Development and Demonstration of the Concurrent Artificially-intelligent Spectrometry and Adaptive Lidar System (CASALS)

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NASA Goddard Space Flight Center

Earth Science Technology Forum
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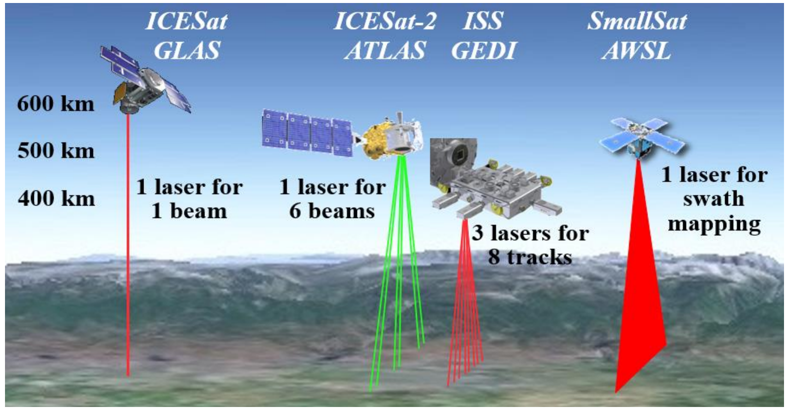
Topics

- What is CASALS
- What are its Benefits
- What is its Applicability
- What is its Readiness for Earth Sciences

What is CASALS?

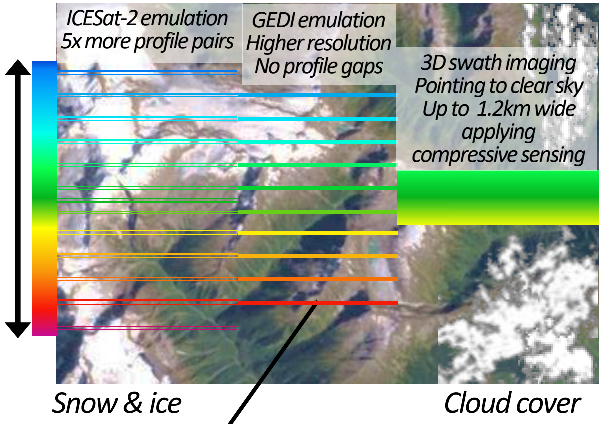
➢ **A payload being developed for a SmallSat, low Earth orbit mission**

- **Adaptive Wavelength Scanning Lidar (AWSL)**
  - Advanced technologies with very high efficiency enabling the first wide-swath 3D lidar imaging from space
  - Fast wavelength tuning and wavelength-to-angle dispersion for adaptive laser beam pointing across the swath
- **Multispectral imaging radiometer**
  - Narrow spectral bands optimized for ecosystem and cryosphere science and applications
  - Looking ahead to guide autonomous lidar targeting, cloud avoidance and adaptive compressive sensing
- **Artificial intelligence**
  - On-orbit real-time decision making
  - On-ground lidar and spectrometry fusion and compressive sensing reconstructions



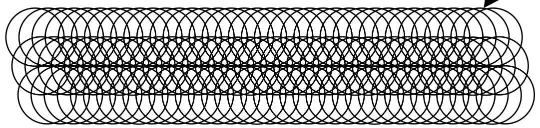
Progression from lidar profiles to 3D imaging

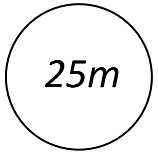
Adaptive wavelength scanning across 7km wide swath



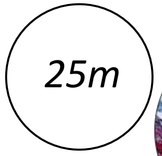
Three examples pointing the laser beam to optimize sampling based on topography, landcover, cloud cover and mission objectives

CASALS 10m laser footprints for 3 adjacent wavelength tracks





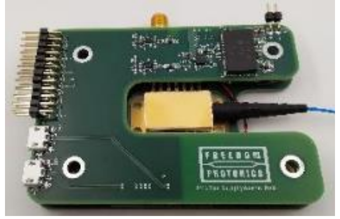
GEDI footprints



Guangning Yang and David Harding, June 21, 2023

Technology Advances Enabling AWSL
funded by GSFC and NASA ESTO, Planetary Science and SBIR

- **Five compact and highly efficient lidar technologies**
  - **Fast wavelength-tuning seed laser scanning 1025nm to 1055nm at pulse rates up to 4mHz ($4x10^6$ pulses/sec)**
    - Two options:
      - ✓ Freedom Photonics Instatune Photonics Integrated Circuit
      - ✓ Excelitas Technologies Axsun swept-source OCT
  - **AdValue 100kW peak power Yb-doped fiber amplification**
  - **Lightsmyth transmissive gratings**
    - Transmitter wavelength to angle conversion for non-mechanical beam scanning
    - Receiver achieving 0.4nm bandwidth solar background rejection for all wavelengths
  - **Leonardo DRS linear-mode, HgCdTe APD detector array**
    - Very low dark count, single-photon sensitive waveforms
  - **Time-multiplexed waveform digitizing to minimize the number of digitizers required**
    - Made possible with the pulses arriving sequentially using a single beam (not simultaneously using beam splitting)

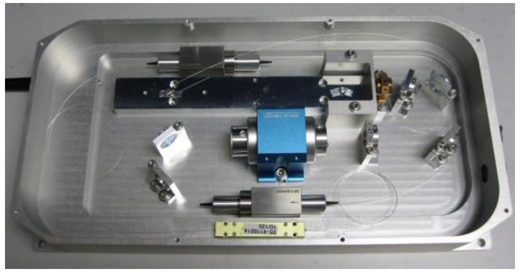


Freedom Photonics Instatune PIC seed laser

AdValue 3-stage fiber amplification

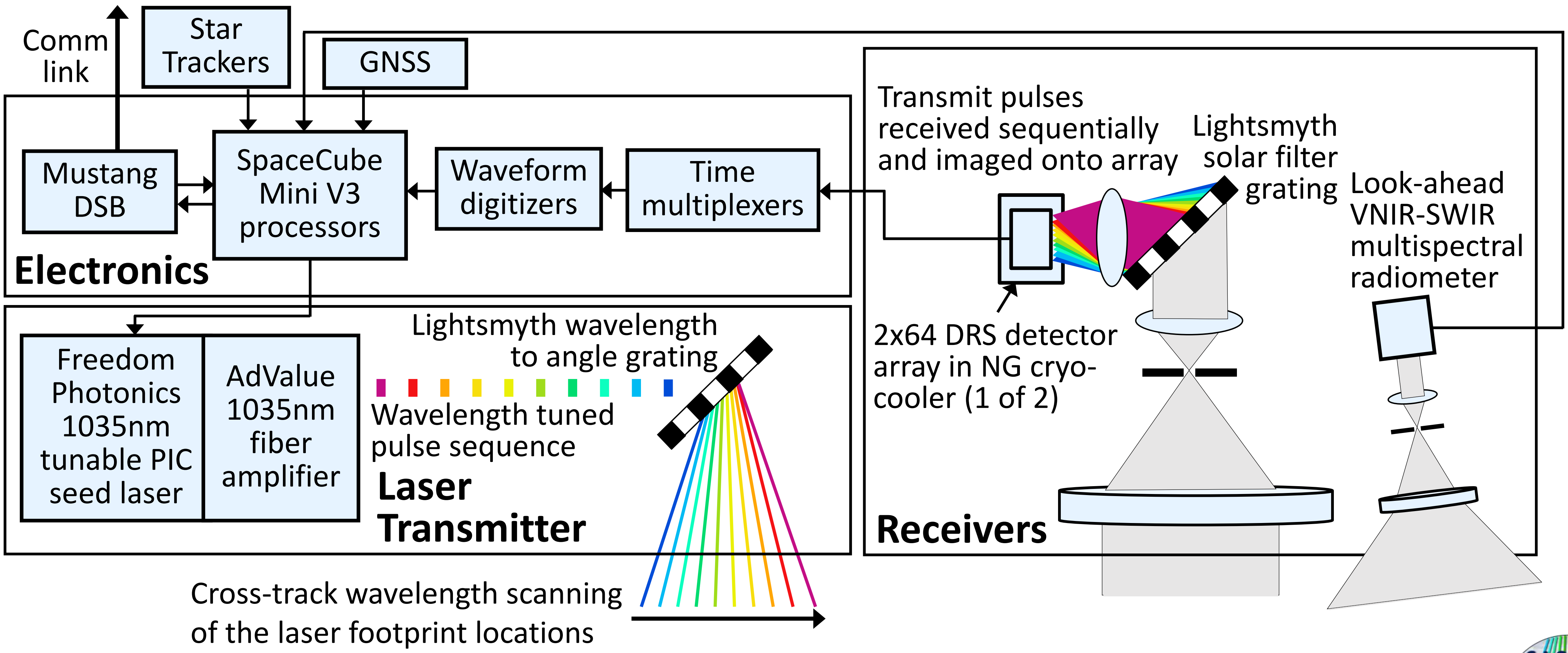
Pump

Amplifier



Leonardo DRS space-qualified 2x8 detector array in mini-Stirling cryo-cooler (2x64 in same packaging planned for space)

Spaceflight CASALS Block Diagram

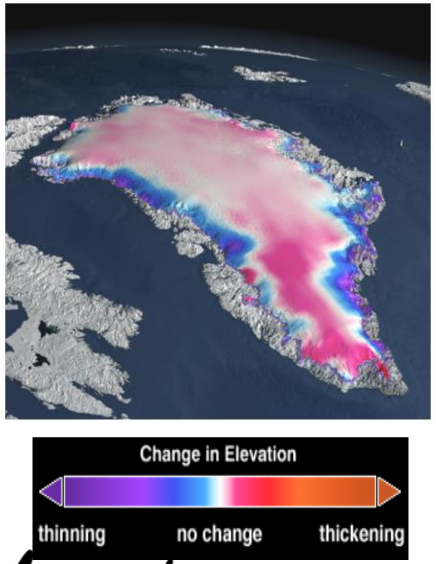


What are CASALS Benefits?

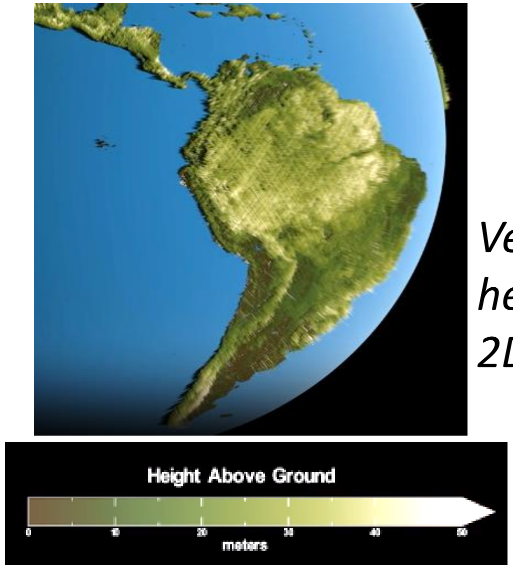
- **The combination of concurrent 3D lidar and spectral imaging:**
  - **Goes beyond regionally documenting the Earth's vertical dimension and its change using lidar profiles**
  - **Enhances understanding of processes driving those changes at local scales**
  - **Improves our ability to model those processes and make predictions**
  - **Informs resource management and hazard mitigation**

Repeated ICESat Single Beam Profiles

Elevation and its change



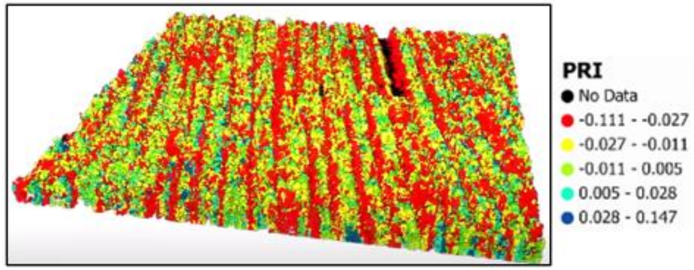
GEDI Multi-beam Profiles



Vegetation height and 2D structure

Lidar and Spectral Fusion

Airborne Operation IceBridge DSM natural color image draped on LVIS lidar digital elevation model. Crane Glacier, Antarctica

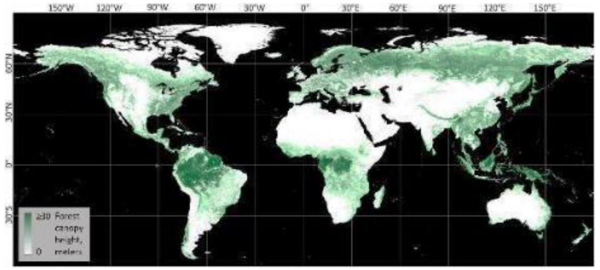


Photosynthesis efficiency spectral index draped on lidar 3D canopy structure. Airborne G-LiHT data. Parker Tract pine plantation, NC

Topography, snow depth, surface composition, vegetation height, 3D structure and function, and their change

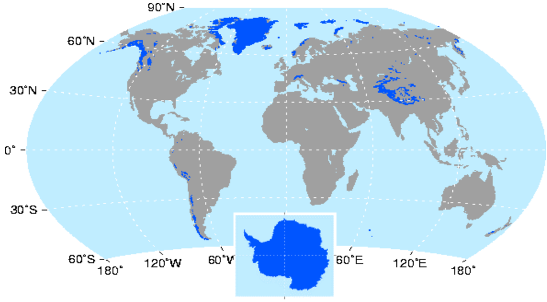
What is CASALS Applicability?

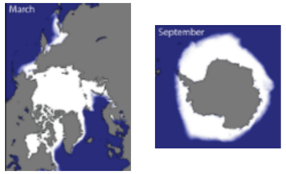
- **Four 2017 Earth Science Decadal Survey Observables**
  - **Terrestrial Ecosystem Structure Explorer**
    - Forest 3D structure, composition and function
  - **Ice Elevation Explorer**
    - Change in ice sheet and glacier elevation
    - Change in sea ice thickness
  - **Snow Depth and Snow Water Equivalent Explorer**
    - Water availability for plants, animals and humans
    - Albedo impact on land – atmosphere energy exchange
  - **Surface Topography and Vegetation (STV) Incubation**
    - Global height mapping at high resolution
    - Likely will be combination of lidar, radar and stereo optical assets



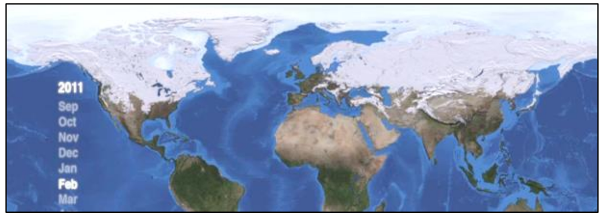
Forest height

Land ice





Sea Ice



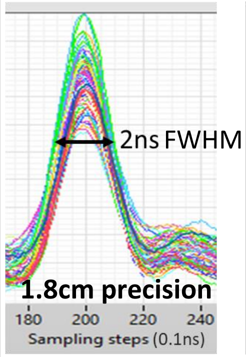
Snow cover

Topography

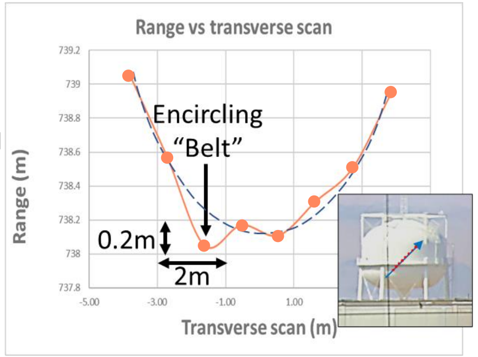
What is CASALS Readiness for Earth Science?

➢ **AWSL TRL advancement:**

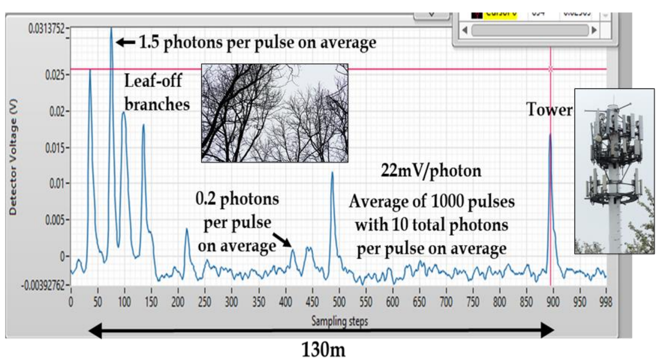
- **Fall 2022 rooftop demo at 1550nm**
  - TRL 3 critical function proof of concept

Range precision
Impulse response averaging 150 photons

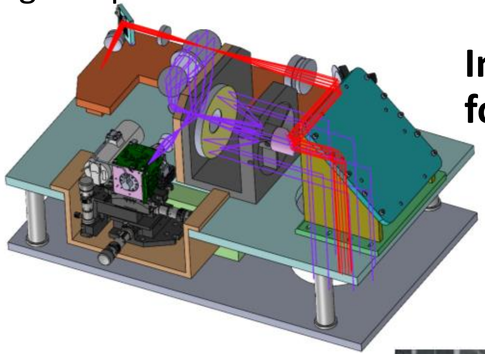


Wavelength scanning
Eight footprints across a water tower



Single photon-sensitive waveforms
Returns from horizontal ranging through bare branches to cell phone tower

- **End of 2023 rooftop demo at 1035nm**
  - TRL 4 validation in lab environment
  - 1035nm efficiencies are required for space



Innovative shared transmitter and receiver telescope for operation at any ranging distance (no parallax)

- Long-distance range and range rate for navigation
- Orbiting the Earth, planets, moons and small bodies
- Entry, descent and landing

- **Summer 2024 airborne demo at 1035nm** with Applanix POS AVX 510 GNSS/inertial sensor and Headwall VNIR-SWIR hyperspectral imager
  - TRL 5 validation in relevant environment
  - NEON sites with hi-res lidar and hyperspectral for validation
  - Wavelength-to-angle tuning over the angles needed for space

NASA Langley Research Center B200 King Air (N529NA)

CASALS Team

- **Lidar Partners**
  - Freedom Photonics, UCSB and Excelitas Technologies – wavelength tuning seed lasers
  - AdValue Photonics – fiber amplifier
  - Leonardo DRS – detector array
- **University Partners**
  - Virginia Tech
  - University of Delaware
- **CASALS Funding Sources**
  - GSFC Radical Innovation Initiative and IRAD
  - NASA ESTO ACT, IIP and AIST
  - NASA SBIR

For More Information

D. Harding, et al., 2021, CASALS: an Adaptive Lidar and Spectrometry SmallSat for a NASA Explorer Mission, *Proceedings of the SilviLaser Conference 2021*, DOI: 10.34726/wim.2023

G. Yang, et al., 2022, Adaptive Wavelength Scanning Lidar (AWSL) for 3D Mapping from Space, *2022 IEEE International Geoscience and Remote Sensing Symposium,* DOI: 10.1109/IGARSS46834.2022.9884418.

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Backup

What is CASALS Readiness for Earth Science?

➢ TRL advancement:

- **AWSL performance model completed and compared to ICESat-2 model**
  - CASALS on ESPA Grande bus vs ICESat-2 (averaging weak and strong beams)
  - Figure of merit = performance / power aperture product

    Adapted from J. Degan, 2002, Journal of Geodynamics, 34, 503–549, DOI: 10.1016/S0264-3707(02)00045-5

    Vegetation structure: (photon increase x coverage)/(power x receiver aperture)

    (8 x 5) / (0.8 x 0.25) = 200x

    Ice sheet elevation: (precision improvement x coverage)/(power x receiver aperture)

    (1.25 x 5) / (0.8 x 0.25) = 30x
- **Assessment of ESPA Grande bus accommodations conducted**
  - Margins for CASALS Current Best Estimate (CBE)

    70% power, 180% mass (General Atomics SSTL-600 bus)

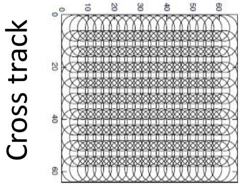
1035nm CASALS vs 532nm ICESat-2

Laser wall-plug efficiency	3x
Detector quantum efficiency	6x
Photons per unit energy	2x
Foliage reflectance	11x
Snow and firn reflectance	0.7x
Atmospheric transmission	1.5x
Solar background noise	0.4x
Solar filter bandwidth	4x
Payload power	0.8x
Telescope area	0.25x
Downlink data volume	8x

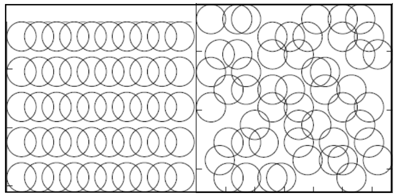
What is CASALS Readiness for Earth Science?

- **Compressive sensing and machine learning reconstruction methods implemented**
  - Led by Prof. Gonzalo Arce and Andres Ramirez-Jaime, University of Delaware
  - Utilizing AWSL ability to adapt footprint sampling and density by varying laser transmitted wavelengths, pulse repetition rate and cross-track scan rate
  - Enables reduction in power and data volume and/or widening of swath while preserving essential information
  - Employs 3-D convolution autoencoder machine learning trained with waveforms derived from very high-density lidar point clouds acquired by the airborne Goddard Lidar Hyperspectral Thermal sensor suite
  - Simulates CASALS waveforms with an average of 20 photons by ~50x weighted down-sampling of the G-LiHT points
  - Tests reconstruction accuracy using withheld full-resolution waveforms derived from G-LiHT as truth

Highest density of overlapping 10m footprints

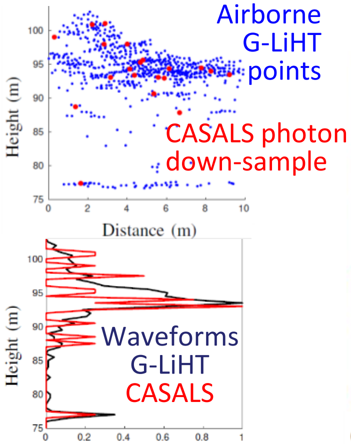


Compressive sensing
25% subsample



Along track

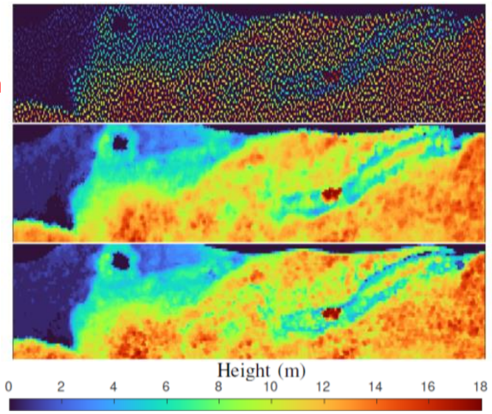
10m footprint waveform modeling



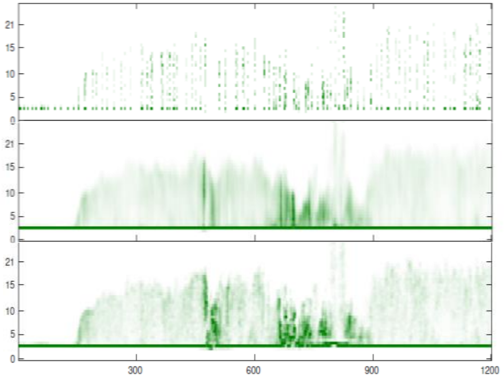
Normalized waveform counts

Florida Everglades canopy structure reconstruction

0.3km x 1.2km canopy height map



1.2km profile view of waveforms



Darker = greater waveform amplitude

25% randomly subsampled footprints averaging 20 photons per waveform (predicted performance at 500km) down-sampled from dense airborne G-LiHT lidar point clouds

Reconstructed waveforms from 3-D convolutional auto-encoder machine learning model developed using G-LiHT training waveforms with ~1000 lidar points per waveform

G-LiHT truth reference waveforms withheld from training for accuracy assessment

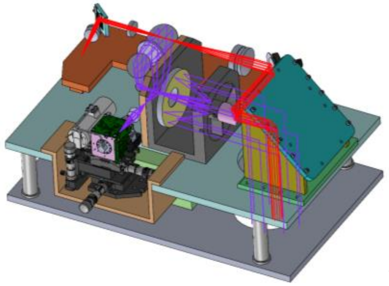
Ramirez-Jaime, et al., submitted, HyperHeight LiDAR Compressive Sampling and Machine Learning Reconstruction, IEEE TGARS

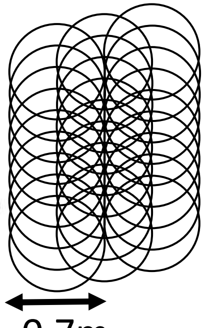
CASALS Summer 2024 Airborne Campaign

Langley Beechcraft B200 King Air (NASA 529)

- 28,000 ft (8.5 km) cruise altitude
- 230 knots (115 m/sec) air speed
- 2 pilots, 2 operators and 750 lb (340 kg) max payload
- 4 hour flight covering 800 nmi (1,480 km)

1035nm Adaptive Wavelength Scanning Lidar (AWSL)





- 0.67° total scan angle using 256 tuned wavelengths
- 110m swath width = 7km from 500km orbit
- 0.7m footprints with 0.43m and 0.24m cross- and along-track spacing
- Waveform for each footprint with ~20 detected photons
- Average waveforms together to emulate 10m footprints from 500km

GNSS/Inertial unit for position and attitude

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

Pushbroom hyperspectral imager

- Headwall Hyperspec Co-Aligned VNIR-SWIR Sensor
- 400 – 1000 nm and 900 – 2500 nm spectral ranges
- 2.2 nm and 6 nm spectral band widths
- 5 m pixels and 3.2 km image width from 8.5 km

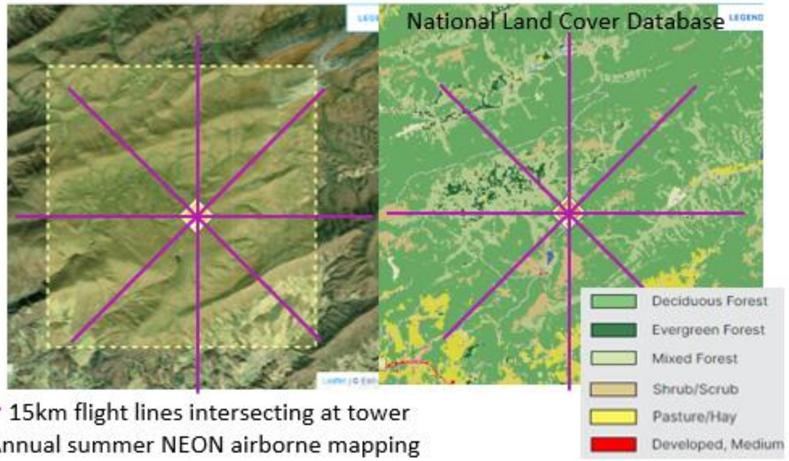
High resolution context frame camera

- Thorlabs DCU223C color CCD Camera
- Fujinon HF75SA-1 75 mm focal length, f/1.8 lens
- 0.5m pixels and 740m x 510m image from 8.5 km
- 80% along-track overlap enabling structure from motion

Validation Targets

NEON eddy covariance flux towers with annual to bi-annual hi-res airborne lidar and hyperspectral imaging

MLBS, NEON Mountain Lake Biological Station, VA



15km flight lines intersecting at tower

Box: Annual summer NEON airborne mapping

PhenoCam Network images every 5 minutes

Autumn senescence

January with snow cover

Airborne and Spaceflight Measurements

- **Summer 2024 airborne demo at 1035nm**

  with Applanix POS AVX 510 GNSS/inertial sensor, Headwall VNIR-SWIR hyperspectral imager and high-resolution frame camera
  - TRL 5 validation in relevant environment
  - NEON flux tower sites with hi-res lidar and hyperspectral imaging for validation
  - Wavelength-tuning over the same angles as needed for space

CASALS Adaptive Lidar	Scan angles	Scan width (km)	Footprint size (m)	Spacing (m) across, along
Spaceflight @ 500km:	1,200	7	10	6, 3
Airborne @ 8.5km:	256*	0.11	0.7	0.43, 0.24

*limited by 8 cross-track pixels in the airborne detector array

CASALS Spectrometry	Image width (km)	Pixel size (m)
Spaceflight @ 500km:	10	10
Airborne @ 8.5km:	3.5	5

Color Frame Camera	Image width (km)	Pixel size (m)
Airborne @ 8.5km:	0.7	0.5

Airborne Swath Widths