

NASA Community Snow Meeting
Day 1 Breakout Session I
Snow Remote Sensing & Measurement Approaches
August 14, 2024



Session Objectives, Format, and Intended Outcome

- **Objective:** Identify advances in snow remote sensing and measurement that have taken place over the SnowEx mission time period. Brainstorm future advances and what is needed to realize them. Incorporate discussion to update “stoplight chart” from SnowEx Science Plan (last updated at Baltimore meeting).
- **Format:** Breakout session groups will be self-selected by sensing technique. Leadership for each breakout session has been identified, provided below. Each group will have access to a Google Drive folder with the breakout session guidelines, formatted summary slides (this file), and a blank Google document where group leaders can take notes.
- **Outcome:** By the end of the hour, the two group leaders will compile 1 presentation slide summarizing the state of the art for each technique. This slide will be presented immediately afterward to the larger group. Based on the full group discussion, recommendations can be made to update the “stoplight chart.”



Group Topics and Session Leaders:

1. **Microwave Scattering:** Mike Durand, Ed Kim
1. **Signals of Opportunity:** Steve Margulis, Eli Deeb, Jessica Lundquist
1. **UAV applications (all sensors):** Dan McGrath, Jennifer Jacobs
1. **Snowpack and Hydrologic Modeling (including machine learning and data assimilation):** Mark Raleigh, Joachim Meyer
1. **Ground-based/observations:** Megan Mason, Ryan Webb, Sveta Stuefer
1. **Snowpack Albedo:** Kelly Gleason, McKenzie Skiles
1. **InSAR:** Jack Tarricone, HP Marshall
1. **Spaceborne lidar/stereo (including lidar snow depth retrieval):** Zach Fair, Yong Hu



Day 1 Breakout Session I Questions:

1. What do you feel are the biggest innovations and applications of this technique in the past decade?
 - a. What has enabled this to occur?
2. What are the biggest remaining challenges and development opportunities for this approach?
3. How do you think this approach fits into a global snow observing system or strategy?
 - a. How well does this approach perform in measuring snow depth, SWE, snowmelt, albedo?
 - b. How well does this approach work under different snow/environmental conditions
 - i. In forests versus open areas?
 - ii. In shallow snow?
 - iii. In complex terrain?
 - iv. Dry versus wet
 - v. Under clouds
 - c. Has the uncertainty been defined? If so, at what scale (basin, mountain range, hemispherical, global)?
 - i. How big is the impact?
4. Does this technique support a path to space?
 - a. If so, how mature is it?
 - b. If not, does it complement spaceborne observations and how?
5. What does this technique rely on or need to pair with to work? What other techniques are highly complementary to this approach? (synergies)



Summary Slide (1) Microwave Scattering

1. Biggest innovations and applications of this technique in the past decade: Breakthrough consisting of many parts! Simplified parameterized radiative transfer model. Algorithms not requiring prior information, subtracting the surface or substrate scattering, measuring and modeling microstructure and advances in the connection between microstructure and retrievals, physical modeling (SNOWPACK, Crocus), C-Band retrievals and physical explanations, using ML for retrievals, deep snow with X-Band, improved understanding, strategies, algorithms in forest environments, increase in modeling/tool accessibility. All or almost all of this in published literature. Enabled by many COMMUNITY EFFORTS: field campaigns, satellite mission proposal efforts
2. Biggest remaining challenges and development opportunities for this approach: Representativeness, cross-pol. Coordination, perhaps a next MicroSnow meeting! Accessibility to the tools,(steep learning curve)!
3. How this approach fits into a global snow observing system or strategy: Estimates snow depth and SWE well in many contexts. Can infer snowmelt indirectly. Does not do albedo. There is a cutoff at which we cannot do trees, but that cutoff is higher than previously thought (see above). Works well in shallow snow, and there is far more hope for deep snow than previously thought (see above). In complex terrain, no issue with incidence angle but radar artifacts (e.g. layover) pose challenges. Works in dry snow only. Clouds are not a problem. Uncertainty has been fairly well defined, but true end-to-end uncertainty propagation is forthcoming.
4. This technique does/does not support a path to space in the following ways: Yes!
5. What this technique relies on, needs to pair with, and/or is complementary with: Both using other satellite data (C-band or L-band) and using priors improve retrieval accuracy.

Summary Slide (2) Signals of Opportunity

1. Biggest innovations and applications of this technique in the past decade:

GNSS reflectometry (L-band) has gone from just an idea to demonstrated in space with L-band. P-band has only been demonstrated at a tower, with success for snow (both SWE and depth and dry and wet). P-band theoretically should work with trees. Tech has some advances from aircraft and 6 SNOOPI acquisitions over water.

1. Biggest remaining challenges and development opportunities for this approach:

We need to demonstrate that at P-band approach works for snow, with inSAR. Aircraft is particularly difficult, but UAV or a smallsat demo mission might help. **Needs a campaign to demo the technology.**

1. How this approach fits into a global snow observing system or strategy:

Limit is money, if you have enough antennas and bandwidth, you have resolution and coverage, but only goes up to 60-ish deg. Don't get the poles, good for global mountains. **Gets deeper snow and forested snow.** Might be insensitive to small SWE changes.

1. This technique does support a path to space in the following ways:

Definitely supports space, just needs more demo. Should work better in space than in an aircraft due to aircraft stabilization and RFI at aircraft altitudes. May be able to partner with commercial (SPIRE or MUON) or DoD.

1. What this technique relies on, needs to pair with, and/or is complementary with:

Needs the communication or navigation satellites (MUOS or GNSS). Pairs well with NISAR (another interferometric technique, for lower snow volumes) or something else that gets the poles. Benefits from L-band InSAR, and C-band (Sentinel) for where snow is wet, but could work alone. Modeling will help. This is good for mountain snow, work with other communities to measure something outside of snow zone too.

Summary Slide (3) UAV applications

1. Biggest innovations and applications of this technique in the past decade:
 - a. Technological advances (increased range, increased payload capabilities, ease of use (software/user interface development), RTK positioning, ability to repeat tracks)
 - b. Wide range of sensing techniques (photogrammetry, lidar, multispectral, thermal, radar, hyperspectral)
 - c. Opportunities for sensor integration (both ground obs and other UAV sensors)
 - d. Applications: both process-scale understanding of snow and ability to span spatial and temporal scales between field observations and airborne/satellite observations
1. Biggest remaining challenges and development opportunities for this approach:
 - a. Legal (line of sight (i.e., limits spatial extent), restrictive airspace regulations, NASA regulations (i.e., crewed aircraft) limit integration into campaigns)
 - b. Logistics (weight, harsh weather conditions impact batteries and equipment)
 - c. Rapid growth of technology leads to equipment becoming obsolete quickly -- opportunity for community resources (e.g., geophysical equipment at Earthscope)
1. How this approach fits into a global snow observing system or strategy:
 - a. Ability to span spatial and temporal scales -- small footprint and larger spatial extent than most ground obs
 - i. Cm to Km scale, minutes to hourly repeat frequency
 - b. Quick response time (big storms, rain on snow events)
1. This technique does/does not support a path to space in the following ways:
 - a. No path to space, but essential for validation and downscaling of satellite-borne approaches
 - b. Stepping stone for demonstrating spaceborne methods
1. What this technique relies on, needs to pair with, and/or is complementary with:
 - a. UAVs are limited by legal regulations; need systems that facilitate/encourage acquisitions
 - b. Can be paired with other ground/UAV observations (e.g. radar and lidar) to derive permittivity/density → SWE

Summary Slide (4) Snowpack and Hydrologic Modeling

ML = machine learning, **DA** = data assimilation, **M**=modeling

1. Biggest innovations and applications of this technique in the past decade:
 - a. **ML**: computing power, data availability, great potential to improve SWE and depth mapping
 - b. **DA**: error characterization, operational/research applications, informing where/when obs. most valuable
 - c. **M**: ability to integrate data, drive data collection strategies, spatial resolution, computing

1. Biggest remaining challenges and development opportunities for this approach:
 - a. **ML**: data availability, quality, trust/skepticism, “black box” nature
 - b. **DA**: need outputs that are useful to users; techniques can be difficult to validate
 - c. **M**: uncertainty in input data, downscaling uncertainty; scaling mismatches between modeling and scales we care about; ML/DA crossover; validation; incomplete parameterizations / process representation over large areas; sub-grid variability; horizontal interactions (most models focus on vertical processes)
 - d. **General**: data access; we don’t fully use the limited observations we have; large spatial variability in snow

1. How this approach fits into a global snow observing system or strategy:
 - a. **ML**: enhancing/combining existing datasets; better outputs in data poor areas
 - b. **DA**: similar to ML; grounding observations in locations where they are not good/available
 - c. **M**: the “glue” to attach components, connect time series, scaling up

Summary Slide (4) Snowpack and Hydrologic Modeling

ML = machine learning, **DA** = data assimilation, **M**=modeling

4. This technique does/does not support a path to space in the following ways:

- **ML**: ...
- **DA**: value of info from future mission, beneficiary of a RS mission
- **M**: in what way are we able to use the RS data in models? Focus on uncertainty again... too uncertain= not useful

5. What this technique relies on, needs to pair with, and/or is complementary with:

- **ML**: EVERYTHING, super flexible, can pair with all types of data, with physical/conceptual models, DA systems
- **DA**: models+obs, any future mission should be accompanied with a DA system, span full research-to-operations pipeline
- **M**: longer term and overlapping missions are desirable, R2O challenge, the challenge of disappearing/changing data streams

Summary Slide (5) Ground-based/observations

1. Biggest innovations:

Field plans:

- a. Increased # of ground obs, people in the field, diversity of expertise in the field (modelers, remote sensors, etc.)
- b. Teaching snow measurement protocols at SnowSchool
- c. Adding drones to study areas has proven helpful

Techniques

- a. Geolocation! (smaller, lighter, better!)
- b. Snow pillows on frozen lakes
- c. Micro-CT scanning/ data processing; SSA; MicroPen
- d. Distributed automated weather systems
- e. Functional GPR sleds/snow machines
- f. Drones

1. Biggest remaining challenges:

- a. Difficulty scaling up to km scale for val/cal
- b. Data frequency, sampling gaps
- c. Documentation of established methods/networks
- d. Experimental design (both advances and room for improvements to cover the spatial domain of interest) - timing and funding make coordinating challenging!

1. Global snow observing context:

Scale is always the issue with ground obs (point scale) especially if the goal is global, what is the updated needs for accuracy/calibration/validation
Needs two-way communication between ground-air-satellite teams

1. Path to space? Yes, but improvements can help - ground based sensors similar to satellite system

- a. In forests versus open areas? **reasonably well**
- b. In shallow snow? **large uncertainty**
- c. In complex terrain? **less certain due to less sampled**
- d. Dry versus wet? **wet is more uncertain, instrumentation is still R&D status**
- e. Under clouds **grounds obs work well here!** (with the exception of extreme storm events)
- f. Need more data:
 - i. Ice lenses/multi-layer and/or heterogeneity
 - ii. Big storm events - large uncertainty
 - iii. Snow drifts

2. Complementary methods:

- a. Could we add more Machine Learning to enhance ground measurements? (use the camera time-lapse data as an example).
- b. Modeling + data interpolation will help support some of data challenges (e.g. data sampling gaps)
- c. More drone applications



Field observations are robust... most of the time!

Snow albedo (reflectance)

Ally Fitts, Cenlin He, Karl Rittger, Kehan Yang, Chris Crawford, Eric Sproles, Ned Bair, Pat Naple, Jeff Dozier, Carl Shmitt, Will Rudisill, and Kelly Gleason

- Biggest innovation: Snow albedo community (developing consensus), Vast improvements with hyperspectral imaging spectroscopy across scales (field, tower, UAV, airborne, and now space with EMIT and SBG). SNICAR and SPIRES modeling advances for better snow albedo predictions. Snow albedo “designated” under SBG highlighted the importance and impacts to Earth’s energy budget.
- Biggest remaining challenge: Lack of consensus observational dataset (ground-based in-situ and satellite reflectance data) to inform better models, no continuity supported snow albedo product generation from the raw data, and lots of uncertainty across scales (e.g., mixels, algorithms).
- Global observing opportunity: Yes! Clear path to space! Mature science that needs global space-based hyperspectral imaging spectroscopy – SBG and CHIME, globally, 30 m, and daily, would be best. Future challenges likely to be data storage, archiving, and access of large data volumes.
- Details: Open areas great, still challenges with forests, shallow snow, and melting snow, shadow, roughness over scales (Temporal frequency and spatial extent – a single observatory is not sufficient – need a constellation of observations in space – and need a network of ground based measurements for validation.) Uncertainty still remains in overlapping issues over spectral, temporal, spatial, and radiometric resolutions. Need consensus algorithms over snow climates.
- We will likely always leverage coupled remote sensing and modeling approaches to resolve snow reflectance over scales and time. Synergies with many other Earth Science missions, atmospheric transport modeling of LAPs, and many applications to hydrology and climate understanding and predictions.

Summary Slide (7) InSAR

1. *Biggest innovations and applications of this technique in the past decade:*

- Marshall et al. (2021) showed robust performance in idealized conditions
- Showed phased-based retrievals works well from a tower and is density independent (Leinss et al. 2015)
- UAVSAR campaign had coverage/coherence across broad snow climates
- Snow signal and potential shown with early spring melt with morning acquisitions (Tarricone et al., , 2023)

1. *Biggest remaining challenges and development opportunities for this approach:*

Define SWE retrieval performance uncertainty with respect to: wet snow, temporal coherence, forest cover, reference phase selection, complex topography, subgrid variability, atmospheric

1. *How this approach fits into a global snow observing system or strategy:*

Can provide SWE measurements in dry snow at fine spatial resolutions, not for wet snow

1. *This technique does/does not support a path to space in the following ways:*

NISAR launching in 2025, continuation of Sentinel-1C & D, SDC, ROSE-L, PALSAR2, HyperTerra+

1. *What this technique relies on, needs to pair with, and/or is complementary with:*

Optical snow cover data (Landsat/VIIIRS/MODIS/S2/SBG), atmospheric models for phase correction, eventually assimilated in land surface models, ICESat-2 for reference phase. Need LiDAR coincident with NISAR to improve understanding of uncertainties

Summary Slide (8) Spaceborne lidar/stereo

1. Biggest innovations and applications of this technique in the past decade: ICESat-2 (2018-present) has shown that we are capable of measuring snow depth with good accuracy/precision and high along-track resolution. Tools such as SlideRule allow easy, on-demand data access and customization. Upcoming mission concepts such as EDGE, STV and ESTO snow lidar offer more opportunities to continue the data record, and improve capabilities. Stereo has the potential to obtain high-resolution data (30 cm GSD) over wide swath (10-20 km) with ~10 cm precision, global coverage from archives (2007-present), on-orbit commercial constellations (40+ satellites). Fusion of lidar and stereo can provide retrievals in open areas and under canopy.
1. Biggest remaining challenges and development opportunities for this approach: Cost! (cheaper concepts proposed, constellations); Coverage; **Data latency** remains a challenging issue, with current platforms having latencies of a month or more (ICESat-2 quicklook products ~3 days, but geolocation error). **Cloud cover and sloped topography** remain challenging, particularly for larger lidar off-nadir angles. **Need for accurate “snow-off” digital elevation/terrain models stereo (although a new snow lidar concept does not require).**
1. How this approach fits into a global snow observing system or strategy: Spaceborne lidar could “train” more dedicated microwave and/or stereo (STV) snow missions. Airborne/in-situ data could train spaceborne lidar, thus creating a training pipeline of sorts. Fusion of sparse, but accurate lidar retrievals with spatially continuous, precise datasets and model output.
1. This technique does/does not support a path to space in the following ways: It can provide snow depths at a potentially global scale, and techniques are being derived for obtain snow density, grain size, etc. ESTO is supporting innovative snow lidar mission concepts. However, limited revisit times and data latency limit its operational potential (can be mitigated with lidar/microwave/stereo fusion).
1. What this technique relies on, needs to pair with, and/or is complementary with: Mission lifetime will be important for current and future missions, especially for operational applications. Cost of future missions may provide challenges, which may encourage low-cost missions (Cubesats, Ride-share missions). Commercial lidars are being developed that could be used as complementary datasets. Pairing space lidar mission with microwave/stereo measurement missions highly desirable.