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# MULTI-BEAM LASER ALTIMETER FOR SURFACE LIDAR OBSERVATIONS FROM SPACE

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The proposed NASA TOPSAT spacecraft mission is intended to provide a complete, digital topography data set for the Earth's land surfaces and ice sheets that has high resolution (30 m horizontal), high accuracy (2 - 5 m vertical), and is referenced to the Earth center-of-mass coordinate system. This data set will be assembled by integrating elevation measurements acquired by L-band interferometric synthetic aperture radar (ISAR) and multi-beam laser altimeter (MBLA) instruments that are operating in a circular, sun-synchronous, 566 km altitude orbit. The L-band interferometry requires dual, co-orbiting, satellites in order to achieve the required km-scale baseline separation between two receiving radar antenna for interferometric phase detection that is proportional to topography height. The MBLA instrument for the TOPSAT Mission provides a direct measurement of Earth surface topography by pulse time-of-flight measurement and serves to establish vertical control and vegetation correction for the radar data, but without the comprehensive coverage of the radar data. Principal design features of the MBLA instrument are described here and rationale is given for the choice of multiple beams. New space-based lidar component technologies that are under development for the MBLA application are described as are recent data sets from airborne laser altimeter sensors that simulate the "surface lidar" capability of the MBLA instrument.

Laser altimetry conducted with gain-switched (Q-switched) short pulses (~ 5 nsec) from solid-state lasers and sub-nsec resolution electronics is capable of sub-meter vertical precision from orbital altitudes of several hundred kilometers (Bufton, 1989). The space application of laser altimetry is a straightforward scaling from laser altimeters now operational on aircraft platforms at 0.4 km - to - 7 km above the surface. Vertical accuracy of the elevation measurement with respect to the Earth-center-of-mass reference frame is dependent primarily on knowledge of the radial orbit height and the pointing attitude of the laser transmitter on the spacecraft. With spacecraft position and attitude knowledge provided respectively by GPS receivers and star cameras, vertical accuracies from the sub-meter level to several meters can be achieved for surface slopes from 0° to 20° (Gardner, 1992). The GPS-derived precision orbit for the spacecraft must be at the 10 cm level and star camera-derived pointing attitude knowledge for the direction of the laser transmitter must be at the several arc sec level in order to achieve these surface elevation accuracies. Horizontal resolution of the elevation measurements is a function of laser beam footprint size at the surface and the spacing between successive laser pulses.

Multiple laser transmitters in a single altimeter instrument can provide across-track as well as along-track coverage that can be used to construct a range image (i.e. a surface elevation map) of the Earth's topography. In our multi-beam laser altimeter (MBLA) concept, five beams, each operating at the 1064 nm laser wavelength of Nd:YAG, are arranged in a linear, cross-track array. Near simultaneous measurements of range to the surface are possible by independent triggering of these multiple laser pulse transmitters and reception of the backscattered laser pulses with a single telescope that is staring at nadir and is equipped with a narrowband interference filter and silicon-avalanche photodiode detector in its focal plane. The single detector receives and distinguishes the multiple laser backscatter returns by time-division multiplexing. Individual laser footprints are 30 m in diameter, commensurate with the ISAR resolution, yielding a cross-track swath width of 150 m. The footprints are also contiguous in the along-track direction, achieved by operating each laser transmitter at ~ 250 pulses per second. The strip-image range map of the Earth's surface produced by an MBLA is superior to simple nadir profiling with gaps between footprints as found in previous laser altimeter concepts. These concepts are aliased in both the along and across track dimensions resulting in the possibility of meters of range error due to unknown surface slopes. The MBLA concept provides an internal measurement of two-dimensional surface slope and thus an unambiguous determination of surface elevation along the nadir track. Determination of slopes for a 5 by 5 array of MBLA data will typically have sub-degree accuracy at 30 m length scales.

Multiple, contiguous beams are also necessary in order to achieve pixel-level accuracy using autocorrelation techniques for vertical control of the ISAR topographic imagery. The search for a minimum difference registration will require rotations and translations of MBLA data with respect to ISAR data. 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 autocorrelation searches. Characteristic decorrelation length scales of topographic slopes on the order of several hundred meters indicate that 5 x 5 arrays of 30 m elevation cells would capture sufficient topographic structure so as to yield unique correlation results.

The illumination pattern incident on the Earth's surface from any one transmitter element of the MBLA is a two-dimensional circular pattern of laser irradiance, with a Gaussian spatial distribution of illumination intensity, that is produced by a single transverse (spatial) mode of the laser cavity. In an ideal altimeter application (e.g. measurement of a smooth water surface at normal incidence) the backscattered laser pulse retains the shape of the incident pulse. However in the general case, the height distribution (i.e. roughness) and slope of the surface produce spreading in time, that can add 10 nsec - 100 nsec or more to the laser pulse width. 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 additional information on surface vertical structure. 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. This "surface lidar" data record is analogous to the complex waveform produced by aerosol and molecular backscatter in atmospheric lidar, but is of shorter duration. 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 30 m. 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 (Harding et al, 1994). Effective extraction of vegetation height and surface roughness data requires independent knowledge of the magnitude of laser incidence angle and the surface slope, both along-track and across-track. Thus MBLA "pushbroom" scan pattern data are needed to deconvolve laser pulse spreading due to surface slope or pointing angle from spreading due to surface roughness and/or vegetation. We plan to incorporate waveform digitization at a rate of at least 1 gigasample per sec for several hundred samples of each laser pulse backscatter from the center beam of the MBLA 5-beam array and use the surface elevation data from all 5 beams to interpret this surface lidar return.

The MBLA instrument is illustrated in concept view in Figure 1. It is divided into two structures, the optical bench assembly (65 kg) and the electronics enclosure (60 kg). This design is driven by optical alignment considerations which demand separation of the laser optical head from the high thermal dissipation of the electronic and power supply components of the laser and minimize the size and load carrying capacity of the optical bench. The size of the optical bench assembly is driven by the 0.9 m diam. telescope. The altimeter telescope primary mirror is attached to the nadir-viewing side of the optical bench and the laser transmitter modules, detector package, and dual star cameras are attached to the opposite side. This construction ties all the transmitter and receiver optics together for maintenance of arc sec alignment in a rigid, athermal design. Excess power is dissipated as heat by radiative transfer from beryllium structural components of the telescope and optical bench and attached subassemblies. Additional radiators are located on the cold side of the spacecraft in order to maintain the optical bench at a stable operational temperature. The principal beryllium components, the telescope and optical bench, have a mature design with a space flight prototype of the 0.9 m diam. telescope now under construction at OCA Applied Optics in Garden Grove, CA. Total mass for this telescope is only 25 kg, yet it is capable of 100 microrad or better image quality. Laser backscatter from the Earth's surface is collected by the MBLA telescope that is fixed in orientation at the nadir track of the spacecraft. A series of two optical lenses and optical bandpass filters are used to collimate, filter, and then focus the backscattered radiation from the telescope entrance aperture on to a silicon avalanche photodiode in the detector plane. Amplified signals from this detector element are processed in the altimetry electronics for the pulse timing and pulse waveform information content. In addition, energy measurements are made for the transmitted and received laser pulses.

The MBLA pulsed laser transmitter is based on high-power neodymium (Nd)-doped solid-state laser crystals and employs the Q-switching technique to concentrate laser energy in a short pulse. Each of 5 laser transmitter modules is optically-pumped by separate AlGaAs laser diode arrays that are coupled into the Nd laser crystals by fiber-optic cables. The laser module design is a second generation diode-pumped concept that is being developed in prototype form by Lightwave Electronics Corp., Mountain View, CA. Each of these laser modules produces a single mode (Gaussian cross-section) laser pulse of ≤ 5 nsec duration at the rate of 250 pps for a total pulse rate of 1,250 pps. Laser pulse energy of 30 mJ 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. Electrical power consumption, ~ 250 W average, for the MBLA is dominated by operation of the 5 laser transmitter modules which have a total emitted power of 38 w.

Pointing attitude knowledge is generated by dual star cameras. Each camera is a second-generation star camera with a 2-dimensional CCD array that is capable of simultaneous tracking of 5 stars. On-board Kalmann-filtering is utilized to compare stellar angular position data with a star catalog and provide an output pointing attitude estimate; in principle eliminating the need for an inertial reference unit. Both star cameras are capable of arc sec (total angle) pointing knowledge limited by the quality of the star catalog.

Airborne laser altimeter investigations with profiling and scanning instruments are now demonstrating the surface lidar capabilities of the proposed space-based MBLA. Pulse time-of-flight surface elevation measurements at the 10-cm accuracy level have been achieved with a scanning lidar on the NASA P3-B aircraft over the Greenland ice sheet (Thomas et al, 1993). A profiling laser altimeter operated by the authors and their colleagues on both the P3-B and the NASA T-39 aircraft is now achieving sub-meter accuracies for surface elevation of the ice sheet and a variety of unvegetated and vegetated land areas. This instrument produces a full waveform record at a repetition rate of ~ 50 pulses per sec with a digitization rate of 1.35 gigasamples per sec and an amplitude resolution of 8-bits. The digitization record is coupled to the time base of the pulse timing counter to form the surface lidar capability. Most measurements have been performed to date at low altitude (~ 500 m) above surface level in order to maximize surface elevation measurement accuracy. The profiling instrument is also capable of operation at altitudes up to 12 km above the surface using a 0.2 m diam. refractive telescope with a 10 mrad field-of-view. Laser transmitter divergence and aircraft operating altitude are adjusted to produce a surface lidar with sensor footprints dimensions from 1 m to 70 m diam. The large footprint data simulate space-based measurements and are being used for algorithm development. Example data sets are presented and discussed.

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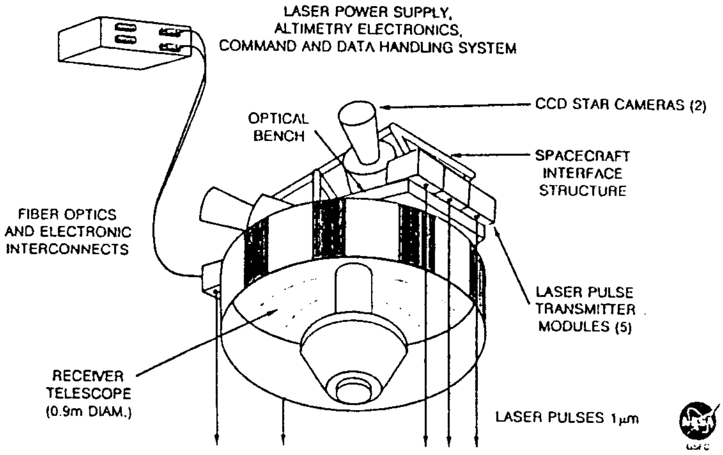

Fig. 1. MBLA Configuration