Using spaceborne lidar for snow depth retrievals: Best practices and recommendations for future studies

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Spaceborne Lidar Can Support Snow Depth Retrieval Efforts

- Three space-based lidar missions have been used for snow depth: ICESat, GEDI, and ICESat-2.
- ICESat-2 can meet accuracy requirements from 2017 Decadal Survey and GCOS ECVs, but not temporal frequency.
- Data assimilation and multi-platform approaches may be useful for future snow depth/SWE.

Techniques to Derive Snow Depth

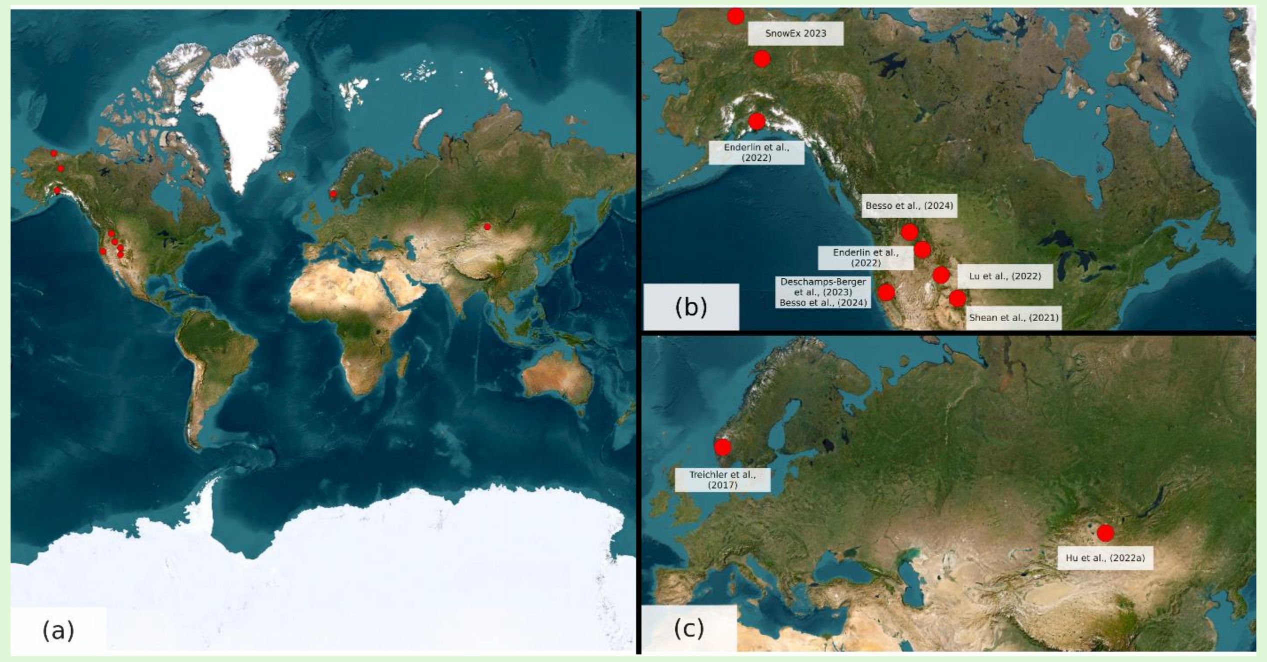


Figure 1. Global map of study sites listed in Table 1, in addition to the SnowEx 2022/2023 sites. The right panels zoom in to specific regions of interest: the Western United States and Alaska (b), and Europe and Asia (c).

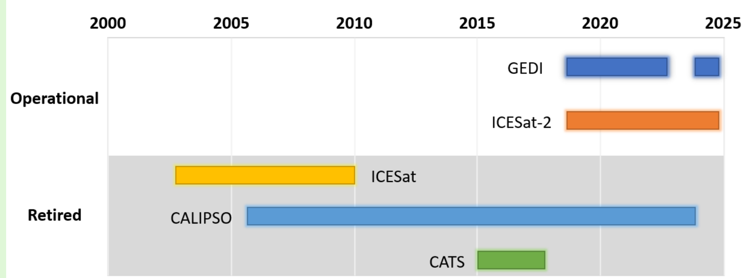
Snow depth retrieval methods with lidar include:

- **Cross-track differencing** – Use successive lidar tracks to estimate snow depth (ICESat-2)
- **Signal convolution** – Deconvolve signal photons to estimate maximum penetration depth into snow (ICESat-2)
- **Differential altimetry** – Find the difference between spaceborne lidar and a reference DEM/DTM (ICESat, GEDI, ICESat-2)

Table 1. List of published studies that use spaceborne lidar for snow depth measurements. The primary study locations, land cover types, and depth retrieval methods are given.

Study	Domain	Land cover	Method	Lidar product	Reference elevation	Validation
Hu et al., (2022a)	Northern Xinjiang, China	Bare earth Grassland	Cross-track differencing	ICESat-2 (ATL08)	---	CMA Stations
Lu et al., (2022)	Western U.S.	Forest Mountain	Backscatter signal convolution	ICESat-2 (ATL03)	---	UA snow depth (4 km) CMC snow depth (24 km)
Treichler et al., (2017)	Hardangervidda, Norway	Mountain	Altimetry-DEM differencing	ICESat (GLAH14)	SRTM DEM (45 m) Kartverket DEM (10 m)	NMI stations Airborne lidar DEMs (1 m)
Shean et al., (2021)	Grand Mesa, CO	Forest Mountain	Altimetry-DEM differencing	ICESat-2 (ATL08, SlideRule) GEDI	Worldview-3 (1 m) 3DEP (1 m) ASO (3 m)	SNOTEL sites
Enderlin et al., (2022)	Reynolds Creek, ID Wolverine Glacier, AK	Mountain glacier Forest	Altimetry-DEM differencing	ICESat-2 (ATL06, ATL08)	Airborne lidar (0.5, 1 m) Worldview (2 m)	---
Deschamps-Berger et al., (2023)	Tuolumne Basin, CA	Forest Mountain	Altimetry-DEM differencing	ICESat-2 (ATL06)	ASO (3 m) Pléiades (3 m) Copernicus (30 m)	ASO (3 m)
Besso et al., (2024)	Tuolumne Basin, CA Methow Valley, WA	Forest Mountain	Altimetry-DEM differencing	ICESat-2 (SlideRule)	ASO (3 m) Airborne lidar (1 m)	ASO (3 m) SNOTEL sites

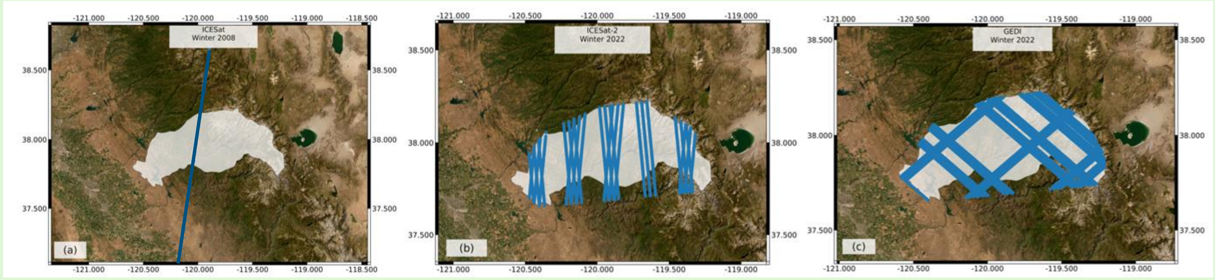
Spaceborne Lidar Missions: Past and Present



- Five known spaceborne lidar missions: CALIPSO, CATS, ICESat, GEDI, ICESat-2.
- Ground and airborne campaigns provide validation for snow-off/-on observations.
- ICESat, GEDI, and ICESat-2 have been used for snow depth retrievals.

- ICESat-2 has global resolution and the finest along-track resolution.
- GEDI has shortest orbital period, but its orbit shifts over time, so repeat tracks are unlikely. It also can only observe the mid-latitudes.
- Coverage over mid-latitude watersheds varies significantly between platforms.

	ICESat	GEDI	ICESat-2	Decadal Survey
Sensor type	Waveform	Waveform	Photon-counting	---
Wavelength	1064 nm	1064 nm	532 nm	---
Footprint	65 m	25 m	11 m	---
Number of beams	1	8	6	---
Repeat time	2-3 times per year	3 days	91 days	3-5 days
Max. Latitude	86°	51.6°	88°	88° (global)
Along-track resolution	172 m	60 m	0.7 m	100 m

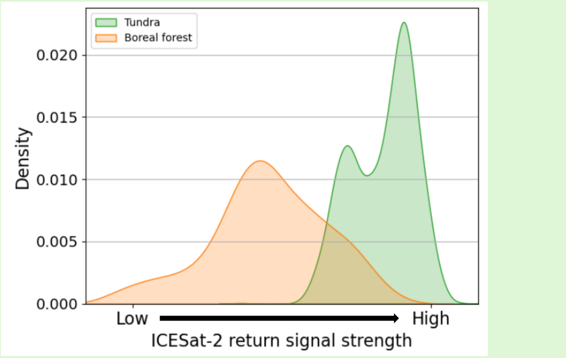


(Top left) Timeline of known spaceborne lidar missions for 2000-present, divided between active and retired missions.

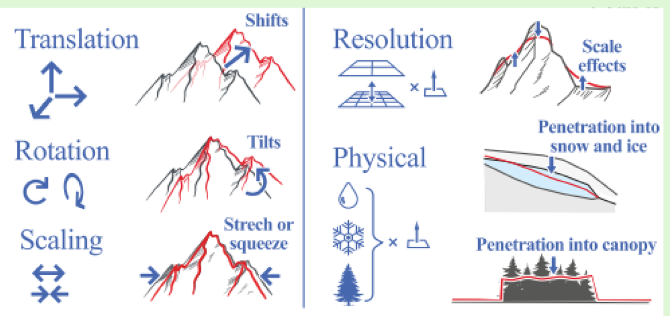
(Middle right) Technical specs for the spaceborne lidar platforms used for snow depth retrievals. The Decadal Survey requirements are also given.

(Bottom left) Spaceborne lidar coverage of the Tuolumne River Basin for a single winter season (mid-December to mid-March).

Common Error Sources



Differences in ICESat-2 return signal strength distributions between tundra (green) and boreal forest (orange) environments. The curves were derived using data from the Alaskan Coastal Plain and Creamer's Field, AK, respectively.
Source: Fair et al., (in prep.)

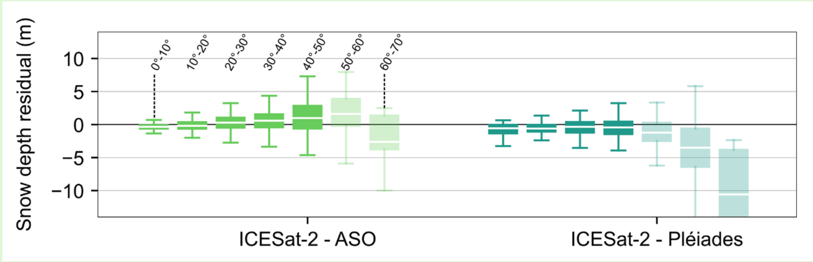


A visualization of systematic errors common to DEM co-registration over snow-covered regions. The gray lines/features represent a reference DEM, whereas the red lines are a theoretical study DEM for comparison.
Source: Figure 2 from Hugonnet et al., (2022)

Vegetation

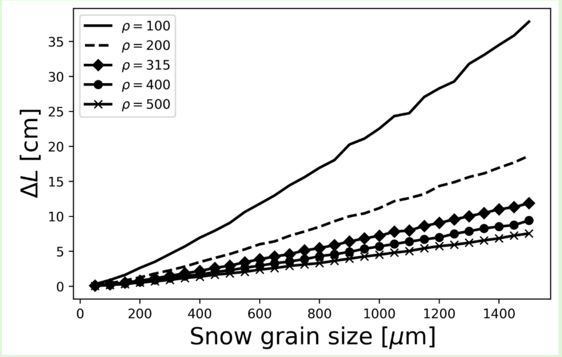
DEM co-registration

Sloped terrain



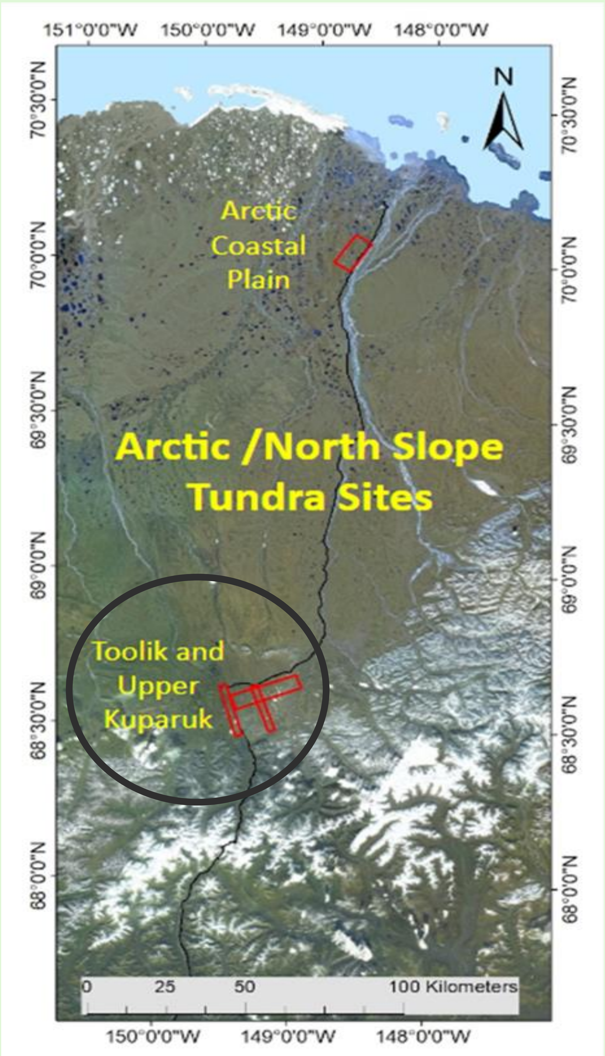
ICESat-2 snow depth errors as a function of slope, relative to two snow depth validation sources: the Airborne Snow Observatory (ASO) and Pléiades.
Source: Figure 5a from Deschamps-Berger et al., (2023)

Lidar snow penetration

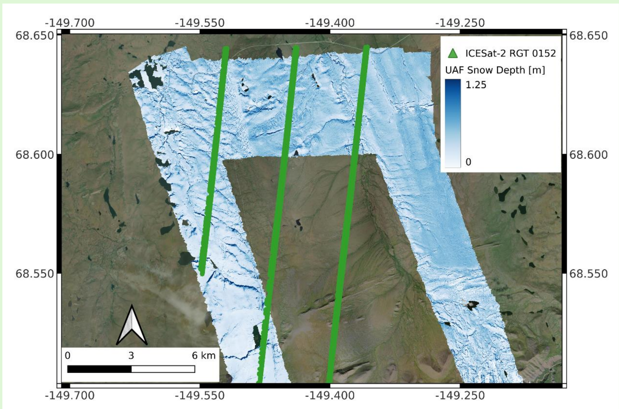


Modeled ICESat-2 altimetry bias due to snowpack penetration, as a function of snow grain size and snow density.
Source: Figure 3 from Fair et al., (2023)

Case Study Over Alaskan Tundra



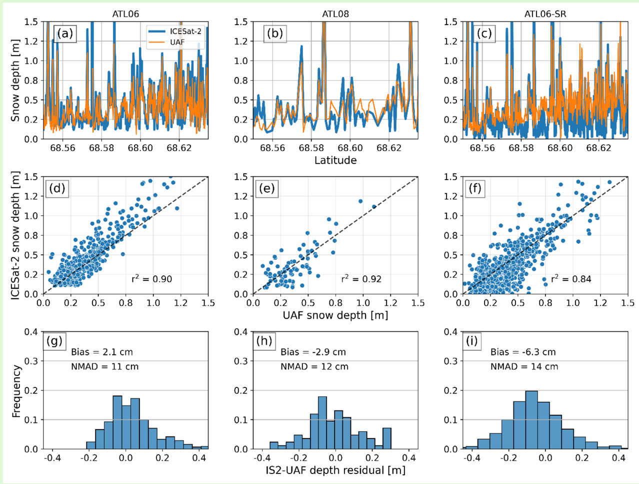
ESRI map of the Alaskan Coastal Plain, where two SnowEx 2022/2023 sites were located. The site relevant to this case study (Toolik) is circled. Courtesy of Sveta Stuefer and Emily Youcha.



Snow depth map of Toolik using airborne lidar (blues). The green lines highlight ICESat-2 coverage from March 31, 2023.

- **Where:** Upper Kuparuk/Toolik, AK
- **When:** March 31, 2023
- **Instruments:** ICESat-2 (ATL06, ATL08, SlideRule/ATL06-SR), UAF airborne lidar

- Strong agreement in depths between ICESat-2 and UAF over tundra environment



(Top row) Along-track snow depths from ICESat-2 (blue) and UAF (orange), using 3 ICESat-2 products.

(Middle row) Correlations between UAF and the 3 ICESat-2 products.

(Bottom row) Histograms of ICESat-2 snow depth error, with median bias ("Bias") and normalized median absolute deviation ("NMAD") also given.

Recommendations for Future Studies

Snow variable	Measurement spec	Does spaceborne lidar fulfill objective?	Comments
Snow depth	25 km resolution 48 day revisit time 5 cm accuracy	Yes No Yes	Accuracy is possible over flat terrain. Other environments have decimeter accuracy.
Snow cover	100-200 km 1-2 times per day	Needs research	Snow cover metrics have been proposed, but not developed.
SWE	4 km resolution 100 m resolution (mountains) 3-5 day revisit time 10% accuracy	Yes Yes No Yes	Gives snow depth, needs density observations to derive SWE.
Optical properties	30 m resolution	Needs research	Optical property retrievals have been proposed but not developed.

A summary of recommended measurement specs for four snow variables, and the feasibility of spaceborne lidar to fulfill these requirements.

Measurement specs are summarized from the 2017 Decadal survey and the Global Climate Observing System Essential Climate Variables (GCOS ECVs).

- **Decadal survey accuracy requirements are achievable** with ICESat-2, but **revisit frequency is not**.
  - ICESat-2 accuracy degrades for slopes > 20° and forest covers > 60%.
  - Timing of data availability needs improvement (1.5 months for ICESat-2).
  - Additional sources of error from snow penetration and DEM co-registration can also impact accuracy.
- ICESat-2 uncertainties can be reduced to decadal requirements using SlideRule, an open-source Python tool.
- **Assimilation of lidar snow depth can improve model output; more research is needed for spaceborne platforms.**

Acknowledgements

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