

DEVELOPMENT OF CONCURRENT ARTIFICIALLY-INTELLIGENT SPECTROMETRY AND ADAPTIVE LIDAR SYSTEM (CASALS) FOR SWATH MAPPING FROM SPACE

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ABSTRACT

We present the design and performance of a Concurrent Artificially-intelligent Spectrometry and Adaptive Lidar System (CASALS) for 3D imaging from Space. With a single fast wavelength tuning laser, CASALS accomplishes a 1,200 resolvable spots swath mapping by grating dispersion wavelength steering. Any subset of these 1,200 spots can be selected by wavelength switching. The validation operating principle was accomplished and reported in IGASS-2022. With configurable base design, we report the designs and progress of the CASALS airplane campaign with 256 contiguous ground spots. It is accomplished with a single fast tuning laser at 1040-nm, 1.152MHz tuning rate, and pulse modulated 2-ns on each wavelength. Return pulses are mapped to an eight-pixel detector array with single-photon sensitivity. The lidar returns are time-multiplexed to two outputs that are digitized with two 1-GSPS-digitizer. A grating spectrometer rejects solar background noise spatially and spectrally. We are developing a 1040-nm CASALS intended for multiple LEO orbit missions: Earth Venture Mission on ESPA Grande, STV Mission on ESPA Grande SmallSat, STV Mission on spacecraft equivalent to ICESat-2.

Index Terms— ranging lidar, adaptive lidar, laser altimeter, imaging lidar, wavelength scanning

1. INTRODUCTION

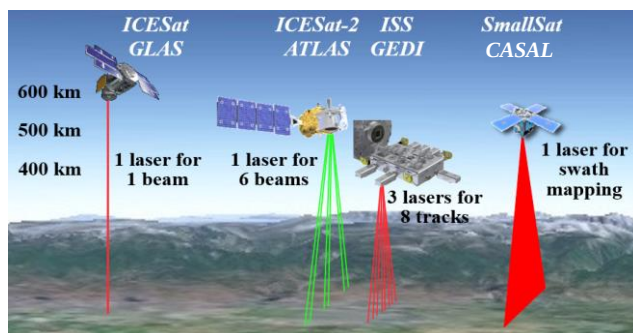


Figure 1. Progression from lidar profiles to 3D imaging, from single-beam GLAS to multiple-beam ATLAS and GEDI. CASALS provides a low SWaP path to spaceflight 3D mapping.

Spaceborne laser altimeters provide high precision global elevation data needed for determining changes in ice sheet heights, sea ice thickness, vegetation structure and land topography as well as for atmospheric cloud and aerosol profiling. NASA has launched three Earth orbiting laser altimeter instruments in the past twenty years (Figure 1). The first was the Geoscience Laser Altimeter System (GLAS) on the NASA Ice, Cloud and land Elevation Satellite (ICESat) [1], operated from 2003 to 2009. GLAS is a single-beam pulsed laser altimeter operating at 40-Hz and the return analog waveform is digitized. The second launched instrument is the Advanced Topographic Laser Altimeter System (ATLAS) on the NASA ICESat-2 mission [2]. It employs a micro-pulse laser operating at 10-kHz pulse rate. The laser beam is passively split into three pairs of beams, where each pair has a weak and a strong beam. The receiver operates in photon counting mode. The ATLAS/ICESat-2 instrument has been operating in space since 2018. The most recent laser altimeter is the Global Ecosystem Dynamics Investigation (GEDI) [3]. It was launched in late 2018 and operates from the International Space Station (ISS). It has three solid-state pulsed lasers, each operating at 241-Hz. The beams are split and optically dithered to form eight ground tracks. Both GLAS and GEDI employ 1064-nm Q-switched solid-state pulsed lasers and detected waveforms from digitized silicon avalanche photodiode (APD) detectors. Their laser pulse rates are low because the relatively low sensitivity of the Si APD detector requires large pulse energy. ATLAS uses a 532-nm micro-pulse solid-state laser at a much higher pulse rate (10-kHz) and high-sensitivity PMT photon-counting detectors that can detect much lower energy laser pulses. To cover more tracks on the surface, two approaches have been adopted for the space missions: 1) increasing the number of lasers (GEDI) and 2) splitting a laser beam to illuminate several tracks (both ATLAS and GEDI). However, more lasers means increased size, weight and

power (SWaP,) and splitting the laser beam requires higher laser pulse energy.

Compared to these three profiling missions, recommendations in the 2017 National Academies Earth Science Decadal Survey for future laser altimetry observations require significantly greater coverage for ice sheets and sea ice (Ice Elevation Observable, IE) and 3D height mapping for vegetation structure and topography (Terrestrial Ecosystem Structure TES, and Surface Topography and Vegetation STV Observables) [4]. Global sampling for IE and TES were recommended to be done as moderate cost Explorer missions (\$350M cap) this decade and global mapping for STV to be done next decade.

There is therefore a great need to drastically improve lidar SWaP efficiency to enable more coverage and use of smaller, cost-effective satellite platforms. This calls for: 1) improved receiver performance with single-photon sensitivity; 2) higher laser wall-plug efficiency; 3) sufficient laser pulse peak power for shot-noise limited receiver performance; 4) full waveform digitization, rather than single photon counting, to improve performance; and 5) innovative receiver electronics to efficiently handle the vast numbers of high-speed lidar return channels. Our CASALS approach addresses these aspects with patented designs and state-of-the-art transmitter and receiver technologies.

2. CASALS ARCHITECTURE DESIGN AND PERFORMANCES

2.1. CASALS instrumentation

Figure 2 depicts the architecture of the CASALS lidar system, illustrating cross-track wavelength-to-angle scanning, imaging of the return pulses onto a detector array, and multiplexing electronics. The details have been reported in previous publication [5].

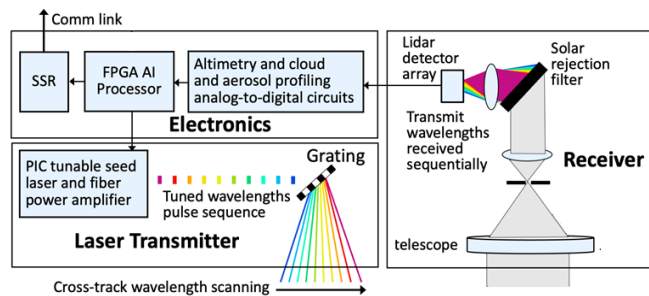


Figure 2. CASALS lidar system block diagram with three major blocks: laser transmitter, receiver, and electronics (see text for details).

The laser transmitter employs a fast-sweep-wavelength-tuning pulsed laser, a high peak power fiber amplifier, and a dispersive grating integrated in the telescope to map wavelengths to angles corresponding to distinct lidar footprints on the surface. A 30-nm laser tuning range can create 1,200 resolvable spots cross-track over an angular

range of 0.825deg, corresponding to 7.2-km from a 500-km orbit. Any subset of 1200 spots can be selected by wavelength switching.

In our coming airplane demonstration, we implemented a 256 cross-track design with a sweep rate of 4.5KHz. The 256 tracks return pulses are mapped to a linear APD arrayed detector. The solar background radiation for each individual footprint is filtered spatially and spectrally by a grating spectrometer. The optical bandpass filter design has 0.6-nm bandwidth for each footprint. A state-of-the-art Mercury Cadmium Telluride (HgCdTe) APD detector array [6] is used for the receiver. It operates in linear mode with single-photon sensitivity and allows multiple photons to be detected simultaneously to overcome solar background and detector dark noise.

All 256 tracks of lidar returns are time multiplexed to two out puts, then waveforms digitized to allow better performance than binary thresholding of the return pulses. The RF-multiplexed outputs allow only two digitizers (1-GSPS) for all 256 lidar returns, which dramatically reduced the receiver electronic SWaP. The time synchronization and data time tagging are performed with a field-programmable gate array (FPGA).

2.2. CASALS performance validation with an 8 tracks 1550-nm design

We have designed an 8 tracks CASALS system with a 1550-nm integrated photonic circuit laser to validate all key performance parameters with laboratory and rooftop testing [5]. With such system, we validated laser beam quality ($M^2(x) = 1.01$ and $M^2(y) = 1.00$) after transmitter dispersion grating for wavelength steering. The transmitter optical path transmittance of 90%. Receiver beam quality of $M^2(x) = 1.08$, $M^2(y) = 1.04$ after the receiver grating for optical filtering, and a receiver filter bandwidth of 0.6nm on each track.

Laser beam rapidly scans 8 footprints (along 45°) by stepping 8 wavelengths. Scans 1 to 5 were shifted in x direction mechanically.

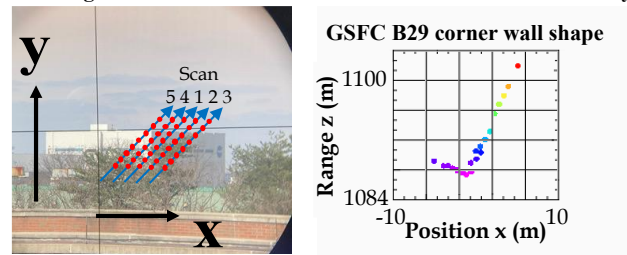


Figure 3. 3D range measurements of Building 29 at NASA GSFC.

The system performances were conducted on the rooftop in the GSFC campus. Both hard surface target of building 29 (figure 3) and vegetation targets of tree branches (figure 4) are tested.

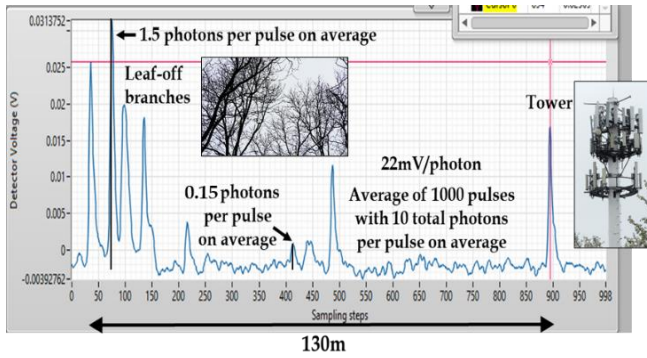


Figure 4. Integrated waveform of returns from leaf-off tree branches and a cellphone tower.

For a solid target of building 29 of NASA/GSFC in 1500-m away (figure 3), range precision of 1.8 cm was measured with 150 detected return photons (integrated over 100 laser pulses). This is in-line with our model prediction of 1.7 cm ranging precision. Near quantum limited performance was demonstrated. For vegetation targets (figure 4), the trees are about 600-m away and spread over 130 m. The cellphone tower return was captured as a reference point. Single-photon sensitivity was achieved with the HgCdTe APD array that detected weak returns from the trees.

With this 8 wavelength 1550 nm tunable laser CASALS lidar, we have fully validated the component level and system level performances on both solid surfaces and distributed vegetation targets.

2.3. 256 tracks CASALS system at 1040nm for campaign and science data validation

Figure 5 shows our airplane demonstration CASALS lidar optical transceiver. The system is configured with 256 tracks and operates at 1040nm wavelength. The airborne lidar prototype will demonstrate all the functionality required for spaceflight, including the co-aligned laser transmitter and receiver using a shared telescope. The co-aligned design is a first of its kind for a laser altimeter in orbit. Here the airborne assembly is shown with the containment cover removed.

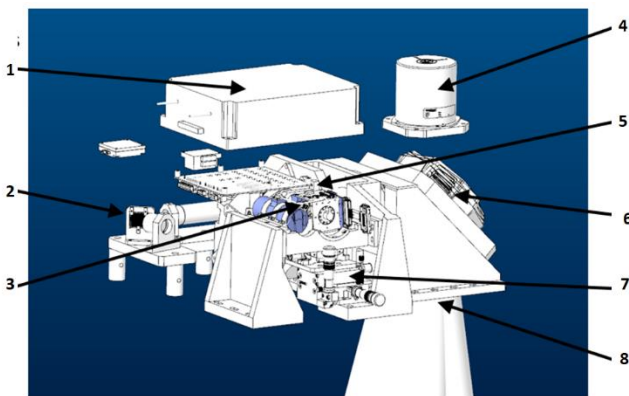


Figure 5. Airplane flight CASALS design. 1. Three stage Yb-fiber amplifier, 2. Diffraction grating for wavelength to angle dispersion, 3. 2x8 HgCdTe avalanche photodiode detector array in tactical cryocooler, 4. Applanix POS 510 GNSS/inertial sensor, 5. Diffraction grating for solar background filtering, 6. Lefthand Design beam steering mirror, 7. Beam alignment mechanism, 8. Transmitter and receiver aperture.

The following are the key components of the CASALS airplane flight demonstration:

Langley Beechcraft B200 King Air (NASA 529)

- 28,000ft (8.5km) cruise altitude
- 230 knots (115m/s) air speed
- 2 pilots and 2 operators
- Nominally 4-hours flight covering 1500 km

1040nm CASALS adaptive beam scanning lidar

- 0.67° total scan angle using 256 tuned wavelengths
- 110m swath width from 8.5km = 6.5 km from 500km orbit
- 0.7m diameter overall lapping footprints
- 0.43m and 0.24m cross and along track footprint spacing
- Waveform for each footprint with ~ 20 detected photons

Hyperspectral pushbroom imager

- Headwall Hyperspec Co-Aligned VNIR-SWIR Sensor
- Aligned with lidar for characterization of surface properties

GNSS/Inertial unit for position and attitude

- Applanix POS AVX 510
- ~ 1 m footprint geolocation accuracy (1 sigma) from 8.5km
- Over-water attitude maneuvers for laser pointing biases

Hyperspectral + panchromatic frame cameras

- Cubert Ultris X20 Plus UV-Vis-NIR + Panchromatic
- Pointing ahead of the lidar by 7 degree providing 8 seconds for real-time image analysis and lidar pointing decision making

The measurements to be acquired by airborne CASALS emulate the planned spaceflight measurements, thereby providing data well suited to develop processing and analysis methods in anticipation of an STV mission.

3. CONCLUSION AND FUTURE WORK

With an 8 wavelength 1550 nm tunable laser CASALS lidar, we have fully validated both component and system levels instrument performance. The field target measurements on both solid surface and distributed vegetation are also conducted from rooftop in GSFC campus. The results

matched our lidar model predictions with close to quantum limit performance.

We have designed and are building a 256 tracks CASALS lidar system at 1040nm wavelength. We have also scheduled an airplane demonstration of this system for providing data suitable to develop processing and analysis methods in anticipation of a STV missions. In this airplane demonstration, a GNSS/Inertial unit will be part of the system for lidar return pulse geo-tagging. A hyperspectral push broom imager will also be part of CASALS instrument suite. It will aligned with lidar for characterization of surface properties.

The measurements to be acquired by airborne CASALS emulate the planned spaceflight measurements, thereby providing data well suited to develop processing and analysis methods in anticipation of an STV mission

4. REFERENCES

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