H.P. Marshall, Carrie Vuyovich, Chris Hiemstra, Kelly Elder, Ludo Brucker, Airborne Teams, Time Series Site Leads, and many, many others from 20+ universities and government labs

Photo Credit, Andrew Hedrick

hpmarshall@boisestate.edu
The SnowEx 2020 Campaign consists of coordinated airborne and field-based experiments in the Western U.S.

1. **A time series experiment with UAVSAR**
   - L-band Interferometric Synthetic Aperture Radar
   - Test in range of snow climates and during accumulation & melt
   - 13 sites, spanning 5 states
   - December 20, 2019 to March 12, 2020, with weekly to bi-weekly aircraft overflights and field campaigns

2. **A detailed experiment on Grand Mesa, Colorado**
   - SWE retrieval from active and passive microwave sensors
   - Surface temperature observations from Thermal IR
   - 5-day snow-off campaign November 4-8, 2019
   - 19-day snow-on campaign January 27 –February 14, 2020
Alignment with THP16 Science Plan

SnowEx 2020: Responds to 6 out of 7 Science Plan Gaps
- Snow climates (Forest, mountain, prairie, maritime)
- Wet snow, accumulation and melt (time series)
- Surface energetics (surface temperature)

SnowEx 2020: Responds to all Science Plan Mission Critical, Crucial, Important priorities
- L-band InSAR (UAVSAR)
- X-, K-, Ka-band Passive microwave (SWESARR)
- X-band, dual Ku-band SAR (SWESARR)
- Ka-band InSAR (GLISTIN-A)
- LiDAR (ASO, Quantum Spatial, CRREL HeliPod)
- Thermal IR (UW)
- Hyperspectral imaging (ASO, Quantum Spatial, SaraniaSat)
- Modeling / Data Assimilation (SEUP, NOHRSC)
- Photogrammetry / Structure from Motion (airborne and satellite based)
- FMCW radar (similar to IceBridge SnowRadar; University of Alabama)
- C-band SAR! (Science Plan team is adding this)
SnowEx 2020 – Time Series

<table>
<thead>
<tr>
<th>Site</th>
<th>Site Name</th>
<th>Site Lead</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lakes Basin, CA</td>
<td>Ned Bair</td>
</tr>
<tr>
<td>2</td>
<td>American River Basin, CA</td>
<td>Roger Bales</td>
</tr>
<tr>
<td>3</td>
<td>Sagehen Creek, CA</td>
<td>Anne Nolin</td>
</tr>
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<td>4</td>
<td>Reynolds Creek, ID</td>
<td>Ernesto Trujillo</td>
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<td>5</td>
<td>Boise River Basin, ID</td>
<td>Jim McNamara</td>
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<tr>
<td>6</td>
<td>Little Cottonwood Canyon, UT</td>
<td>McKenzie Skiles</td>
</tr>
<tr>
<td>7</td>
<td>Grand Mesa, CO</td>
<td>Hiemstra, Brucker</td>
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<tr>
<td>8</td>
<td>Senator Beck Basin, CO</td>
<td>Andy Gleason</td>
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<td>9</td>
<td>East River, CO</td>
<td>Jeff Deems</td>
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<td>10</td>
<td>Cameron Pass, CO</td>
<td>Dan McGrath</td>
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<td>11</td>
<td>Fraser Experimental Forest, CO</td>
<td>Kelly Elder</td>
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<tr>
<td>12</td>
<td>Niwot Ridge, CO</td>
<td>Noah Molotch</td>
</tr>
<tr>
<td>13</td>
<td>Jemez River, NM</td>
<td>Ryan Webb</td>
</tr>
</tbody>
</table>
Time Series Summary

- 6 successful UAVSAR flights, between December 20 and March 12
- UAVSAR flight had conflicts with ISRO-ASAR, aircraft and instrument issues
- LiDAR acquisitions over Idaho, Colorado
- WV, ICESat2 collections
- Coordinated modeling
- Field teams deployed 9 times across 13 sites, providing unique time series of coordinated snowpit observations
- 100+ students, researchers from 20+ organizations
- 200+ pits during 9 week time series
- Liquid water content observations
- Temperature, density, SWE, depth, stratigraphy, microstructure, hardness

Snow microstructure observations, long-range L-band InSAR
Time Series Summary

- Ground based radar
- Terrestrial LiDAR scanning
- Drone flights (Thermal IR, SfM) (coordinated activity)
- Coordinated with LiDAR surveys by U.S. Army Cold Regions Research and Engineering Laboratory
- Coordinated with USDA NRCS Snow Surveys
- Wide range of snow climates
- Winter Wildland Alliance SnowSchool partnership: K-12 students collected snow observations and submitted to SnowEx via CommunitySnowObs.org
- Time series cancelled early due to COVID-19 pandemic
- UAVSAR flight hours will be rolled over to 2021

Exec Director of national WWA SnowSchool program demonstrates snow density observations with K-12 students in Idaho
Time series example: Cameron Pass

Repeat GPR surveys, SfM, TLS, UAV GPR

See Dan McGrath’s poster.

See also other GPR-related posters by Webb, Meehan, Bonnell
Recent L-band InSAR results from SnowEx 2020

- UAVSAR pair from Grand Mesa, Feb 13 - Feb 1, 2020
- Quantum Spatial Inc (QSI) lidar flights for depth change, Feb 12-Feb 1, 2020
- Lidar accuracy ~3-5cm per flight, expected ~6-10cm accuracy for depth/depth change products
- UAVSAR depth inversion uses phase change and incidence angle, with measured surface density (200 kg/m³). No tunable parameters!
- Zoom in on 2km x 2km region with dynamic range in depth
- $R$-value = 0.76, RMSD=4.7cm depth, 0.9cm SWE
- Independent high-resolution spatial snow information is critical for evaluation of radar approaches
Independent field observations of depth change show a mean depth change of 9cm over this period.

In these conditions (surface density ~200 kg/m^3), 360 deg phase change can capture 46cm depth change. Reference location and surface density estimate required.

Correlation loss after 3-12 weeks depending on conditions, much shorter in vegetation.

SnowEx2021 focused on capturing larger SWE/depth changes, and exploring transition between dry and wet snow.

Technique shows promise for defining snow accumulation patterns.

More work needed to define limitations in vegetation and steep topography.
SnowEx 2020 – Grand Mesa

Primary Objectives:
1. Collect data needed to test and validate SWE retrieval from active and passive microwave sensors
2. Collect thermal IR data to assess the value of kilometer-scale satellite IR observations (e.g., GOES-16/17) for snow energy balance modeling

• Focus on flat, open shrubland and meadows and transitioning into forests
• Ground observations of:
  • Snow depth and surface temperature spatial variability
  • Vertical profiles of snow stratigraphy and microstructure
Planned Ground Observations:
• Snow pits (150)
• Snow Depth Transects
• Terrestrial Laser Scanner (TLS)
• Passive microwave radiometer
• Ground penetrating radar
• Snow microstructure (grain size, SSA)
• Snow surface temperature

Planned Airborne Instruments:
• Active/Passive microwave (SWESARR)
• Thermal IR (UW)
• L-band InSAR (UAVSAR)
• LiDAR (Quantum Spatial)
• Hyperspectral imaging (Quantum Spatial)
• Gamma (NOAA NOHRSC)
• FMCW radar (University of Alabama)
Grand Mesa Ground Campaign

- 153 Snow Pits
- Over 30,000 snow depth measurements
- SSA profiles at 99 pits
- 976 SMP profiles at 48 pits
- 73 snow casts at 12 pits
- PM radiometer measurements at 20 pits + grid
- IR radiometers & temperature profiles installed at 2 locations for 2-week period
- 4 radars covered over 500 km
- ASD measurements during both Quantum hyperspectral flights
- 9 TLS sites scanned
- 8 storm boards & 12 snow stakes installed and measured three times (2, 8, 13 Feb)
- SUS-V mobility measurements (coordinated activity)
- Drone flights (Thermal IR, SfM) (coordinated activity)
Airborne Campaign

University of Alabama FMCW Radar

Quantum Spatial Lidar & Hyperspectral

NOAA NOHRSC Gamma Airborne Survey

Swesarr Active/Passive UW Thermal IR On NPS/CIRPAS Twin Otter

UAVSAR? L-band InSAR, on JSC GIII

Photo by Kehan Yang
The airborne SWESARR observations

Team members
Batu Osmanoglu – Instrument Lead
Rafael Rincon – Radar Lead
Derek Hudson – Radiometer Lead
Ludovic Brucker – Radiometer Scientist
Martin Perrine – Radar Engineer
Chase Kielbasa – RF Engineer
Paul Racette – ex-Radiometer Lead/Antenna Design
Steve Seufert – Mechanical Engineer

1 antenna for observations at:
• 3 passive bands (X, Ku, Ka)
• 6 active bands (X, Ku-low, Ku-high)

Radar’s altitude range: 1.5 – 3 km agl
Grand Mesa Lands End backscatter (11 Feb.)
Grand Mesa brightness temperature (11 Feb.)

Simultaneous observations at:
- 10.65, 18.7, and 36.5 GHz
- 45° incidence angle
- horizontal polarization

Adjusted along-track

Snow Water Equivalent Synthetic Aperture Radar and Radiometer

SWESARR

Tb Ka (36.5 GHz)

Contains modified Global SnowSat data 2020, processed by ES5.
University of Alabama, Remote Sensing Center

Drew Taylor, Stephen Yan, Prasad Gogenini, and others

Airborne UWB FM-CW Radar

- 2.7-10.7 GHz/10.7-18.7 GHz
- 1 W peak transmit power
- 4 kHz PRF / 180 us pulse
- 1.52 cm vertical resolution in snow
- $\sim$50 m x 300 m horizontal resolution

Simulated return from snow-air interface
Simulated return from snow-land interface
$\sim$50 dB SNR
$\sim$175 dB loop sensitivity
SNR gain due to real-time hardware averaging

- Snow depth appears resolvable under forest canopy
- Nadir observations worked well
- SAR approach still in progress
- Drone-based capability
- Future plans for installation on G-5, greatly enhancing possible range (currently on Twin Otter)
Thermal IR results

Snow Surface Temperature & Thermal Infrared Remote Sensing
Grand Mesa IOP - SnowEx 2020

Steven Pestana¹
Jessica Lundquist¹
Chris Chickadel¹,²

¹ Civil and Environmental Engineering, UW; ² Applied Physics Lab, UW
Photo credit: Chris Chickadel
Fieldwork and ground-based data collection

West Met Station

Snow Pit 2S10

Radiometer Footprints

Datalogger Location

Snow Temp. Sensors (buried)

Filled-in snow pit

Grand Mesa map image and GIS files: Chris Hiemstra
Snow Pit 2S10

Preliminary snow-surface and depth profile temperature data:
https://github.com/spestana/snowex2020-snow-temp
SNOWEX 2021 OBJECTIVES

**UAVSAR**
1. Define the snow conditions where L-band InSAR is likely to work (maintain coherence)
2. Quantify the accuracy of L-band InSAR retrievals of snow depth, density, SWE, and wetness

**Albedo**
1. To evaluate the spatiotemporal variability in snow albedo, the controls on this variability, and the uncertainty of remote sensing measurements relative to mountains, forests, and as snow albedo declines over time.

**Prairie**
1. Quantify the accuracy and uncertainty in SWE retrievals L-band InSAR in a Prairie environment, specifically assessing the impact of shallow, drifted snow, terrain with variability soil temperature and moisture conditions, and wet snow
2. Characterize the spatial heterogeneity of snow characteristics due to wind redistribution, landscape, and sublimation, and assess the scales at which different processes dominate, as well as the ability of remote sensing techniques to characterize spatial distribution.
POSSIBLE SNOWEX 2021 TARGETS

• Combines highest priority targets from L-band InSAR, Albedo, Prairie groups

• UAVSAR/AVIRIS-NG will be based out of Houston – proximity of sites is important for conserving flight hours

• Leverages ongoing field efforts, as little field budget is available

• Targets sites with planned UAV efforts

• Targets sites with ground-based L-band radar (InSAR and GPR)

• Plan will be flexible; UAVSAR flights depending on conditions
# SNOWEX 2021 RECOMMENDATION

<table>
<thead>
<tr>
<th>Site</th>
<th>Timeline</th>
<th>UAVSAR Flights</th>
<th>AVIRIS-NG Flights</th>
<th>UAV flights</th>
<th>Continuous Obs</th>
<th>Ground Activities</th>
<th>Ongoing/Partner Activities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Senator Beck, CO</td>
<td>Dec 2020 – May 2021</td>
<td>12</td>
<td>3</td>
<td>broadband albedo, met station</td>
<td>Field spectrometer, snowpits/depth during flights</td>
<td>SaraniaSat hyperspec/thermal IR</td>
<td></td>
</tr>
<tr>
<td>Cameron Pass/ Fraser, CO</td>
<td>Dec 2020 – May 2021</td>
<td>12</td>
<td>0</td>
<td>Optical SfM, UAV GPR</td>
<td>broadband albedo, met station</td>
<td>Snowpits/depth during flights</td>
<td>Ground-based GPR / SoOp towers, tower radar</td>
</tr>
<tr>
<td>Grand Mesa, CO</td>
<td>March – May 2021</td>
<td>3</td>
<td>3</td>
<td>Multispectral, thermal IR</td>
<td>broadband albedo, met station</td>
<td>Field spectrometer, snowpits/depth during flights</td>
<td>SaraniaSat hyperspec/thermal IR, NOHRSC Gamma, UA FMCW</td>
</tr>
<tr>
<td>CARC, MT</td>
<td>Dec 2020 – Mar 2021</td>
<td>4</td>
<td>0</td>
<td>Lidar, broadband, hyperspectral, thermal IR</td>
<td>Met/snow/soil</td>
<td>Field spectrometer, snowpits/depth during flights</td>
<td>NSF agricultural initiative, NOHRSC Gamma</td>
</tr>
<tr>
<td>Little Cottonwood Canyon, UT</td>
<td>Dec 2020 – May 2021</td>
<td>12</td>
<td>0</td>
<td>Optical SfM</td>
<td>broadband albedo, met station</td>
<td>Snowpits/depth during flights</td>
<td>Ground-based L-band InSAR, infrasound avalanche detection</td>
</tr>
<tr>
<td>Boise Basin, ID</td>
<td>Dec 2020 – May 2021</td>
<td>12</td>
<td>0</td>
<td>Optical SfM, thermal IR</td>
<td>broadband albedo, met station</td>
<td>Snowpits/depth during flights</td>
<td>CRREL helipod, ground-based L-band InSAR, tower radar</td>
</tr>
</tbody>
</table>
Promoting a snow community culture of data and code sharing, equal access, collaboration, inclusion.

SnowEx Hackweek, Summer 2021, eScience @ UW
We need tutorial leads!
Contact hpmarshall@boisestate.edu if you are interested in helping to develop/deliver tutorials
Diversity and equity in Geosciences

• Bernard and Cooperdock, 2018, Nature Geoscience, 11, 292-296
• No progress in increasing diversity over last 40 years
• SnowEx welcomes and strongly encourages participation from people of all backgrounds, races, religions, gender

• Ideas about how to improve? Contact hpmarshall@boisestate.edu
Thanks!