medium rate data channel at ~ 10 to 50 kbps when the channel is available. The operational cycles for the SLA are contiguous or segmented as required by Shuttle operations and priorities. The nominal minimum operational cycle length is about two orbits (about 3hrs), but shorter periods of operations are implemented if necessary to obtain data over high-priority targets. Maximum operational periods normally extend to about 10 hours, typically during crew sleep cycles. After laser transmitter operation is secured and SLA payload power is removed, the HMDA door on the LAC is closed to complete payload operations.

SHUTTLE MISSION REPORTS

SLA-01: The first on-orbit test of The Shuttle Laser Altimeter, the flight of SLA-01, occurred on the Endeavour Space Shuttle vehicle in a 310 km altitude, 28.45° inclination orbit during the STS-72 mission of January 11-20, 1996. The SLA-01 payload operated successfully for 83 hours in space and logged 3 million laser pulse measurements, more than 90% of which resulted in valid measurements of Earth system phenomena, including landforms, ocean surfaces, and clouds. On orbit operations of SLA-01 produced a series of laser pulse echo measurements with 100 m diameter sensor footprints spaced at regular 100 msec intervals along the nadir track of the Space Shuttle, yielding a nominal 700 m spacing between footprints. While primarily designed as a laser altimeter that measured distance to the Earth surface by time-of-flight pulse ranging, the laser pulse digitizer in SLA-01 produced detailed pulse shape measurements of each laser echo and enabled both a surface lidar mode of operation and a conventional atmospheric lidar mode of operation. SLA-01 operations were conducted almost exclusively during crew sleep periods. Thus, land observations were biased to a particular pattern leading to intense coverage of Africa, southern Asia, and central South America in a band between 28° north and south latitudes. Further details on the results of the SLA-01 mission are reported in [1].

SLA-02: The space flight of SLA-02 occurred aboard the Discovery orbiter as part of STS-85, during the period August 1-14, 1997. It concluded successfully, with nearly all mission science and engineering objectives achieved. The prime mission of the SLA-02 experiment was to demonstrate, by virtue of its role as a combined engineering/science pathfinder for orbital surface lidar, robust ranging and echo recovery from all major Earth surface types from which a near-global sampling of land-cover vertical characteristics could be derived. Due to the 57° orbital inclination on the STS-85 mission and the attention of the mission planners to the Earth-viewing (at nadir) requirements of the SLA-02 investigation, excellent coverage of all major land-cover classes was achieved. SLA-02 was intended to improve upon the successful SLA-01 experiment by enabling more flexibility in echo recovery operations, as well as higher vertical resolution of land and ocean within-footrpint height distributions. SLA-02 incorporated a Variable Gain Amplifier (VGA) system in the altimeter receiver electronics package that permitted the instrument operators on Earth to control the gain of the Si:APD detector. In addition, a solar rejection filter was installed to reduce background noise during daylight conditions.

SLA-02 operated for ~ 81 hours in Earth orbit in its required nadir-viewing geometry as part of the STS-85 mission. The data were acquired during 21 primary observation periods, mostly of short duration (less than 1 to 3 orbits) but with the final two periods each extending for 8 orbits. Most of SLA-02's data acquisition periods were interspersed with other payload operations and communications attitudes which were not Earth viewing and thus not acceptable for SLA operations. All of the observational data acquired during its 81 hours of data acquisition was recorded within the SLA-02 instrument on two hard disk drives. Only a fraction of this complete dataset was directly transmitted to the Earth during limited Medium Rate downlink times facilitated by TDRSS. By commanding gain adjustments using the VGA to account for large variations in backscatter signal level, SLA-02 echo peak amplitudes were normally kept below detector saturation levels, eliminating an echo saturation problem that affected a significant fraction of the SLA-01 data. SLA-02 fired its laser transmitter approximately 2.92 million times during its 80+ hours of operations in Earth orbit. The laser transmitter and associated altimeter receiver electronics performed essentially as anticipated (nominally), with the exception of an echo "jitter" affecting the position of the backscatter signal within the waveform data record. Waveform resolution was reduced after this anomaly began in order to compensate for the jitter.

As a part of the SLA-02 data processing, each shot is categorized as over ocean or land, and as a return from a cloud top, the Earth's surface, noise, or as shots for which no return was detected. Table 2 summarizes the percentage of shots in each category for SLA-02. The method for defining surface returns uses a maximum difference between the geolocated laser footprint elevation compared to sea level, for the ocean, and to a 10 km resolution gridded elevation model, for the land. The method probably underestimates the ocean surface percentage and overestimates the land surface percentage. Many of the no return shots likely intercepted thin clouds which yielded low-amplitude backscatter energy below the background-defined instrument detection threshold.

	No Return	Noise	Cloud	Surface	Total
Land	6.2	0.9	4.2	14.5	25.8
Ocean	18.5	3.0	25.2	27.5	74.2
Land & Ocean	24.7	3.9	29.4	42.0	100.0

Table 2. Classification of SLA-02 laser shots, as percent of processed returns.

DATA DISTRIBUTION

Data sets from the first two flights of SLA are publicly available from the project web site at: http://denali.gsfc.nasa.gov/lapf. Not all acquired altimetry data could be fully processed due to problems associated with merging the altimetry, attitude, and orbit data records. Ground tracks for the processed data are depicted in Figure 5. Data products for SLA-01 consist of the position (latitude, longitude, and elevation) of the highest detected feature within each laser footprint, enabling topographic profiles of very high vertical accuracy to be constructed after filtering out cloud returns. For SLA-02, a comprehensive data structure is provided which includes, for each laser shot, the geolocation results, return classification type, a geoid correction to convert from an ellipsoidal vertical datum to mean sea level, engineering parameters, the raw backscatter echo, and numerous characterizations of the echo shape. SLA-02 processing methods and the data set parameters are described in detail in documentation available from the web site.

PATHFINDER ACCOMPLISHMENT: SENSOR DEMONSTRATION OF LASER ALTIMETRY FROM ORBIT

Prior to SLA-01, laser altimetry from space was confined to brief episodes of (1) the Apollo Laser Altimeter and its measurements of Lunar topography during the 1970s; (2) Soviet operation of a series of geodetic spacecraft that included laser range data with boresighted photography during the 1980s [7]; and (3) the return to the Moon with the Clementine

Laser Altimeter in 1994 [8]. All of these missions produced sparse data at pulse rates of a few pulses per minute with the first generation of pulsed, solid-state laser technology. The flights of SLA-01 and SLA-02, using second-generation diode-pumped Nd:YAG lasers, represented the first substantive data set that has become publicly available for the Earth surface from orbit. It is also a data set that achieves sub-meter precision and sub-10 m accuracy in determination of surface elevations and does so at the modest pulse rate of 10pps.

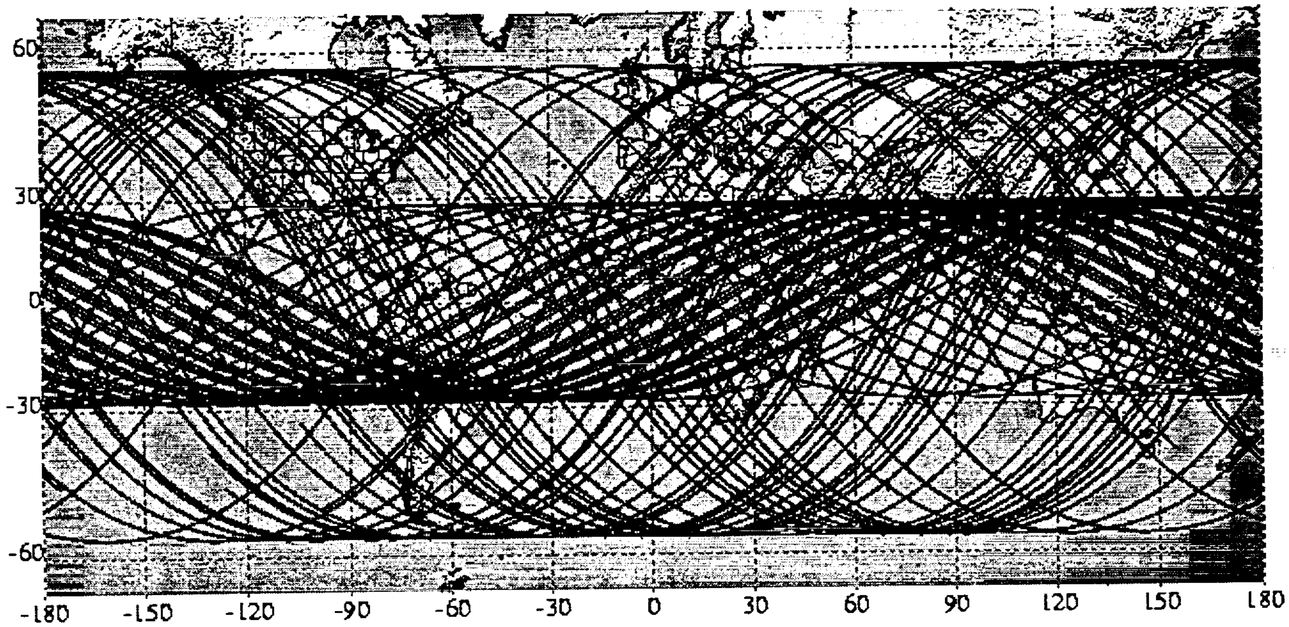

Figure 5. Ground tracks for fully processed observations from SLA-01 (28.5° inclination) and SLA-02 (57° inclination)

SLA data depend on unique determination of each laser footprint elevation. There is no averaging to boost detection signal-to-noise. As a result the design and performance of laser pulse ranging to the Earth's surface in the presence of an interfering atmosphere is a major pathfinder accomplishment of the SLA mission series. The following link analysis and table of results provide design points that were verified in on-orbit operations and are thus available to guide the development of future down-looking laser sensors.

The pulse energy, E_R, received by the SLA telescope in the LAC can be computed from the following formula:

$$E_R = E_T \; A_R \; T_O \; T_A^2 \; R_S / \pi Z^2$$

where E_T = transmitted pulse energy (~30mJ), A_R = telescope area (0.1m^2), T_O = optics transmission (0.6), and Z = orbital altitude (300km). Furthermore, at 1064nm wavelength the vertical-path atmospheric transmission, under good conditions of clear to light haze, is approximately T_A = 0.7 and the approximate values of diffuse reflection for the Earth's surface are given by, R_S = 0.2, 0.2, 0.4, 0.7, and 0.9 for soil, ocean waves, vegetation, snow, and sand. Experimental values of E_R from SLA data can be computed from: $E_R = W_R \; \Delta T$ where $W_R = V_R / (R \; G)$, W_R = pulse peak power (W) received, V_R = pulse peak voltage (V) received, ΔT = impulse response of detector (20nsec for SLA-01, 10nsec for SLA-02), R = detector responsivity (7.7x10^{5}V/W) and G = post detection gain (242 for SLA-01, and 0.5 to 250 for the variable gain amplifier in SLA-02). The results for these computations over vegetated land are listed in Table 3 where fJ is fempto-Joules (10^{-15}J).

	E_R Computed (fJ)	ΔT (nsec)	Post detection gain	V_R Measured (V)	E_R Measured (fJ)	S/N Computed	S/N Measured
SLA-01	1.25	20	242	1 -to- 4	0.32	19	13
SLA-02	1.25	10	75 –to- 150	0.5 –to- 2	0.17	19	8.6

Table 3. Computed and measured signal detection values for the SLA missions.

Results in Table 3 show order-of-magnitude correspondence between computed and measured pulse energies for both SLA missions, but show less signal than expected. This may be due to atmospheric losses. The signal-to-noise ratio S/N computations that are listed in Table 3 follow the approximate formula:

$$S/N = N_R / [F . (N_R + N_B) + N_D]1/2$$

where the received number of photoelectrons for signal (N_R), optical background (N_B), and detector dark current (N_D) follow from the standard deviation of pulse energies, e.g. $N_R = n . E_R / h\nu$, where n = silicon avalanche photodiode quantum efficiency (0.35), F = detector noise factor (3), and $h\nu$ = energy per photon at 1064nm wavelength ($1.87x10^{-19}$J). Background S/N was estimated at ~ 130 photoelectrons during the daytime for land observation and detector noise (dark current) photoelectrons are ~ 26. This latter noise source is the effective noise limit for SLA observations of the Earth's surface in eclipse. Note that use of the variable gain amplifier did not appreciably alter measured S/N, but had the considerable advantage of permitting us to adjust the post-detection gain during the mission to maintain the optimum voltage range for digitization of pulse waveforms.

PATHFINDER ACCOMPLISHMENT: GEOREFERENCING OF LASER SPOT LOCATIONS ON THE EARTH'S SURFACE

Analysis of SLA data involves the combination of laser altimeter range to the surface measurements with Shuttle pointing data and a precision orbit for the Shuttle center of mass. The SLA experiment only measured the range data and depended on Shuttle inertial reference units (IRUs) for the precision pointing angle knowledge. Pointing data accessed on the MEWS Shuttle data server in post-mission analysis is thought to be accurate to somewhat better than the 0.01° total angle. Shuttle IRUs are updated with start tracker calibrations when their drift approaches 0.01°. Orbits were computed by the SLA data analysis team at Raytheon (formerly Hughes) STX from TDRSS range and range-rate tracking data [9]. They achieved better than 5 meter radial accuracy in determination of the Shuttle orbit, which is an independent, unprecedented achievement. They also exploited the large sensitivity of laser range measurement to laser beam pointing angle biases by applying a range residual analysis in order to determine and improve upon Shuttle laser beam pointing angle and range biases. This was accomplished by minimizing the residuals between SLA elevation results and a reference surface defined by mean sea level for areas of open ocean. Surface elevations for the open ocean are known, through measurement and modeling, to the 12 cm (1-sigma) level, providing a reference surface with global access throughout the missions. The basis of the range-residual technique is a Bayesian least-squares estimation and batch processing approach. A rigorous measurement model is employed where the various parameters of the model (e.g. laser altimeter pointing and range parameters, and orbit tracking measurement model and force model parameters) are estimated to minimize the range residuals. The methodology and computational model for the range-residual calibration technique are provided in [10]. The methodology utilizes GEODYN, a state-of-the-art orbit determination and geodetic parameter estimation software suite developed at Goddard Space Flight Center. Modifications to GEODYN have been implemented to include a rigorous laser altimeter range measurement model and a new cross-over algorithm [11]. The range-residual analysis was actually used for simultaneous estimation of orbit biases, pointing biases, and range biases. The net result of this analysis for SLA-01 and –02 data was orbit knowledge improvement, range bias determination, and pointing angle calibration to yield SLA surface elevation knowledge at the sub-10m level and georeferencing of the horizontal location of SLA footprints to better than several hundred meters. The GEODYN laser altimeter capabilities initially developed for SLA form the basis of the geolocation methods to be utilized by the upcoming VCL mission, and will serve as a calibration/validation technique for the ICESat mission.

The SLA Data Analysis Team also pioneered the use of "dynamic" cross-over analysis through their use of SLA data crossing points in the open ocean. Residual analysis was applied to verification of the topographic information contained in these orbital track crossover points. The approach of [11] constructs constraint equations which are formulated in terms of a minimum distance between two curves of geolocated altimeter bounce points, instead of a height discrepancy between the curves at a predetermined point as is typically done for radar altimeters. As with range-residual analysis, crossover residual analysis made use of the GEODYN software suite. This crossover residual analysis approach was developed to exploit the small footprint capability of laser altimetry and also to take into account the effect of attitude parameters. This requires that each crossover constraint equation takes into account a series of laser altimeter ranges from each of the two altimeter passes (ascending and descending) that surround the open ocean location where a conventional (height discrepancy) cross-over occurs. The cross-over analysis methodology developed with SLA has been used extensively (and recently) for detailed analysis and dramatic improvement of the Mars Orbiting Laser Altimeter (MOLA) data. The success with MOLA illustrates the success of SLA as a pathfinder investigation. It should be pointed out that the success of the SLA data analysis is due in large part to the strong need to improve Shuttle pointing and orbit determination to match the data quality of the sub-meter ranging data available from the altimeter instrumentation.

PATHFINDER ACCOMPLISHMENT: SURFACE LIDAR PULSE WAVEFORM ANALYSIS

SLA also served as an orbital pathfinder for establishing surface lidar methods that characterize the height distribution of the Earth's surface within individual laser footprints by evaluating the backscatter waveform [1]. The broadening in time of the echo, as compared to the transmit pulse, provides information on ground slope and roughness, and the height of vegetation and/or buildings. The SLA waveform processing algorithms parameterize the return signal resulting from the interaction of the transmitted laser pulse with the intercepted surface on the ground, and identify the response from the multiple targets encountered within the footprint. Returns are modeled as a single Gaussian function or as the sum of several Gaussians when multiple, discrete peaks are present in the echo. In this manner, the vertical extent and approximate height distribution of intercepted surfaces can be derived. Most of the waveforms are single peaked and can be fit by a single Gaussian function, characterized by its maximum amplitude, location of this maximum amplitude in time with respect to the ranging electronics trigger time, and its half width. When complex surfaces are intercepted within the footprint (as with the presence of cloud layers, complex topographic relief, vegetation, or buildings) multi-Gaussian functions are summed to model the resulting multi-peaked waveforms (Figure 6). Gaussian functions are fit to the backscatter echo using a constrained, least-squares residual minimization technique that is initialized with initial estimates for peak position, amplitude, and half-width obtained from the first and second derivative of the echo signal. This waveform fitting methodology developed for SLA has been adapted for use in the planned ICESat data processing system, demonstrating another of the pathfinder aspects of the SLA experiment.

SLA FUTURE MISSIONS

The direction of the future SLA-03 and -04 missions and the instrument complement to be flown in them is being defined from lessons learned in SLA-01 and -02 and the requirements for future free-flyer instruments. Planned improvements are in laser pulse rate, beam quality, pulsewidth, and laser divergence. The eventual goal is a device capable of at least 30 mJ per pulse energy at 1064 nm wavelength, 10 mJ per pulse energy at 532 nm wavelength with a sub-10 nsec pulsewidth, and an increase in laser repetition-rate to approximately 100 pps in a single mode (Gaussian) far-field pattern with 0.1 mrad divergence. The green wavelength will be used in conjunction with the ISIR Hitchhiker payload and its Atmospheric Lidar Module to accomplish sensitive, photon-counting of atmospheric clouds and aerosols. The one-order-of-magnitude increase in laser pulse-rate to 100 pps and the decrease in laser divergence to 0.1 mrad is driven by the desire to produce near-contiguous measurements of Earth surface topography with ~ 30 m diameter sensor footprints. Contiguous profile data avoids potential aliasing of topographic relief and vegetation cover characteristics, enables more rigorous cross-over analyses, and achieves better synergy with space-based radar interferometry and stereoscopic imagery used for topographic mapping. The ultimate goal is across-track measurements and along-track measurements that have this same level-of- performance in a true multi-beam laser altimeter/surface lidar. The direction of the SLA Program beyond the -03 and -04 missions is toward a one-year observation period using a continuation of the familiar Hitchhiker interface implemented on the International Space Station.

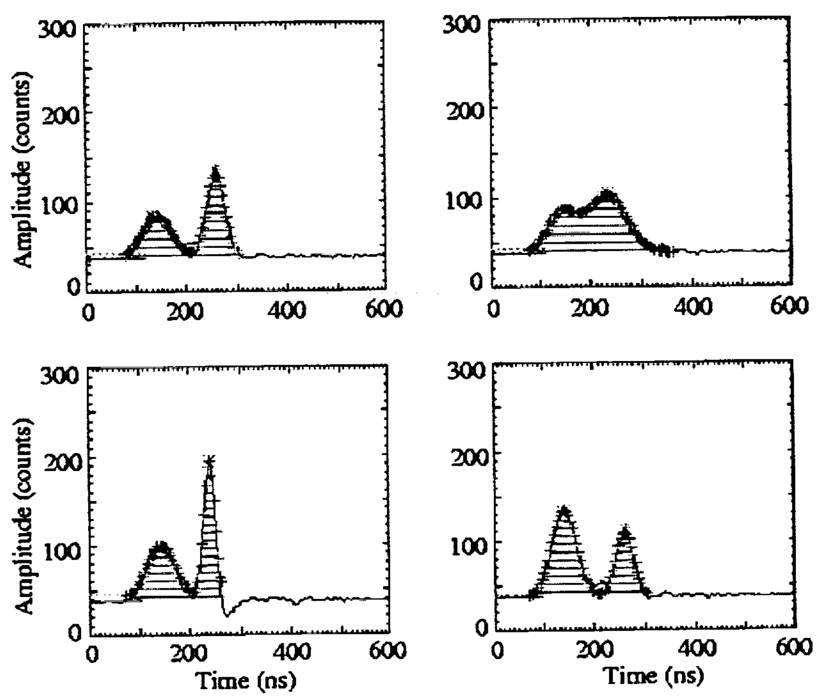

Figure 6. Representative SLA-02 waveforms showing multi-Gaussian fits, with the earlier peak most likely a return from a vegetation canopy and the later peak a return from the underlying ground.

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