An Electronically Steerable Flash Lidar (ESFL)

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***Abstract*— Current space-based lidar systems for Earth remote sensing have a number of inherent limitations that impact their use for broader science applications. These include no cross-track coverage, fixed spatial sampling that forces pointing control to be performed by the spacecraft, cloud loss over many types of scenes, and, in general, lifetimes set in part by the number of laser shots fired. The Electronically Steerable Flash Lidar (ESFL) is a new concept developed to help in overcoming these limitations. It combines a new "Flash" focal plane technology that allows both imaging and waveform ranging, with a multi-beam steering capability. Steering is achieved via an acousto-optic beam deflector that splits the laser into multiple beams that can be independently accessed and pointed without the need for mechanical scanners or boresight mechanisms. A full demonstration unit of ESFL was completed and successfully tested both in laboratory and aircraft flight tests. One to ten beams were controlled at the full frame rate (30Hz) of the focal plane. Laboratory testing showed that ESFL can be used to point between clouds identified by a separate visible camera. Multiple operating modes were demonstrated including a geolocation mode where a beam tracked a pre-defined transect defined by its GPS determined latitude/longitude as the aircraft carrying the lidar passed over. ESFL was flight tested over a broad range of land and forest scenes illustrating its ability to terrain map as well as profile forest canopies.**

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I. INTRODUCTION

Laser remote sensing brings unique measurement techniques to studies of different planetary bodies from orbit. Mars, Mercury, Moon, and Earth have been mapped from orbit as well as aspects of the Earth's atmospheric layers, all using lidars (or laser altimeters). Two laser missions, ICESat (recently ended) and CALIPSO are performing extended measurements of the Earth. Many of the unique properties of lasers that enable these missions – including an active light source for day/night operation, well-collimated beams, narrow spectral linewidths, precise timing of short emitted pulses, high peak power pulses, and reasonable electrical wallplug efficiencies. However, with the advantages of laser remote sensing come some inherent disadvantages, at least as currently manifested. The need for higher signal-to-noise ratio requires larger laser energies and efficient use of the laser light. These place a premium on making highly reliable lasers with well-controlled beams. For ICESat and CALIPSO, single well-collimated laser beams pointing near nadir are used, resulting in narrow (< 100 m footprint) transects being measured - a very sparse sampling of the Earth and its atmosphere. These well-collimated beams must be carefully aligned (bore-sighted) with the collection optics field of view, and dense clouds block the beam preventing measurements below. The use of agile spacecraft to change the pointing allows some beam re-direction, but with limitations on the pointing and also impact on satellite performance.

There exist technologies today that if reliably applied could help to mitigate many of these limitations, enabling both improved science and mission reliability. A mission design was developed for an Electronically Steerable Flash Lidar (ESFL) with a path to flight for the DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice). [1] Under NASA ESTO funding, a demonstration unit was constructed and it is currently in aircraft testing.

II. SYSTEM DESCRIPTION

A notional schematic of a space-based version of ESFL is shown in Fig. 1. The output of a single laser is split into multiple beams cross-track to the satellite motion using an Acousto Optic Beam Deflector (AOBD) . The acousto-optic crystal acts as transmissive diffraction grating. When a radio frequency (RF) signal is applied to a piezo-electric transducer mounted to the crystal, stress-induced modulation of the index of refraction occurs. The RF signal is generated by direct digital synthesis in a field programmable gate array. Multiple RF tones can be applied simultaneously to the crystal, each producing a diffracted beam at an angle determined by the RF

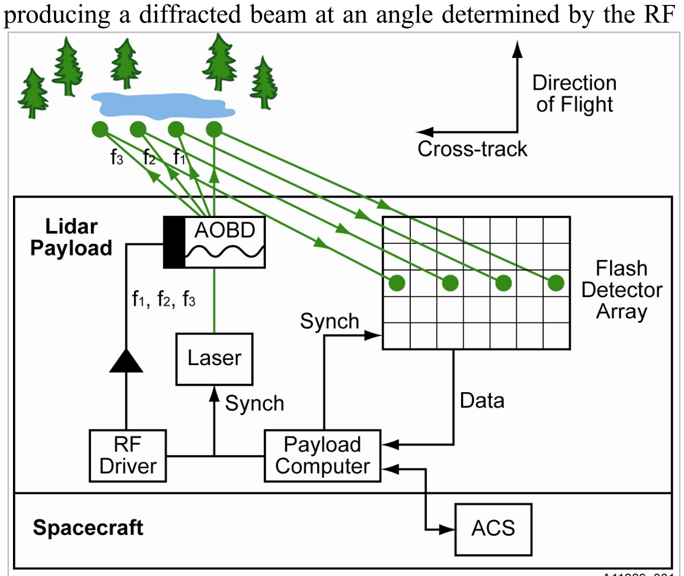

Figure 1. A schematic of the Electronically Steerable Flash Lidar concept.

frequency. Precision pointing control of the beams is enabled by the ability to accurately control the frequencies of the tone. The tones can be continuously swept and provide random access in the cross-track direction for beam location. The number of independent beams that can be produced depends on the wavelength, aperture size, beam size, as well as the number of RF tones - up to approximately one hundred beams at 1064 nm for common beam sizes. The optical beam power can be efficiently split into the different "beamlets", leaving a small fraction in an undeflected beam, which can still be utilized for measurements. The speed at which the beams can be re-configured is a small fraction of the pulse rate of the currently space qualified lasers used in lidars.

Not shown in Fig. 1 is the transmission telescope that collimates the outgoing beams and sets the required beam footprint size on the ground to that needed for the measurement, a 25 m beam diameter for DESDynI for measuring forest canopies. Also not shown is the receiver telescope that images those spots onto the optical detectors. Different types of detectors and configurations can be used. Fig. 1 shows a square "Flash focal plane array", a CMOS-based "smart pixel" device that measures both the intensity and time of flight independently for each pixel. By using an array which is carefully aligned to the spacecraft attitude control system (ACS), the location where the light falls on the array defines the location on the ground of the beamlets. While the figure shows the laser spots being imaged onto single pixels, it is also possible to subsample the laser spot on the ground using multiple pixels.

How could this concept help in a mission such as DESDynI? The lidar goals of the mission are to measure the Earth's forest canopies in order to resolve structure for biodiversity and improve measurements of biomass which in turn can provide estimates of carbon storage. This is to be done with a multibeam lidar with 25 m footprints and 1 m vertical accuracy. [1] ESFL will allow the number of beams and their spacing to be varied to allow the spatial sampling to match the type of forest and any detailed measurement goals. Fewer beams with higher energy (within eyesafety limitations) can be used over dense forest canopies, and larger numbers of beams can be used over less dense canopies and give better topographic slope measurements, improving the forest height estimate. If fine spatial information is desired, the beams can be made contiguous cross-track, or they can be spread apart to provide a broader statistical view of the forest. The Earth has a wide range of ecosystems – ESFL can be readily adapted to match them.

Beyond enabling improved spatial sampling of forests, ESFL can also improve other aspects of forest measurement. For example, all optical remote sensing of the Earth surface suffers from data loss due to dense clouds. This loss can be as high as 50% on a global average. This is especially true for lidars with fixed pointing beams. But forest scenes are distributed and broken cloud fields provide openings to the ground. This can be seen in the CALIPSO Wide Field Camera data (http://www-calipso.larc.nasa.gov/products/wfc/) that collects cloud context information for the CALIOP lidar onboard. Using a cloud context camera pointed ahead, along-track, would allow holes between clouds to be identified and the information fed-forward to the beam deflector to increase the probability that the forest can be measured. Another advantage provided by ESFL is that, to detect changes in the scene (e.g. over ice)a method is to adjust the satellite's attitude to have the beam follow the same transect on the ground. Exact repeat is critical to prevent measurements on slopes to be differentiated from changes in the surface. Having a steerable beams can relax requirements on the satellite pointing control, sharing the system level requirement between the attitude control system and the beam deflector.

Lidars in orbit are in general starved for photons – signal to noise is a critical. How many beamlets can be utilized, and with what cross-track coverage, hinges on a large number of practical instrument issues, the fundamental radiometry, and the details of the measurement that is to be made. One challenge is that lidar concepts to date assume fixed numbers and pointing of beams. When those requirements are relaxed, new science and measurement techniques are enabled, in turn changing how the requirements should be written. A self-consistent design has been completed based on experience with the CALIPSO design. [2] Using realistic input parameters, the design predicts up to forty beams could be utilized over a cross-track swath on order of 10 km.

An important consideration for ESFL is its impact on laser reliability. Laser reliability for the currently used diode-pumped solid state lasers used in space is controlled by a number of factors. [3,4] One critical metric is the total number of pulses fired; a second is the total energy per pulse. CALIPSO has demonstrated 1.6 billion shots on its first laser before being shut down and switched over to its second laser which is up to 0.7 billion shots at this point. All shots have been at greater than 210 mJ and at a repetition rate of 20 Hz (for a total of 500 MJ of optical energy or 10 GW of optical power over the mission to date). Current 1064 lasers at high TRL level are now operating up to 1 J per pulse at 40 Hz. ESFL's design allows the along-track and cross-track spatial sampling to be balanced, allowing contiguous spatial coverage and lower total number of shots required to meet the mission goals – improving the overall mission reliability.

III. Aircraft Demonstration

NASA Earth Science Technology Office funded an aircraft demonstration unit of ESFL to be built under an Instrument Incubator Program grant. The program was constructed with a "path-to-space" requirement on the subsystem designs. Integral to the program are science co-Investigators who reviewed the design, concept of operations, chose the forest test sites, performed scientific data analysis and modeling, and provided students for ground truth collections. An accelerated two year schedule is being performed to have the demonstration complete in the timeframe of decision making on the DESDynI project.

A system description of the ESFL demonstration unit is given in Table I. The unit has completed calibration (intensity, ranging, geolocation, waveform shape) and laboratory characterization. A set of engineering aircraft test flights were flown over the eastern Colorado plains. Fig. 2 shows a set of three sequential laser pulses operated at 25 Hz with the number of beamlets changed for each pulse. A geolocation mode, where a beam tracked a specified transect on the ground was also demonstrated. Additional data was collected in forest scenes at the US Forest Service Manitou Experimental Forest in southern Colorado. Full waveform data of the coniferous trees was collected for comparison against traditional scanning lidar data and ground truth measurements. An example of data from Manitou is shown in Fig. 3. A second flight campaign was completed over the Stephen Austin experimental forest in Texas, a mixed coniferous hardwood forest. A third flight campaign is being planned.

The cloud avoidance capabilities of the design were demonstrated in the laboratory. A simulated cloud scene similar to those measured by the CALIPSO WFC and scrolling at similar satellite rates was created and projected on the laboratory wall. The lidar's integrated visible camera was aligned looking forward alongtrack and a simple threshold algorithm was implemented in the lidar computer to identify the clouds and repoint the beams to miss the clouds. A witness camera that could image both the infrared laser and the visible "clouds" was used to record the scene. Cloud avoidance was demonstrated using one to ten beams; a single three beam frame is shown in Fig. 4.

TABLE I. TABLE 1. DESIGN AND OPERATING PARAMETERS FOR THE ESFL DEMONSTRATION UNIT

Laser Energy	25 mJ
Laser Wavelength	1064 nm
Lidar Receiver Field of View	8.6 °
Lidar Receiver focal plane	128 by 128
Number of Beamlets	1-10
Secondary Instruments	Visible Camera/GPS/IMU
Aircraft Altitude	300- 600 m
Vertical Bin	0.75 m

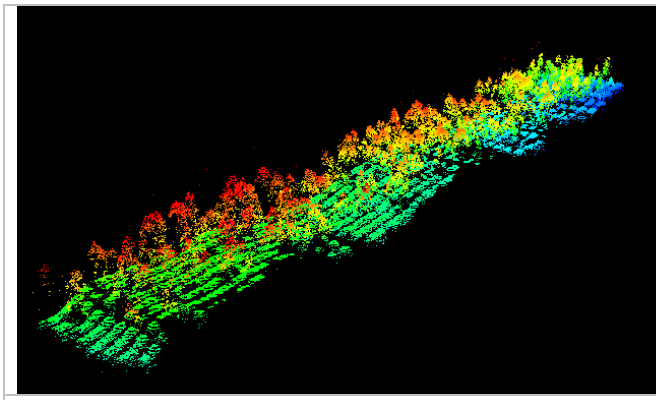

Figure 3. A swath of Full lidar waveform data collected over the USFS Manitou Forest. An eight beam "pushbroom" configuration was used.

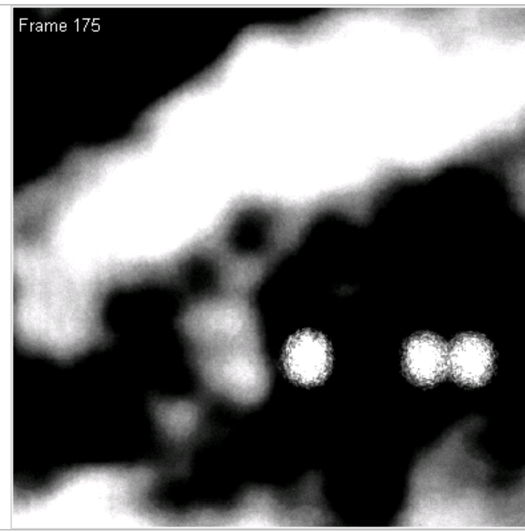

Figure 4. Example from a laboratory demonstration of how ESFL could be used to steer the beamlets around clouds. Three ESFL beamlets (round spots) are shown as they deflect around the cloud scene.

Preliminary modeling of the impact of ESFL on a space mission design for measuring forest biomass was completed.[5] That study showed that using an ESFL-like design could significantly improve the accuracy of the biomass measurements because of the improved ground slope measurements, and decrease the mission time needed to collect data over the Earth by a factor of three or more.

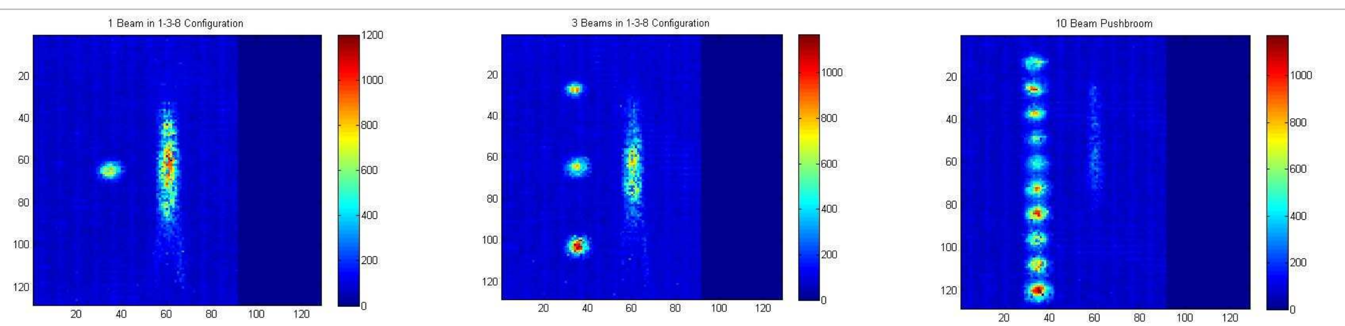

Figure 2. The image of the scattering form the ground of three sequential laser pulses taken form an aircraft. ESFL has been commanded to change the number of beamlets for each laser pulse. Along track direction is left to right. Elongated beam is the undeflected beam which has been optically reshaped and re-aligned to fall ahead of the deflected beams.

ACKNOWLEDGMENT

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Patents are pending

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