Technologies Development for the Lidar Surface Topography (LIST) Mission

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1. Introduction

The present generation of orbital laser altimeters all profile surface height along one measurement line. In this paper, we describe ongoing technologies development efforts for the Lidar Surface Topography (LIST) mission.

2. The LIST Mission

In 2007 the National Research Council (NRC), in response to requests from NASA, NOAA and the U.S. Geological Survey (USGS), conducted a decadal survey to generate consensus recommendations from the Earth and environmental science and applications communities regarding a systems approach to space-based and ancillary observations that encompasses the research programs of the three agencies.[1] The NRC recommended a total of fifteen missions with benefits range from information for short-term needs, such as weather forecasts and warnings for protection of life and property, to the longer-term scientific understanding necessary for future applications that will benefit society in ways still to be realized. Of the fifteen spaceflight missions recommended in that report, the LIST mission most fully integrates this interdisciplinary framework in its objectives. LIST will provide high-resolution elevation images of the Earth's solid surface and its overlying covers of vegetation, water, snow, ice and man-made structures. This foundation data is fundamental to understanding, modelling and predicting interactions between the solid Earth, hydrosphere, biosphere, cryosphere and atmosphere. The mission will dramatically advance quantitative understanding of natural hazards, landscape evolution, carbon storage in vegetation and its exchange with the atmosphere, habitat quality and its response to disturbance, ice sheet mass balance and its response to climate change, changing sea ice contributions to ocean-atmosphere energy exchange, and the storage and transfer of on-land water resources. Each of these is of vital significance to the prosperity, health and sustainability of our modern society.

LIST is a tier-3 mission, with a potential launch date well into the 2020's. Achieving the stated goals of the LIST mission, full global mapping of surface topography and vegetation structure with 5 m spatial sampling and 10 cm vertical precision, presents an imposing set of technology challenges. It represents for global topography a 100x spatial sampling improvement and 10x to, where vegetated, 200x vertical improvement, as compared to NASA's Shuttle Radar Topography Mission. For vegetation structure, ice sheet and sea ice measurements it vastly expands upon the limited spatial sampling of its predecessor lidar missions, ICESat with its one laser profile and ICESat-2 and DESDynI Lidar with several, to achieve complete mapping in a wide swath with on-the-order 1000 laser beams.

3. Advanced Mission Concept for LIST

An advanced mission concept study for LIST requested by NASA Science Mission Division (SMD) and conducted at GSFC in mid-2007, detailed requirements and technology challenges for the mission. The greatest challenge for the mission is the volume of the primary global map data product, consisting of 7 trillion 5 m pixels reporting surface elevation and vegetation vertical structure, where present. Another great challenge is achieving single-photon detector sensitivity in order to measure very weak ground surface returns with 10 cm elevation precision from beneath dense forest canopy cover, and to do so through thin to moderate cloud cover. This must be accomplished in a swath width of at least 5 km to acquire global coverage in a reasonable mission duration. An instrument with large dynamic range is required to accommodate highly varying apparent reflectance conditions due to rapid changes in surface reflectance, atmospheric transmission and canopy cover. Efficiencies significantly exceeding current generation laser altimeters are necessary to minimize required power, mass, size, complexity and cost. The instrument approach detailed in the remainder of this paper is specifically designed to accommodate these LIST mission challenges.

As described by the LIST study findings, the instrument required to meet the LIST objectives far exceeds those of existing space laser altimeter technologies. In simple terms, an instrument should generate a swath width of 5 km, image this swath onto a detector array and produce an image that describes the topography of the sampled area, including through foliage if covered by vegetation, and the 3-D structure of the vegetation cover. Beginning in 2005, we began development of an ESTO funded Instrument Incubator Program (IIP) called the Slope Imaging Multi-Polarization Photon-counting Lidar (SIMPL).[2] The SIMPL instrument was developed to demonstrate micropulse laser altimetry measurement methods that will enable more efficient observations of topography and surface properties from space.[3-5] In 2008, we were awarded the Efficient Swath Mapping Laser Altimetry Demonstration IIP (2008-IIP) to develop and demonstrate critical technologies (efficient laser and detector) for the LIST mission with the objective to mitigate risks and demonstrate measurement techniques by designing and building a non-scanning, 16-beam micropulse altimeter instrument that spans a swath of 80-m with 5-m spatial resolution to support the LIST mission.[6-9]

4. Laser Technology

Over the past year, four US-based vendors have been developing space qualified MOPA lasers for ICESat-2.[10] The ICESat-2 laser transmitter performance requirement is very similar to that of the LIST mission in terms of overall wall-plug efficiency, wavelength stability, pulse width, repetition rate and beam quality. The pulse energy requirement for LIST from orbit is estimated to be about 50 μJ (see Table 2), we envisioned that the LIST instrument will be made up of 10 modules, each capable of producing a 10x10 beam, spanning 0.5 km. Thus 10 modules will provide enough coverage to meet the LIST requirements. In this case, a laser producing >5 mJ will be needed for each of the ten modules. This is about doubling the energy requirement for ICESat-2 and is within the design margin of the laser for ICESat-2. We will continue to monitor various laser development for space applications and make recommendation to the LIST mission to mitigate risks and costs.

The laser transmitter design used for ICESat-2 will be at Technology Readiness Level (TRL) 6 by 2013. The Lunar Orbiter Laser Altimeter (LOLA) instrument on board the LRO spacecraft was the first multi-beam spaceborne altimetry instrument.[11,12] A diffraction optical element (DOE) was used to generate a 5-beam pattern for altimetry measurement. In addition, for ICESat-2 and the Swath Mapper IIP, we are also investigating the use of a different technique with microlens arrays (MLA) to generate the multi-beam pattern.[13] We are already generating a 4x4, 16-beam pattern for use in the airborne instrument with an objective to demonstrate measurement approach for LIST. The development of a 10x10 pattern from a DOE or microlens arrays will mitigate risks associated with the LIST mission.

For the LIST mission, a DOE or MLA approach can be used to generate a 10x10 beam pattern, if clocked at a certain way, one can trace out a contiguous swath of 100 beams, each having the desired footprint.

Ten such systems will be able to meet the 1000 beam, 5-m spot as required by the LIST mission.

5. Detector Array Technology

Another critical enabling technology for next-generation laser altimetry and surface/biomass mapping from space is high -sensitivity low-noise avalanche photodiode (APD) detectors that provide single-photon sensitivity. Analog or linear APD with low noise floor are sought after for all low light applications. For spaceborne instruments, low noise, high sensitivity ultimately single photon sensitive photodetectors have direct implications in instrument design. A highly sensitive detector can relax the energy requirement on laser transmitters on the instrument and thus overall power constraints.

The backscatter laser signals by surface and biomass (e.g. grass, trees, etc.) at the satellite altitude are very weak. Detectors with high quantum efficiency (QE) and internal gain are needed to overcome detector amplifier noise and achieve the required signal-to-noise ratios. APDs are one candidate detector approach. Common APD detectors include Si APD detectors, InGaAs APD detectors, HgCdTe APD detectors, etc. Si APD detectors are limited to 1 micron or less since it becomes transparent beyond 1 micron and the QE peaks at about 600 nm and drops rapidly towards 1 micron. For most Si APDs, the QE at 1 micron is only about a few percent. InGaAs APD detectors have been widely used in optical communication systems and the QE in the 1 micron region is about 60-70%. One of the major drawbacks of InGaAs APDs is high excess noise, defined as additional noise caused internal amplification or gain. This is due to the high ionization ratio, k, defined as ratio of hole to electron ionization probabilities. With a high k material such as InGaAs, excess noise increases rapidly with APD gain. The excess noise limits the usable gain to achieve the maximum signal-to-noise ratio. In contrast, HgCdTe APDs[14-16] have a k value of zero. Since the internal amplification is almost deterministic, it exhibits very low excess noise. In a separately NASA ESTO funded Advanced Component Technology (ACT) program,[17] we are exploring a near single-photon sensitive detector array operating in analog mode, with > 1 GHz bandwidth. Further development is necessary to meet the LIST requirements. Presently candidate detectors for LIST include HgCdTe on CdZnTe APDs, impact-ionization-engineered InAlAs APDs[18] and multi-element anode InGaAsP intensified photodiode[19] detectors (IPD).

In addition to high quality and low defects material that leads to high internal gain and low excess noise APD detectors, another key component of high performance LADAR focal plane array (FPA) is the ultra-low noise and high speed read out integrate circuit (ROIC). There have been some investments in this area other groups. One such example is the Air Force Research Laboratory (AFRL) funded ultra-sensitive detection (USD) program.[20] The primary objective of the USD program is to detect and accurately range to missile clusters at thousands of kilometers distances. Challenges include very weak return signals, one or few photons per pulse, potential of very closely spaced multiple returns (ns apart) from a single laser pulse as a result of closely spaced multiple targets in the FOV, wide dynamic range (1 to > 2000 return photons depending on targets),[21] the need for very fast frame rates to mitigate distortions by atmospheric turbulences, requirement of no persistent residual image, low false alarm rate, etc. These challenges are similar to some of the challenges of accurate LIDAR surface topography from space.

6. Conclusions

We are developing the measurement approach and lidar technologies for the LIST mission by ESTO funded IIPs and also leveraging other missions' technologies development efforts. Our objectives are to mitigate the major risks and developing efficient measurement techniques for the LIST mission.

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8. References

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