Space Laser Altimetry: Laser Engineering for Multi-Beam Applications

Jack L. BUFTON* and J. Bryan BLAIR**

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The relatively new technique of laser altimetry, the measurement of Earth surface elevation by timing the propagation interval and digitizing the echo of short laser pulses, is in transition from an airborne remote sensing activity to space-based measurements of global topography. Space-based laser altimeters not only measure distance to the Earth's surface along the nadir track of a host spacecraft, but conduct a surface lidar investigation to reveal the complex shapes of land surface and its vegetation cover. Multi-beam concepts extend the coverage and accuracy of space applications of laser altimetry.

Key Words: Laser Altimeter, Lidar, Multiple beams, Space, Topography, Vegetation

1. Laser altimetry and surface lidar

Timing measurements of the propagation of short laser pulses between a remote sensing platform and the Earth's surface define the technique of laser altimetry. The primary scientific objective of laser altimetry is determination of the detailed shape (*i.e.* topography) of the Earth's surface; obtained by converting the pulse time-of-flight data from the laser altimeter sensor to surface elevation and position information. The data conversion process requires not only knowledge of the speed of light in the atmosphere and calibration of instrument timing and range biases, but accurate knowledge of the platform position (trajectory) and laser beam pointing angles. A single laser altimeter pulse measurement reveals the three-dimensional position of the laser spot or "footprint" on the Earth's surface with respect to a selected reference frame. Combining the results of data

from multiple laser footprints along the ground-track of the laser altimeter sensor produces a profile of surface topography. If the product of the laser pulse rate and footprint size are equal to the sensor platform ground-track velocity, the altimetry profile measurements are contiguous and the surface topography profile produced by the laser altimeter is free from aliasing for an accurate representation of the surface elevation at a spatial resolution equal to the footprint size; a major goal of spaced-based sensor design.

By adding a capability to analyze the shape of the laser echo from the Earth's surface, it is possible to transform the simple distance measurements of laser altimetry into a "surface lidar" that is capable of within-footprint vertical structure measurement as well as surface shape. Specifically the addition of a high-speed pulse waveform digitizer to laser altimeter timing electronics results in a data record which can be interpreted

* Laboratory for Terrestrial Physics (Goddard Space Flight Center, Greenbelt, MD 20771, USA)

** Laser Remote Sensing Branch (Goddard Space Flight Center, Greenbelt, MD 20771, USA)

to reveal the height distribution within a single footprint. Typical laser pulses emitted by gain-switched solid-state lasers produce 5-to-10nsec duration pulses which are approximately Gaussian in time and in irradiance cross-section. When these pulses strike the Earth's surface the spatial and temporal distribution of laser irradiance is altered by the shape and reflectivity of the surface within the sensor footprint. Pulse spreading is typically 10-to-100nsec for laser altimeter footprints of 10-100m diameter. A waveform digitizer operating at several hundred Megasamples per sec can then be employed to measure the distortion of the original pulse shape. An important example of the usefulness of waveform digitization is the remote sensing of vegetation canopy height and structure that can result from the characteristic signatures of partial reflection from the vegetation and partial reflection from the underlying ground as the laser pulse reflects from leaf and branch surfaces and penetrates through holes in the canopy.

Previous analyses of laser altimetry¹⁻⁴⁾ examined the factors and techniques involved in conducting profiling laser altimeter measurements and in extracting surface topography information. Recent years have seen the evolution of such laser altimetry data from airborne to space-based platforms. There have been recent reports^{5,6)} in the literature of Russian space flights of laser sensors equipped with timing and pulse digitization capability using technology that is an improvement over the earliest space-based laser altimeter, the Apollo Lunar Laser Altimeter in the 1970s. All of these systems were quite sparse in production of surface information due to their operation at a few pulses per minute, which resulted from use of first-generation, inefficient flashlamp-pumped ruby lasers laser transmitters. In January 1996 the Shuttle Laser Altimeter (SLA)⁷⁾ had its first operational use during the STS-72 Mission and demonstrated the space-based application of laser altimetry and surface lidar techniques at higher (10 pulses per sec), yet modest pulse rates. Over 50 complete orbits of laser profiling data were acquired with this pathfinder instrument, achieving several million pulse measurements of land, vegetation, ocean, and cloud heights⁸⁾. The SLA-01 sen-

sor was developed from pulsed Nd:YAG laser technology first developed for military applications and planetary remote sensing missions⁹⁻¹¹⁾. Its laser transmitter was based on the Mars Observer Laser Altimeter laser of 40mJoule pulse energy, 1064nm wavelength, and 8nsec pulse width¹⁰⁾.

If some means of across-track pointing or scanning can be incorporated into the laser altimeter design, the two-dimensional profile of surface topography achieved by the current generation of space-based sensors can be expanded into a three-dimensional map of the Earth's surface along the satellite ground track. A three-dimensional strip image of topography produced in a laser sensor swath is a goal of laser altimetry from space because its accurate representation of the surface enables numerous Earth science investigations¹²⁾. In this paper we examine sensor design, engineering issues, data interpretation methods of multi-beam laser altimetry. In doing so we believe that the numerous advantages of this technique are brought to light.

2. Multi-beam techniques

Multiple laser transmitters in a single altimeter instrument can be used to increase the coverage and sampling of the Earth's surface, by adding across-track information so that an altimeter sensor "swath" of topography data is produced. In one multi-beam laser altimeter (MBLA) concept that we have developed, 3 beams, each operating at the 1064nm fundamental wavelength of the Nd:YAG laser are arranged in a triangular pattern within a 20mrad circle that is centered on a nadir pointing direction. When one vertex of the triangle is oriented along the flight direction, as illustrated in Fig. 1, we produce three tracks of Earth surface information. For a nominal, circular orbit altitude of 400km the across-track separation is 4km and the result is an 8km wide swath or strip image of Earth surface topography. In our concept, simultaneous measurements of range to the surface are possible by sequential triggering of 3 laser pulse transmitters and partitioning the output of each laser transmitter into 3 beams, one for each vertex of the triangle. The recep-

Fig. 1 Three-beam laser altimeter mission concept.

tion of the backscattered laser pulses with a single telescope that is staring at nadir and is equipped with a narrow band interference filter and 3 silicon-avalanche photo diode detectors in its focal plane, yields simultaneous range data for each transmitted pulse. Individual laser footprints are 25m in diameter, commensurate with high resolution topographic maps and LANDSAT Thematic Mapper pixel resolution. The 25m diameter sensor footprints of our MBLA concept are contiguous in the along-track direction. This is achieved by operating each laser transmitter at a pulse rate of 100 pulses per second and interleaving all 3 transmitters with a sequential, repetitive firing order.

The strip-image range map of the Earth's surface produced by our MBLA concept is superior to simple nadir profiling with gaps between footprints as found in previous laser altimeter concepts. The gaps produce data aliasing. For example, the concept of the Geoscience Laser Altimeter System (GLAS) sensor in the NASA Earth Observing System will use 40 pps in a single beam of 70m diameter footprints resulting in 175m gaps between footprint centers¹³⁾. While this degree of aliasing of surface topographprofile data is

not a serious concern over the low relief surface of the polar ice sheets, the intended target of the GLAS Mission, it is a serious concern for remote sensing of complex terrain at lower latitudes. For the varied topography of Earth landforms (particularly vegetation canopies) the 3-beam MBLA concept we describe has several advantages: (1) continuous (*i.e.* contiguous) coverage with no data aliasing along track; (2) 25m footprints that provide near-optimum resolution of vegetation structure on a single pulse basis; (3) multiple profiles in a strip image that measure independent areas and increase the along-track coverage; (4) almost an order-of-magnitude increase in number of crossing points (9 for MBLA vs. 1 for GLAS) that occur when MBLA ground tracks intersect; and (5) surface slope determination and/or pointing angle calibration. Elimination of data aliasing along track is an obvious, important advantage for landform sensing. Furthermore, airborne laser altimeter studies have shown that vegetation height and vertical structure remote sensing with a laser altimeter is optimized when the laser footprint diameter is on the order of the diameter of 1-to-2 tree crown diameters ($\sim 25\text{m}$)¹⁴⁾. This permits a single laser footprint to produce backscatter from gaps between trees while not unduly suppressing the weighting of backscatter from the canopy top. The overall objective is to increase laser pulse rate to achieve adequate vegetation resolution while conserving the scarce resources of laser transmitter power and data handling budgets in the laser altimeter instrument by minimizing pulse rate.

When an MBLA ground track crosses a previously measured MBLA ground track, 9 crossing points are generated. It is at ground track crossing points where definitive studies can be made of MBLA internal measurement consistency and any changes in topography and vegetation can be assessed. At the equator these tracks are tilted from each other by 65° . At higher latitudes the tilt between tracks decreases as $\cos^{-1}(65^\circ - \phi)$ where ϕ = latitude (deg.). Given two equator crossings per orbit, the accumulation of MBLA ground tracks is such that global coverage with 8km swaths is possible (assuming uniform density of coverage) after 150 days of on-orbit operations. Multiple, contiguous

beams also facilitate vertical control of the topographic imagery using auto correlation techniques at the pixel level. Altimeter profiles provide an aliased, two dimensional representation of topography that does not readily yield convergence to a unique registration solution. A strip image of topography from the MBLA, on the other hand, can provide a complete three-dimensional representation of the surface that can more readily be used in auto correlation searches. Characteristic decorrelation length scales of topographic slopes on the order of a kilometer²⁾ indicate that MBLA ground coverage we propose would capture sufficient topographic structure so as to yield unique correlation results. Note also that the number of topography control points produced by this MBLA concept is $\sim 10,000$ for one month of operations from an initial 400km circular orbit at 65° inclination and would be $\sim 1.2 \times 10^5$ on the average per 1° cell at the equator for this orbit in one year of operation. Our expectation for successful measurements from orbit, as confirmed by experience with SLA-01⁸⁾, predicts that $\sim 50\%$ of these pulses will result in surface elevation measurements when the deleterious effects of cloud cover, false alarms, and missed pulses are taken into account. Thus the expectation is that the MBLA sensor we have described can produce $\sim 5 \times 10^4$ valid topography control points per 1 degree cell of land surface area at the equator in a 1-year mission.

The continuous generation of 3 simultaneous measurements of range to the surface can be used to assess 2-dimensional surface slope at the scale of the triangle size (4km) in our MBLA concept. When individual slope data from multiple pulses are combined, the average slope for a region can be estimated. Alternatively, over a known Earth surface, the 3-beam range data can be used to derive on-orbit estimates of the MBLA pointing angle. Perhaps the best known component of Earth surface topography on a global basis is the ocean surface. The TOPEX/POSEIDON Mission routinely generates data for ocean surface topography at the 10 cm or better level of vertical accuracy at spatial scales as small as 1km¹⁵⁾. The MBLA set of 3 range measurements with 10 cm precision when com-

bined with 10 cm knowledge of the ocean surface will result in the determination of a plane, and thus the normal angle to the plane. The sensitivity of this calculation is such that roll and pitch angles of $0.02\text{m} / 4,000\text{m} = 5 \times 10^{-6}$ rad (~ 1 arc sec) can be determined in a statistical (1 sigma) sense from multiple sets of 3 simultaneous MBLA range measurements for each of the 3 MBLA laser transmitters. At the nominal transmitter rate of 100 pulses-per-sec 10 sec of data (3,000 pulses total for 3 beams) over the ocean surface should result in pointing angle calibrations at the arc sec level. We can then use the measured angle over the ocean to remove time-dependent biases in the MBLA pointing angles for nearby data sets that apply to landforms. This is a technique that supplements the on-orbit measurements of laser optical bench pointing angles from conventional star camera and gyroscope sensors. Note that the TOPEX/POSEIDON data can also be employed for removal of MBLA range and timing biases by an iteration process.

Another important technique we apply to the MBLA sensor is recording and analysis of the complex shape of each laser pulse echo (*i.e.* pulse backscatter) from the Earth's surface. The application of GHz-bandwidth digitization to the receiver pulse waveform provides pulse shape data that can be used to correct the range measurement and provide information on surface vertical structure within a single laser footprint. Our "surface lidar" data record is analogous to the complex waveform produced by aerosol and molecular backscatter in atmospheric lidar, but is of shorter duration, typically less than several hundred nsec compared to 100 μ sec for atmospheric lidar. The surface lidar waveform shape is a record of the convolved effect of three properties causing elevation variations across a footprint: surface slope, surface roughness and vegetation cover. At its simplest, waveform digitization, in unvegetated areas provides a measure of within-footprint surface roughness caused by topographic variations at all length scales less than the footprint diameter. In areas of at least partially open vegetation canopies, waveform digitization provides a means to measure the within-footprint elevations of both canopy tops

and sub-canopy ground, yielding a resulting determination of vegetation height⁽¹⁴⁾. In closed canopy vegetation we typically obtain a spread waveform from the canopy top and the canopy vertical structure along with an impulse response backscatter event from the underlying surface, yielding a direct measure of canopy height and structure in a single pulse. We plan to incorporate waveform digitization at a rate of 250 Megasample per sec for several hundred samples of each laser pulse backscatter. This will yield sub-meter canopy architecture measurement in vegetated areas and ensure sub-meter overall precision in recovery of surface elevation by pulse centroid correction.

3. Laser pulse transmitter

The MBLA pulsed laser transmitter modules are based on high-power neodymium (Nd)-doped solid-state laser crystals (yttrium aluminum garnet, YAG) and employ the Q-switching technique to concentrate laser energy in a short pulse. Each of 3 laser transmitter modules is optically-pumped by separate AlGaAs laser diode arrays that dissipate most of the waste laser heat and are efficiently coupled to the thermal transfer components of the optical bench. The laser module is a second generation diode-pumped device that is being developed for space flight. Each of these laser modules produces a single mode (Gaussian cross-section) laser pulse of ~ 5nsec duration at the rate of 100 pps. Laser pulse energy of 10mJ per pulse will be sufficient to establish a link performance for the MBLA instrument that results in 95% probability of detection of the Earth's surface under clear atmospheric conditions and permits surface lidar investigations. Thus total energy per pulse must be at least 30mJoule for the 3-beam pattern.

Verification of the laser link performance was achieved during the SLA-01 Mission. The link equation in terms of received photoelectrons N_e given a received signal E_r (Joule) for our avalanche photo diode detector with 35% quantum efficiency can be estimated according to the following formulae,

$$N_e = 0.35 \cdot E_r / 1.868 \times 10^{-19} \text{ (Joule per photoelectron at } 1064 = \text{nm)}$$

$$\text{where: } E_r = E_t \cdot A_r \cdot t_a^2 \cdot t_o \cdot r_s / (z^2 \cdot \pi);$$

$$E_t = \text{transmitted pulse energy (joule);}$$

$$A_r = \text{re-ciever telescope area } 0.1\text{m}^2;$$

$$t_a = \text{transmission of the Earth's atmosphere} \\ = 0.7;$$

$$t_o = \text{optical system throughput} = 0.6;$$

$$r_s = \text{diffuse surface reflectivity} = 0.2 \text{ (soil and ocean), } 0.4 \text{ (vegetation), } 0.7 \text{ (snow);}$$

$$\text{and } z = \text{orbital altitude} = 300\text{km.}$$

For the proposed MBLA instrument A_r increases to 0.55m^2 for its 0.9m diam. telescope (vs. 0.38m diam. for SLA-01) and the orbital altitude increases to 400km . Since the reduction in N_e due to the increase in z for MBLA is more than compensated by its increase in A_r , the transmitter pulse energy required for MBLA can be reduced. Furthermore, the SLA-01 on-orbit pulse waveform data revealed high signal-to-noise detection with frequent pulse saturation for a nominal ocean surface return ($N_e \sim 1500$ photoelectrons per pulse). Thus the MBLA receiver level of ~ 1200 photoelectrons per pulse for a nominal ocean return, given 10mJoule transmitted pulses, appears to be adequate for strong signal reception. Note that at this level the noise-in-signal is ~ 35 photoelectrons. The detector circuit dark noise and preamplifier noise contribute ~ 15 photoelectrons of noise to the detection process leading to a signal-to-noise ratio of 24 (13.8db) for nighttime conditions. During the daytime solar background will make a significant contribution to total noise for a nominal optical bandpass of 1.5nm . The result is a reduction of signal-to-noise by a factor of two to about 10db , still an adequate level of laser altimeter system performance.

A prototype of the MBLA laser transmitter has been developed by Fibertek, Inc. of Herndon, VA⁽¹⁶⁾. It weighs 12kg and is assembled as shown in Fig. 2 in a compact rectangular enclosure complete with turning mirrors and steering prisms for alignment to the receiver field-of-view. Note that this laser enclosure is

Fig. 2 Multi-Beam Laser Altimeter (MBLA) Instrument concept.

sealed at 1 atmosphere of nitrogen to prevent contamination of the sensitive optics and ensure in excess of a full year of operation in space. Electrical power consumption for the MBLA instrument is dominated by operation of the 3 laser transmitter modules which have a total emitted power of 9 W. Each 3 W output laser is designed to achieve a 6% overall electrical-to-optical efficiency. Total laser power for full MBLA operation is thus 150 W. All lasers are operated at full repetition rate of 100 pps over $\sim 1/3$ of each orbit that passes over land surfaces. Over significant portions of the ocean surfaces laser repetition rate can be reduced to 30 pps thereby reducing orbital average power for the laser transmitters by a factor of ~ 2 .

4. Sensor design for space-based observations

The MBLA instrument is illustrated in concept view in Fig. 3. Its form and content are determined by the need to combine a large receiver telescope (for sensitive laser light detection) with 3 laser transmitters (multiple beams) and the combination of star sensor and gyroscope (accurate pointing knowledge). All these subassemblies are mounted to an optical bench constructed of beryllium or composite materials for light weight, thermal transfer, and maintenance of arc sec stability. Excess power is dissipated as heat by radiative transfer from the bench to the solar shield/radiator that surrounds the telescope, retaining the octagonal shape of bench and spacecraft. The size of the

Fig. 3 Multi-beam laser altimeter transmitter module (courtesy of Fibertek, Inc.)

optical bench assembly is driven by the 0.9m diam. of the telescope primary mirror. The solar shield/radiator is also formed of flat panels. The beryllium telescope, has a mature design with a space flight prototype of the 0.9m diam. telescope just completed at OCA Applied Optics in Garden Grove, CA¹⁷. Total mass for this telescope is only 28kg, yet it is capable of 70 μ rad or better image quality and is an excellent "photon bucket" for collection of laser backscatter from the Earth's surface and atmosphere. The MBLA telescope is fixed in orientation at the nadir track of the spacecraft, but has a 20mrad field-of-view to permit simul-

taneous operation with all 3 beams. A series of lenses and optical bandpass filters are used to collimate, filter, and then focus the backscattered radiation from the telescope entrance aperture on to 3 silicon avalanche photo diodes in the detector plane. These multiple detectors provide strong redundancy to preserve a single beam of data for a minimal measurements of Earth surface topography, yet work together by cross-strapping to provide complete information for all 3 beams at a total laser pulse information rate of 300pps.

Amplified signals from MBLA detector elements are processed in altimetry electronics that uniquely combine the pulse timing and pulse waveform digitization functions in a very low chip-count hybrid circuit in our current MBLA concept. This technology is currently available at 250 Megasample per sec with up to 12-bits of pulse waveform amplitude resolution in various architectures. The lidar electronics architecture is the core of the MBLA sensor capability and uniquely combines surface lidar and atmospheric lidar functions in a single circuit and in a single instrument. The lidar electronics function by digitizing continuously at 250 Megasample over the 2msec transit time for the laser transmitter pulse to be emitted from MBLA, scatter from the Earth, and be detected back on the instrument. Despite the rather large amount of data available in the lidar circuits, only the transmit and receive pulses are selected by the computer and enter the MBLA telemetry stream. On the average 10 samples of the transmit pulse will be retained as will 50 samples of the receive pulse for each of the 3 detectors for the surface lidar function. The average data rate is thus about 700kbps or less than 350kbps after compression. Note that this full data rate is collected only over the land surfaces. Data rates reduce to approximately 1/8 of the above over the ocean where laser transmitters reduce their pulse rate from 100 pps to 10 pps to conserve laser pulse lifetime and limit the data volume per day for telemetry.

Atmospheric lidar data are also collected continuously throughout the MBLA mission. For this auxiliary data set the laser pulse backscatter from all laser beams is combined at the output of the 3 APD detec-

tors, diverted into a separate atmospheric lidar digitizer channel, summed electronically, and then digitized at a rate no greater than 2.5 Megasample per sec. Atmospheric lidar digitizer signals are then digitally averaged over a full 1-to-3 sec period before being reported in telemetry. This provides a 7-to-25km spatial average of cloud and aerosol layers continuously throughout the MBLA Mission, but adds only 1% or less to the data rate and data volume produced by the MBLA instrument. All the waveform data (both surface and atmospheric lidar data) are sent via telemetry to the ground for processing and archiving. The lidar waveform data dominate the housekeeping, GPS, and pointing angle data sets. In our sensor concept all MBLA data electronics, except the detectors and the laser power supplies are located inside the spacecraft bus to avoid duplication of electronics and electronic packaging.

Pointing attitude knowledge at the 2.5 arc sec (3 sigma) level is generated by the combination of a single star camera and gyroscope. These sub-assemblies are visible in the MBLA instrument concept in Fig. 3 where they are mounted on the zenith side of the optical bench. The Star Sensor is a second-generation device¹⁸⁾ with a 2-dimensional CCD array that is capable of simultaneous tracking of 10 or more stars and has 1024 by 1024 pixel resolution. On-board Kalman-filtering is utilized to compare stellar angular position data with a star catalog and provide an output pointing attitude (quaternion) estimate.

5. Altimetry and surface lidar applications

The MBLA instrument described here will produce a data set that has enabling capabilities for a variety of Earth science applications¹²⁾. Chief among the enabling functions are the production of topography control points and the sensing of vegetation height and vertical structure. Examination of data from the SLA-01 Mission gives us an indication of the utility of the MBLA laser altimeter technology in Earth orbit. Laser pulses at 1064nm wavelength were transmitted from SLA-01 and weak, backscattered laser radiation (laser pulse echoes) from the Earth's surface and at-

mosphere were detected by the telescope and its silicon avalanche photo diode detector. The SLA-01 sensor used 100m diameter laser footprints, each separated by 740m, to profile Earth surface topography along the nadir track of the Space Shuttle. Almost every laser footprint measurement contributed a unique, unaveraged range measurement for the Earth surface or a cloud-top. The on-board data system had pulse time interval measurement at 5nsec resolution and also recorded 100 samples of the temporal shape of the laser echo from the Earth's surface with similar sample resolution. Analysis of topography control points to date from the SLA-01 Mission reveals that 1 meter vertical accuracy in determination of laser pulse spots is attainable when the SLA-01 range data are combined with a precision orbit for the spacecraft (i.e. Space Shuttle) and the full angular accuracy of the on-board star trackers and IMUs is employed in data analysis⁸⁾. Looking ahead to operation of an MBLA sensor with spacecraft position and attitude knowledge respectively provided by GPS receivers and star cameras, vertical accuracies from the sub-meter level to several meters are expected for surface slopes from 0-to-20 degrees⁴⁾. We are currently evaluating flight opportunities for the MBLA sensor to enable extensive land surface observations from Earth orbit.

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