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Snow Depth Retrieval from Lidar on an Airborne Platform

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The Core Concept:

Snow acts as a weakly absorbing, diffusive scattering medium for 532-nm laser light (like that used by ICESat-2).

Instead of just measuring the surface return, the technique tracks the path length of photons that bounce multiple times *inside* the snowpack before exiting.

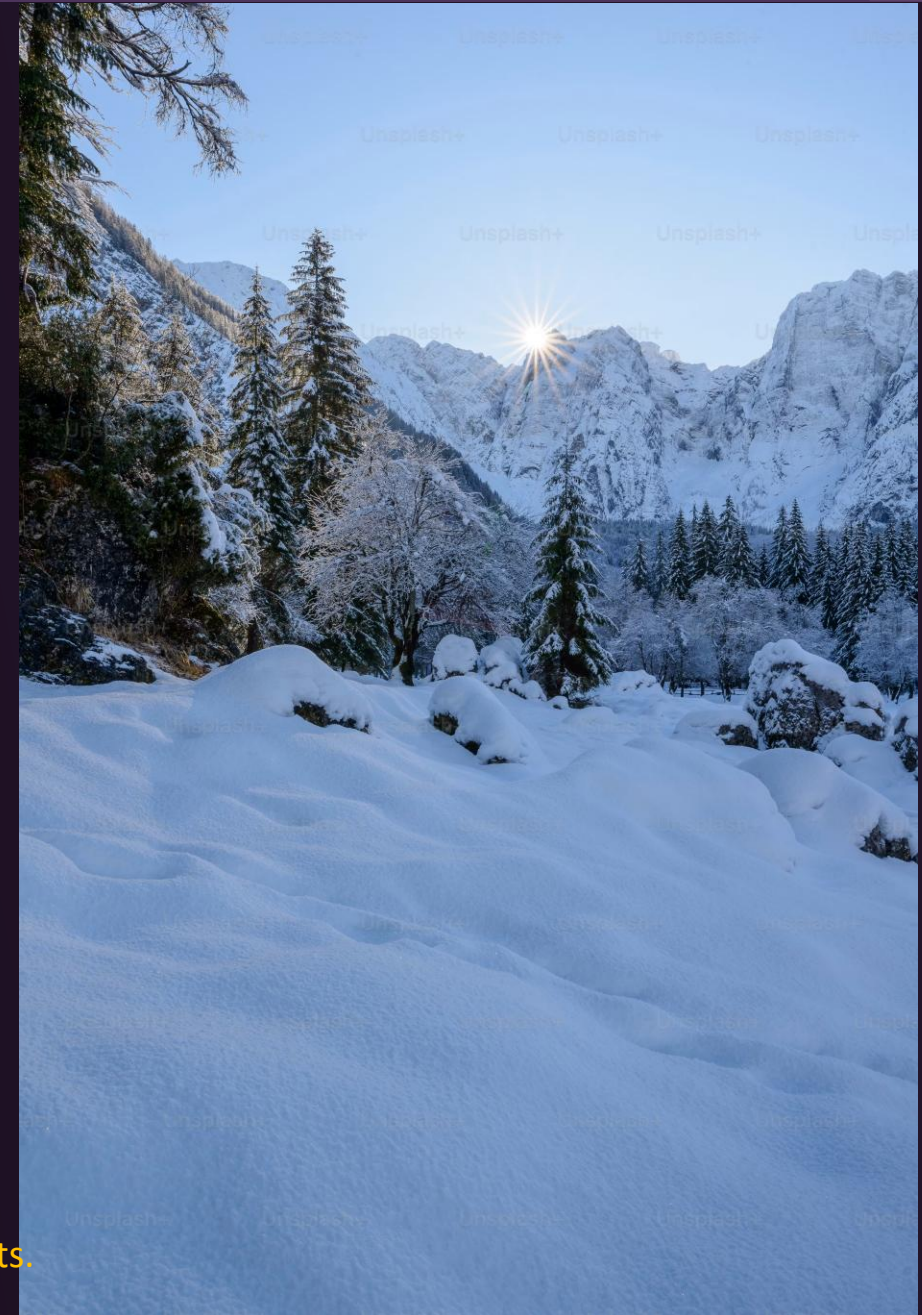
Path Length Distribution:

Monte Carlo radiative transfer simulations reveal that the lidar backscattering path length follows a Joint Gamma (Γ) Lognormal distribution.

Key Analytical Relationships:

Method 1 (First Moment): The average path length ($\langle L \rangle$) of the scattered photons is exactly twice the snow depth (H).

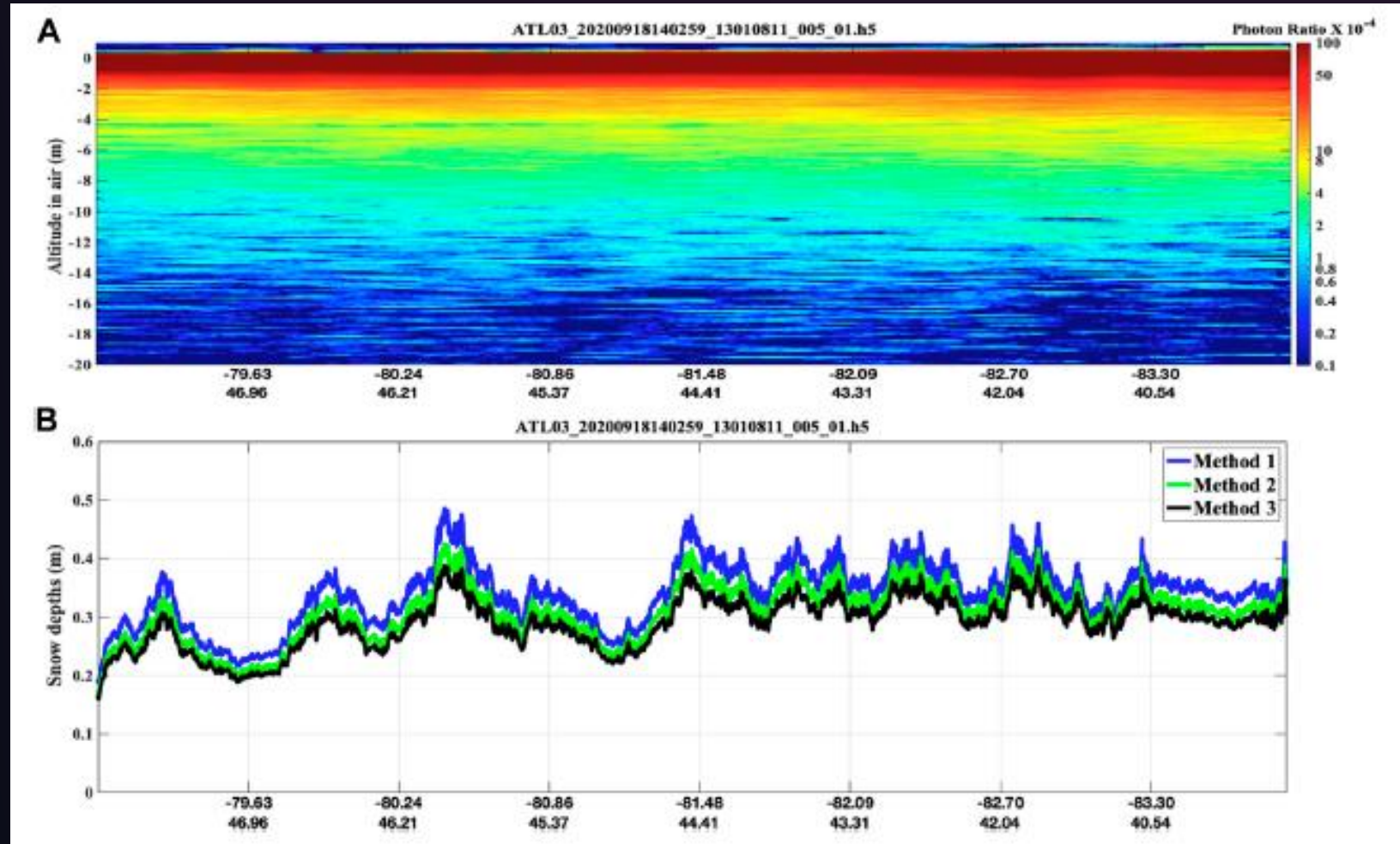
Formula: $H = \langle L \rangle / 2$



Methods 2 & 3 (Higher-Order Moments): Snow depth can also be cross-verified using the second ($\langle L^2 \rangle$) and third ($\langle L^3 \rangle$) moments of the path length distribution along with the diffuse scattering coefficient (k_{sd}).

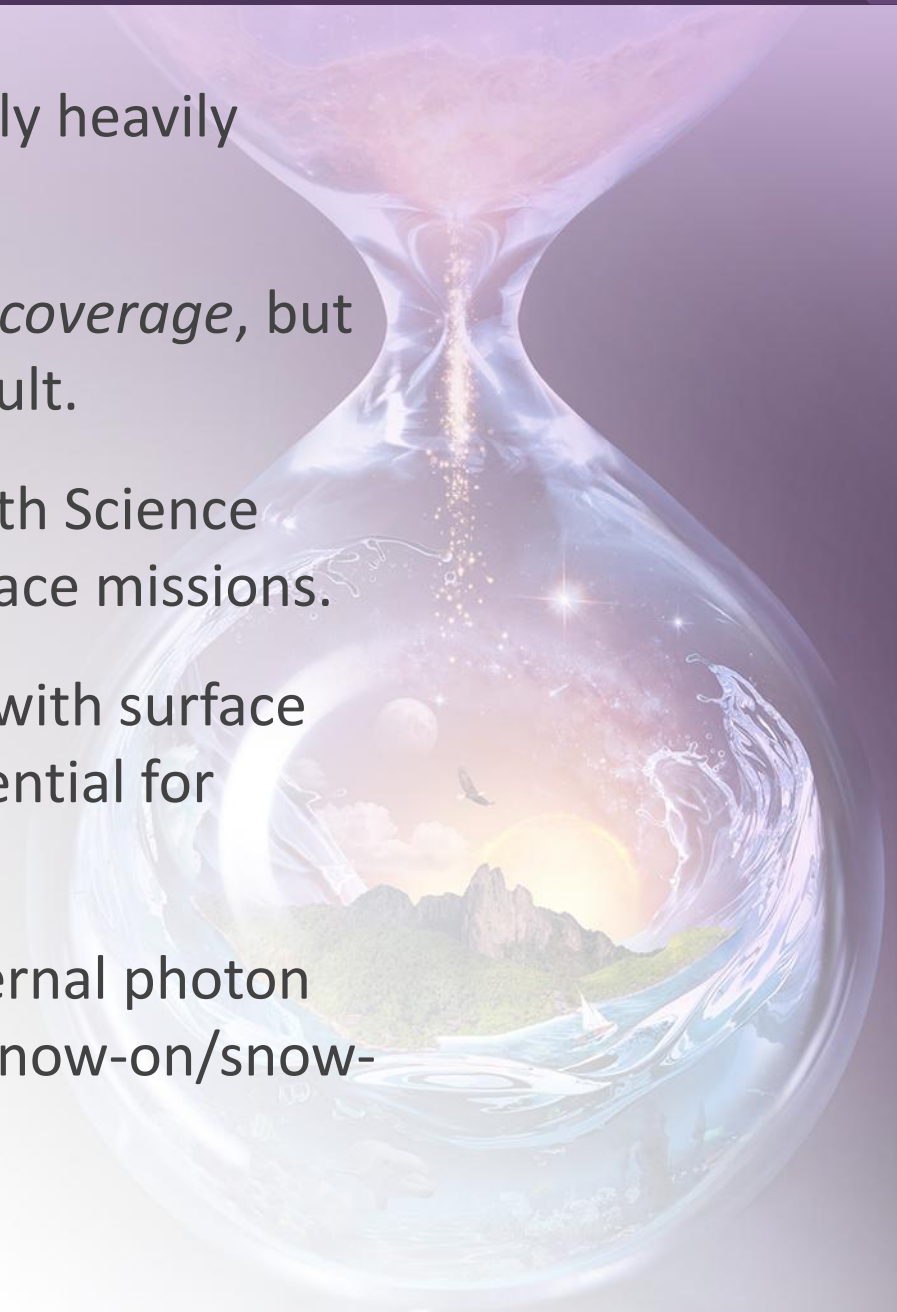
$$H = (\langle L^2 \rangle / k_{sd})^{1/3}$$

$$H = (\langle L^3 \rangle / k_{sd}^2)^{1/5}$$



Hu, Y., et al. (2022). Deriving Snow Depth From ICESat-2 Lidar Multiple Scattering Measurements. *Frontiers in Remote Sensing*, 3. DOI: 10.3389/frsen.2022.855159

- Global Water & Climate:** Snowpacks are a vital water supply heavily regulate Earth's climate and ecosystems.
- Beyond Surface Extent:** Passive satellites easily map snow *coverage*, but capturing true, global snow *depth* remains historically difficult.
- Top Decadal Priority:** Due to its critical impact, the last Earth Science Decadal Survey explicitly targeted snow depth for future space missions.
- Unlocking Sea-Ice Thickness:** Lidar snow depth combined with surface elevation enables accurate sea-ice thickness estimates, essential for climate modeling and defense.
- Direct, Single-Pass Tracking:** High-resolution lidars use internal photon scattering to calculate depth in a single pass, eliminating "snow-on/snow-off" multi-survey methods.



Dual-Wavelength Lidar System & Snow Depth Retrieval Algorithm

Parameter	Value
Wavelengths	355 nm (UV) & 532 nm (VIS)
Detection Mode	- Elastic Channels Dual Pol, high-bandwidth to enable pathlength approach to snow - Inelastic channel - photon counting, spectrally resolved for Raman and Fluorescence
Data Reduction	Quantum noise removal - Dirac3
Target	Snowpack vertical backscatter profiles
Platform	Twin Otter w/ TOIL or similar
Altitude	1 km AGL with scan mirror +/- 5°

Snow Depth Retrieval Algorithm (*Hu et al., 2022*) The lidar backscatter path length distribution $p(L)$ follows a **Gamma distribution**:

- **Method 1:** $H = \langle L \rangle / 2$ (1st moment)
- **Method 2:** $H = (\langle L^2 \rangle / k_{sd})^{1/3}$ (2nd moment)
- **Method 3:** $H = (\langle L^3 \rangle / k_{sd}^2)^{1/5}$ (3rd moment)

Three independent depth estimators provide built-in cross-validation

Quantum-Enhanced Signal Processing: Real-Time Solar Noise Subtraction Onboard

The Problem: Solar Background Noise in Daytime Lidar

- Daytime lidar measurements at 355 & 532 nm are severely degraded by solar background photons
- Solar noise corrupts the backscatter path length distribution $p(L)$, biasing moment calculations and thus snow depth retrievals
- Traditional approaches: narrow bandpass filters, temporal gating can remove mean background but residual noise remains and limits accuracy of snow depth calculations

Quantum Computing Solution

- Deploy a compact, ruggedized **quantum computer** for data processing using quantum algorithms to remove noise
 - Distinguish solar background photon statistics from true snow-backscatter photon statistics in real time
 - Exploit the known Gamma-distribution shape of $p(L)$ as a **quantum prior** to constrain the separation
 - Produce a cleaned $p(L)$ profile for immediate moment calculations and snow depth outputs mid-flight

NASA's SnowEx Mission: Unveiling the Secrets of Grand Mesa's Snow



Twin Otter International Ltd

2027 Flight Plan Summary

- Twin Otter Check out flight scheduled for Jan 2027 and includes VIS/SWIR spectrometer FLORA Twin Otter deployment
- Fly Grand Mesa, CO over 2 weeks coordinated with Boise State Univ. and LaRC and planned for Feb/March 2027 (pending weather and SNOWWI campaign timing)
 - Partner and coordinate with HP Marshall (BSU) for ground measurements and validation
 - Perform data validation and snow pathlength retrieval and signal noise removal (quantum computing)
- Repeat passes at multiple altitudes (0.5, 1, and 2 km) to test retrieval altitude sensitivity
- Day + night flights to directly assess quantum noise subtraction benefit (day = high solar noise; night = baseline)

Flights of Opportunity 2027+

Fly over varying terrain including steep slope angles and varying degrees of tree canopy (ex: Sierra Mountains)

Repeat early and late season for snow variability

Time flights with ICESat2 and NISAR pass

Single-Pass Lidar Retrieval: Accurate snow depth in a single flight pass by tracking the internal photon pathlength distribution avoiding uncertainties associated with pointing errors

Quantum & AI Noise Reduction: Demonstrate ruggedized quantum computing (Dirac3) and AI (Deep-Unet) models to perform (near real-time) solar background noise subtraction, effectively enabling high-fidelity daytime lidar measurements.

Mission Impact: Complete first demonstration of quantum signal processing, which promises to exponentially reduce the power requirements and costs of future space-based lidar missions by significantly enhancing the Signal-to-Noise Ratio (SNR)

Dual-Wavelength Robustness: Demonstrate dual-wavelength system (355 nm & 532 nm) to capture independent estimates of snow grain size and diffuse scattering, while allowing for direct cross-comparison with spaceborne ICESat-2 measurements.

Flight Validation: Demonstrate algorithm and hardware readiness through targeted airborne campaigns (e.g., Grand Mesa, Boise) across varying terrains, altitudes, and tree canopies, heavily supported by ground-truth Cal/Val partners.

Back Up Slides



Snow depth from Space lidar measurements: ICESat-2

ICESat-2 vs SnowEx 2022, 2023

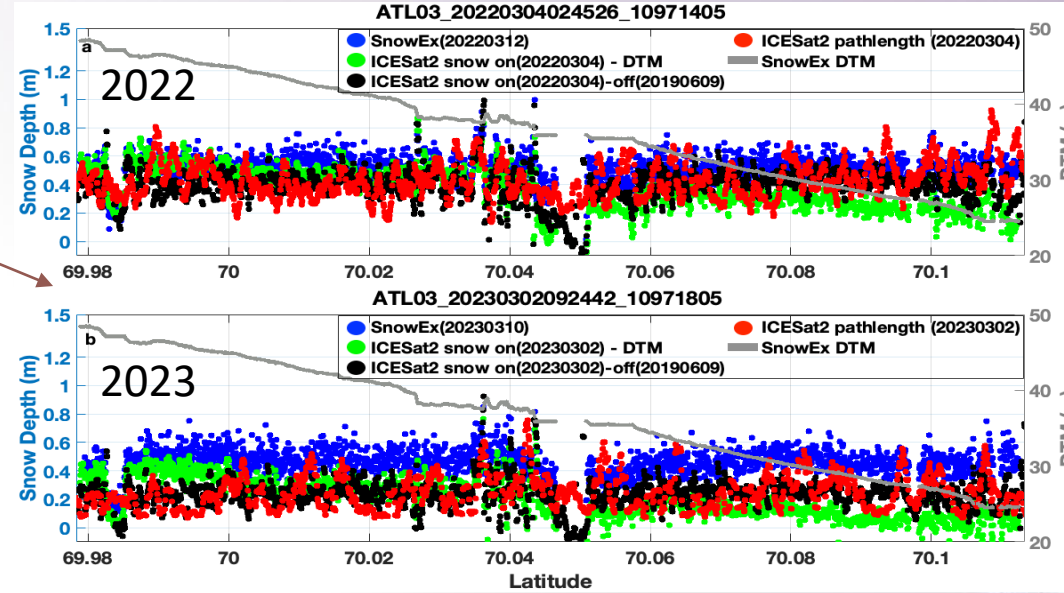
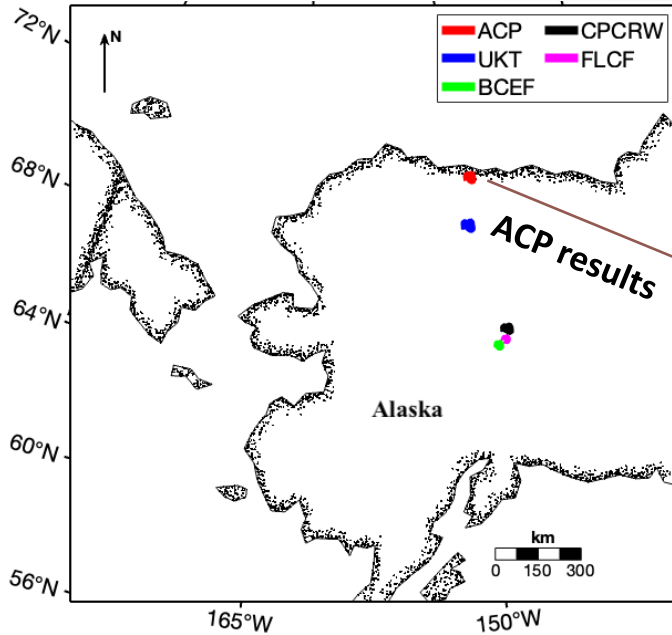
Two snow depth methods

1. Snow on-off method

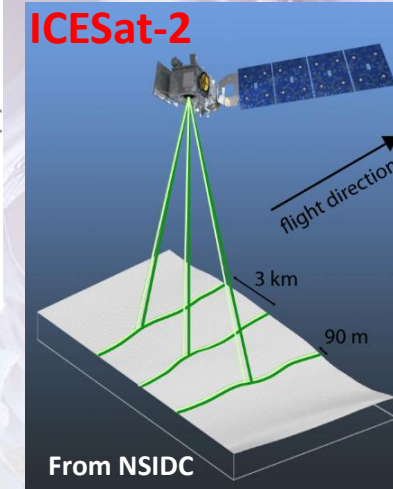
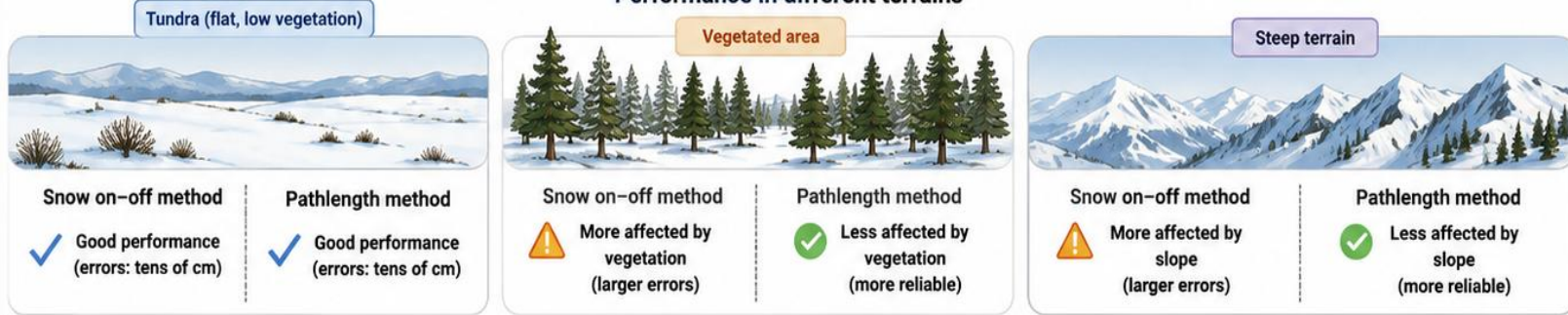
$$D_{\text{depth}} = E_{\text{snow}} - \text{DTM}_{\text{ground}}$$

2. Pathlength method

$$D_{\text{depth}} = f(\text{pathlength})$$



Performance in different terrains



Provide SD by two methods (1& 2)

snow depth

Provide SD by method 1



Quantum Computer Test Metrics

Speed: Latency from raw lidar pulse to snow depth output (target: <TBD sec per profile)

Accuracy: RMSE of H (target: <TBD cm) with /without quantum noise subtraction

Noise Removal Data reduction metrics with/without quantum noise subtraction

Survivability: Continuous performance log vs. aircraft environmental data (vibration, T, pressure)

Quantum Advantage: Quantify SNR improvement and reduction in moment estimation uncertainty

Expected Deliverables

- Technology readiness assessment for quantum computing in airborne/spaceborne lidar
- Validated airborne snow depth retrieval algorithm at 355 & 532 nm
- First airborne demonstration of onboard quantum signal processing for lidar
- Peer-reviewed publication: *"Airborne Lidar Snow Depth Retrieval with Quantum-Enhanced Signal Processing"*
- Cal/Val dataset for ICESat-2 snow depth products

Key Science Questions for Quantum Computing



Question	Measurement
How fast is the quantum processor?	Benchmark processing speed vs. classical CPU on identical lidar profiles
How accurate are snow depths with/without QC?	Compare H retrievals with and without quantum noise subtraction vs. ground truth
Can the quantum computer survive airborne conditions?	Vibration, temperature cycling, EMI, pressurization — log performance vs. environmental telemetry
What is the quantum advantage threshold?	Minimum signal-to-noise conditions where QC outperforms classical methods

Why Dual Wavelength (355 & 532 nm)?

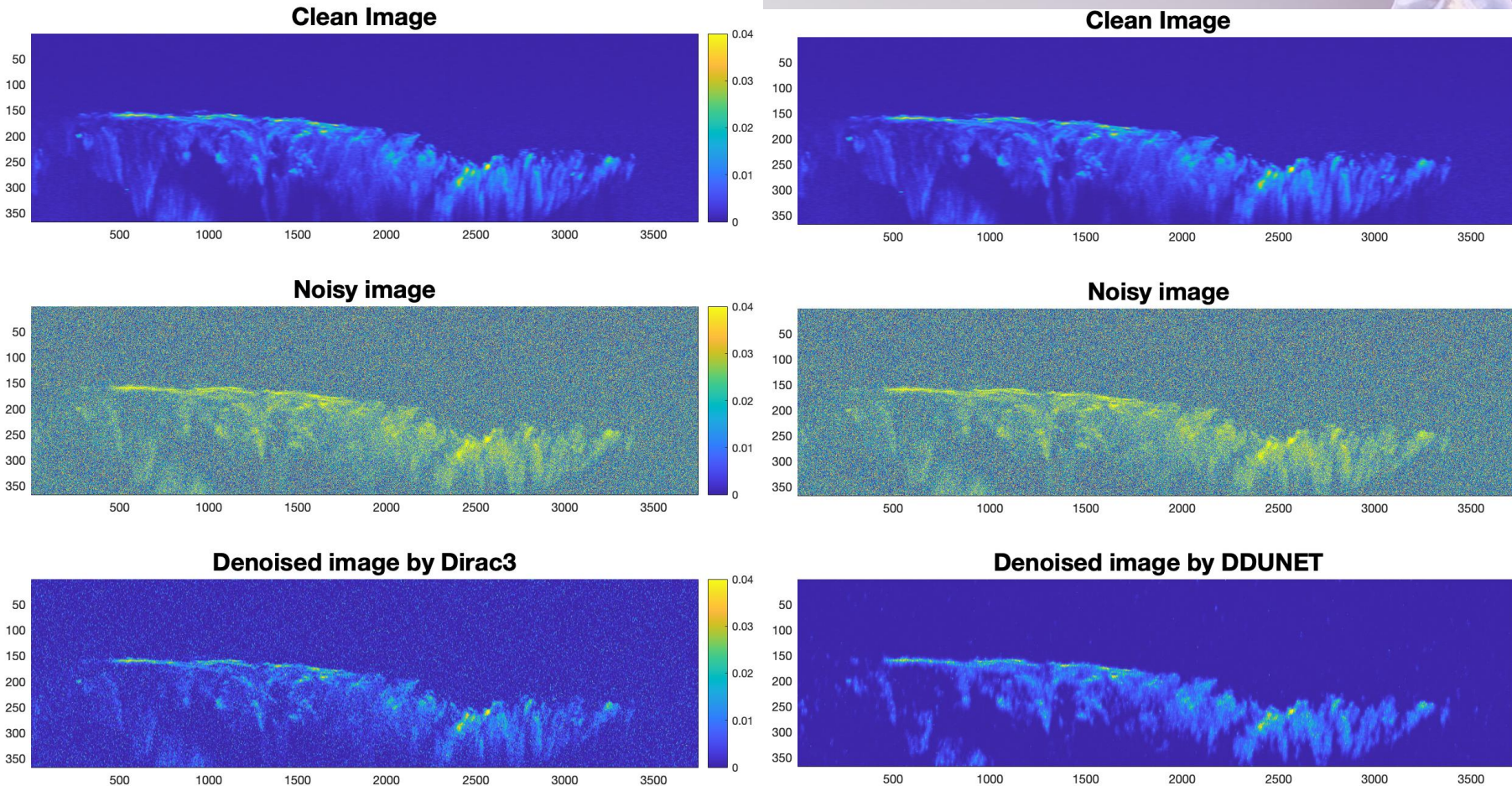
- 532 nm: lower absorption in snow, aligns with ICESat-2 wavelength for direct cross-comparison
- 355 nm: higher sensitivity to grain size and absorption coefficient k_a ; cross-wavelength ratio constrains diffuse scattering coefficient k_{sd}
- Together: independent estimates of k_{sd} and H enable full retrieval robustness testing

Validation Targets

- Boise State University **CryoGARS Lab**: spatial variability measurements, high-resolution snow depth surveys, drone-based (copter) snow mapping — ideal Cal/Val partner
- Grand Mesa, CO survey site from SnowEx: spatial variability in measurements with Western edge of site with shallow snow depths and Eastern edge has deeper snow depth (2-3m) due to winds. Boise State Univ has logistics and infrastructure in place. Possible survey planned for winter of 26-27 (will know by August).
- Northern winter field sites: Boise region, deep seasonal snow, variable terrain, utilize Boise State ground validation site

Develop AI and quantum denoising methods for LiDAR measurements to improve snow depth retrieval.

*Raw Lidar Signal → Noise Reduction → Enhanced Signal
→ Improved Snow Depth Retrievals*

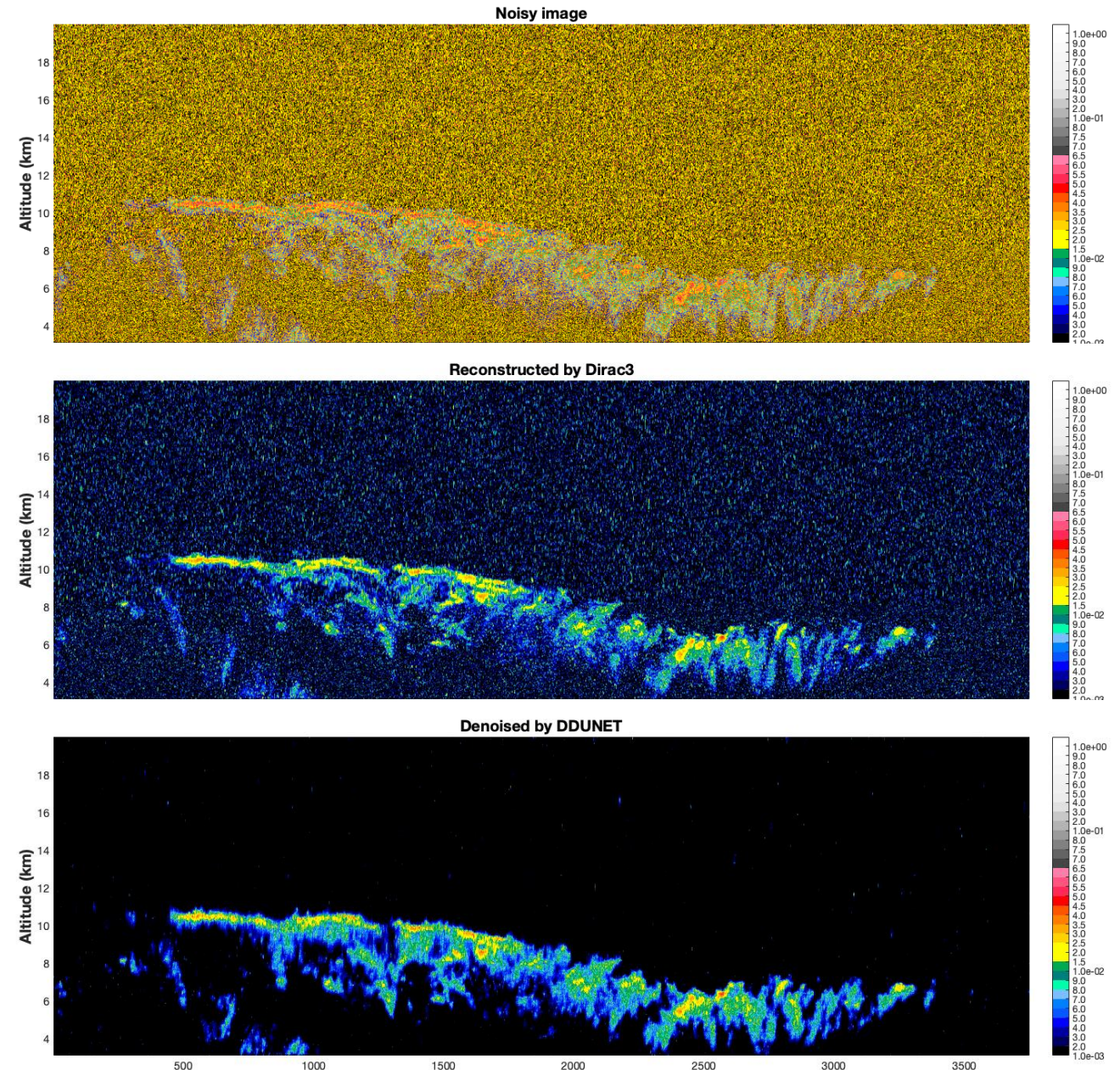


Noise Reduction

Example

Noisy Daytime Cloud measurements
above snow with solar background
noises

- Dirac 3 (QCI Entropy Computing System)
Denoising results
- AI (Deep-Unet) model
Denoising results

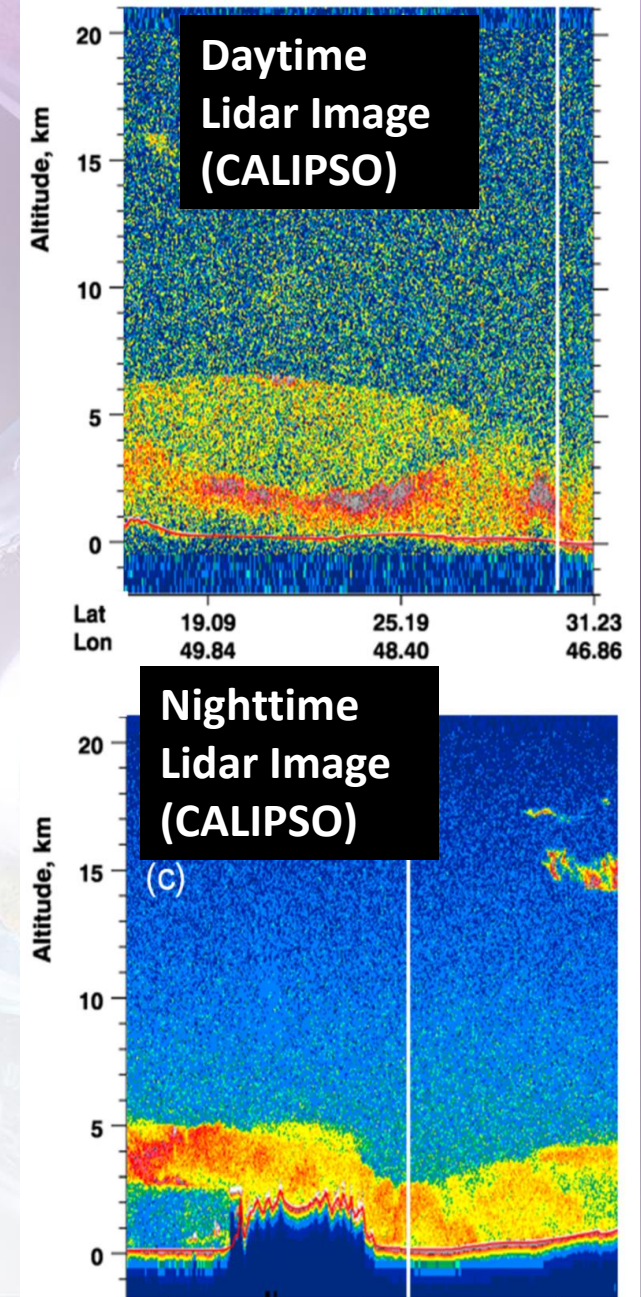


Connection between Hardware and AI

Signal-to-Noise Ratio (SNR) drives mission costs up exponentially

Daytime SNR drives space lidar mission costs by requiring heavier, higher-power optics and lasers to overpower solar background noise.

Sunlight noise reduction (AI and Quantum Based) enhances SNRs and thus reduces space lidar mission costs

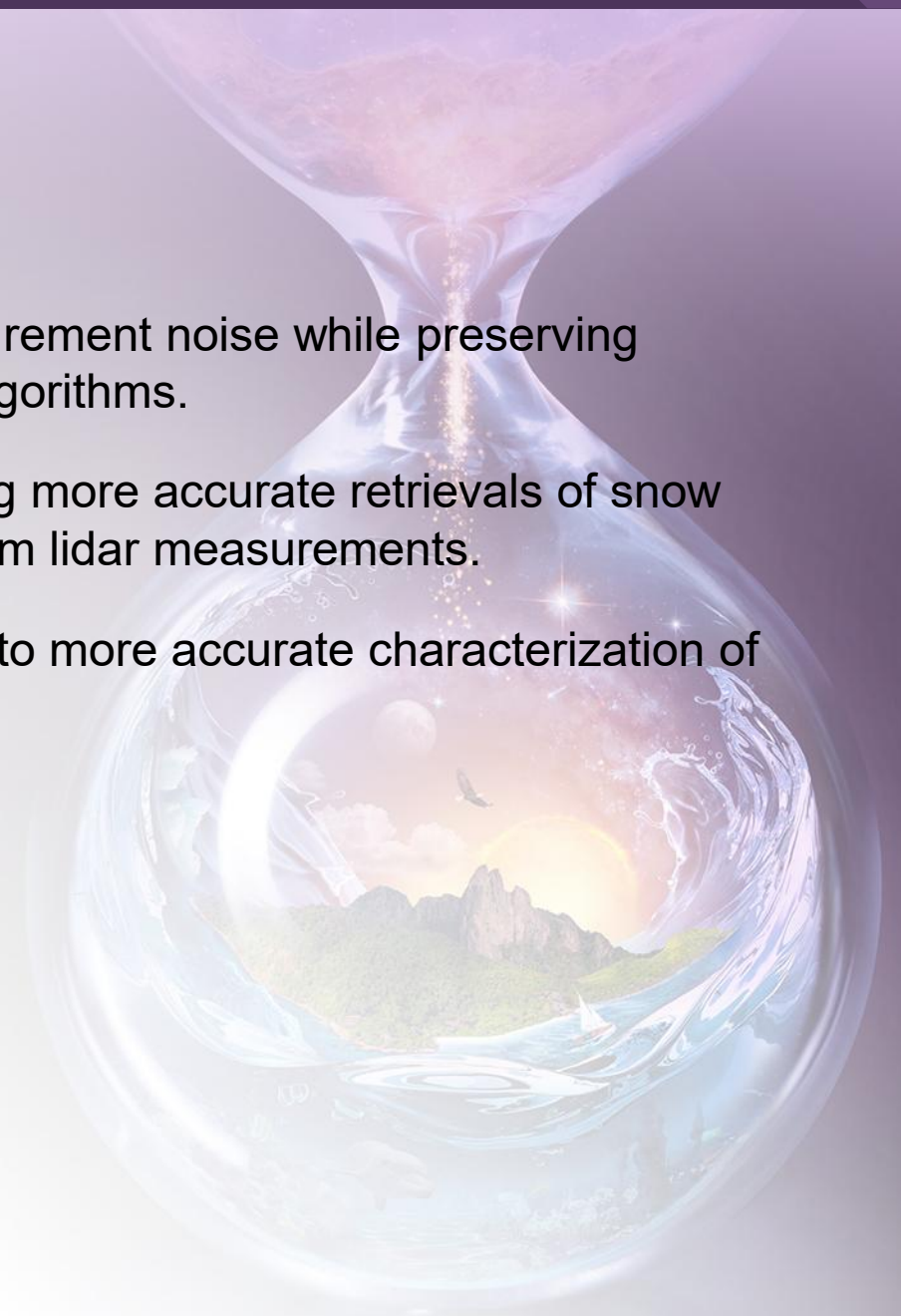


Why noise reduction is needed?

Noise reduction improves data quality by removing random measurement noise while preserving geophysical features, providing more reliable inputs for retrieval algorithms.

Noise reduction enhances the signal-to-noise ratio (SNR), enabling more accurate retrievals of snow depth, water optical properties, and phytoplankton distributions from lidar measurements.

Noise reduction also preserves weak backscatter signals, leading to more accurate characterization of snow stratigraphy and subsurface ocean features.



ICESat-2 vs SnowEx 2020- 2024

Snow Depth Comparisons in December-March from 2020 to 2024:
Two method comparisons: Pathlength vs Snow on-off

Region	SD	Bias (cm)	Median (cm)	MAE (cm)	RMSE (cm)
Tundra	Pathlength vs. Snow on-off	5	4	20	26
Boreal Forest	Pathlength vs. Snow on-off	22	20	47	58