NASA'S SNOWEX CAMPAIGN AND MEASURING GLOBAL SNOW FROM SPACE

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Outline

- Importance of snow
- Overarching SnowEx/snow science questions
- Global snow measurement options
- Why SnowEx?
- SnowEx Year 1
- What's next?
- A global snow mission
- Summary

Why is seasonal snow important *scientifically*?

- Largest areal extent of any component of the cryosphere.
- Over 60% of the northern hemisphere land surface (30% of Earth's total land surface) has snow cover in midwinter.
- Plays a strong role in Earth's Water, Energy, & Carbon Cycles
- Important storage element of the Water Cycle
- Dramatically changes land surface thermal regime & atmospheric boundary conditions for months
- Changes planetary albedo for months
- A major survival factor for flora and fauna

- Spatial scales are global & regional
- Temporal scales are seasonal to decadal to even longer

Why is seasonal snow important *societally*?

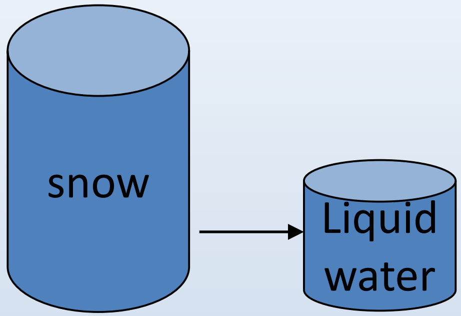
Four major societal impacts:

1. **water resources**
2. **natural hazards**
3. **water security**
4. **weather/climate**

These societal impacts express themselves at spatial scales that are local, regional, & global.

The temporal scales are often shorter than for science.

WANTED: Snow Water Equivalent



Snow Water Equivalent (SWE)

- melted height of a column of snow over a unit area

SWE = snow depth x density

- Can sense SWE directly, or
- Sense depth and estimate density to get SWE

Snow Covered Area (SCA)

- Binary snow mask
- Accurate products already exist

- Improving global SWE estimates is the main goal of a snow mission
- Some global SWE products already exist, but large uncertainties remain due to its inherently-variable nature, and confounding factors like forests & terrain
- SWE is consistently identified as a key variable needing improvement in an *integrated global measurement system,* which is the top priority of the Decadal Survey Water Panel
- How does SnowEx help?

SnowEx Guiding Questions

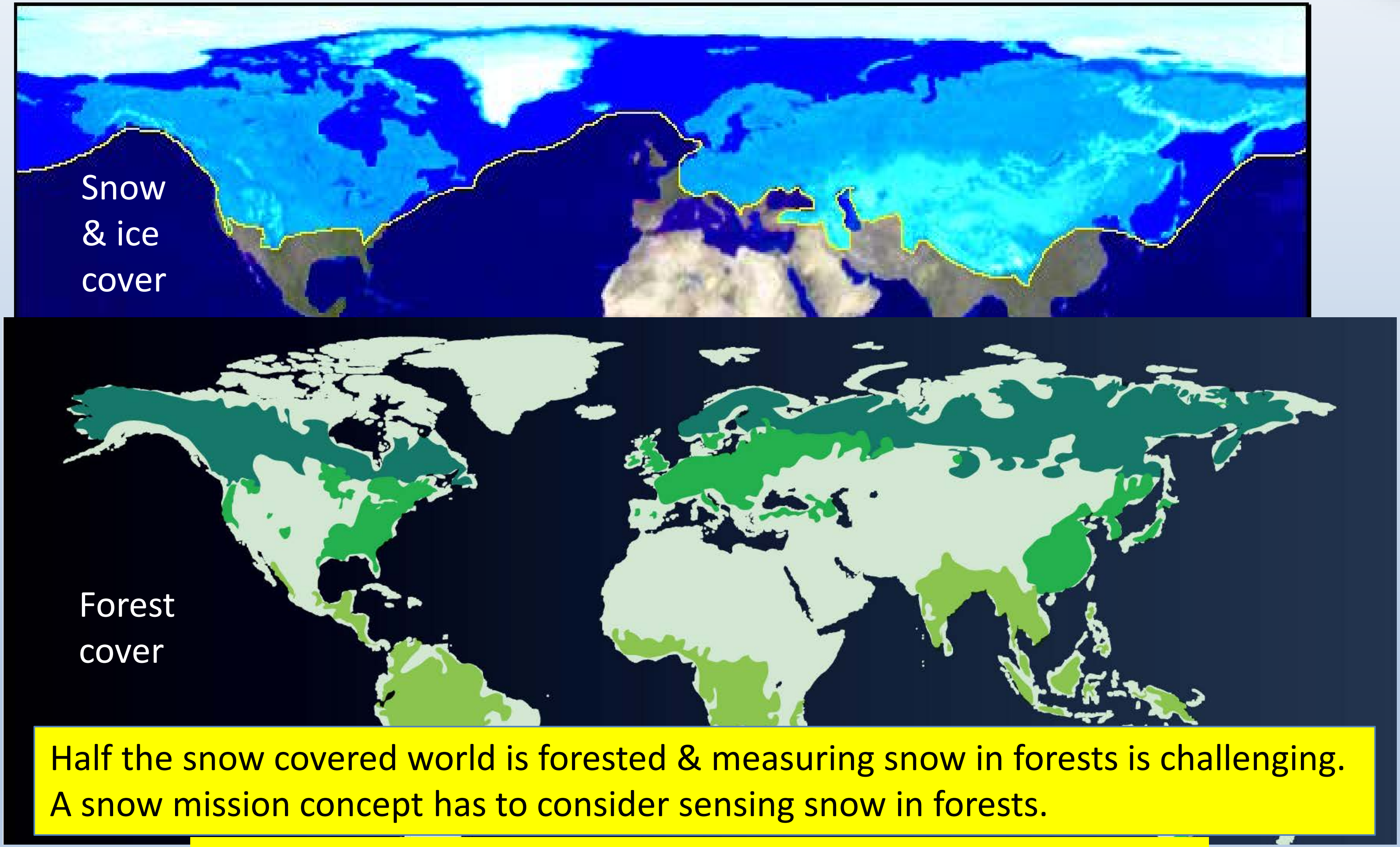
- **Overarching SnowEx/Snow Science Questions:**

How much water is stored in Earth's terrestrial snow-covered regions? And how & why is it changing?

- **SnowEx Year 1 Fundamental Questions**
  - **Q1 –** What is the distribution of snow-water equivalent (SWE), and the snow energy balance, in different canopy types and densities, and terrain?
  - **Q2** – What is the sensitivity and accuracy of different SWE sensing techniques for different canopy types, canopy density, and terrain?

- **Thus, SnowEx Year 1's focus was snow in forested areas**

The Forest Snow Issue



Half the snow covered world is forested & measuring snow in forests is challenging. A snow mission concept has to consider sensing snow in forests.

So far, lidar is the only technique proven to see through forests.

Sensing Techniques for Global Snow

- **Many sensing techniques are sensitive to snow variables**
  - SWE: passive microwave, SAR, InSAR, active-passive microwave
  - Snow depth: lidar, passive microwave, InSAR, Structure-from-Motion
  - SCA: VIS/IR, passive microwave, multispectral, hyperspectral
  - Albedo: VIS/IR, multispectral, hyperspectral

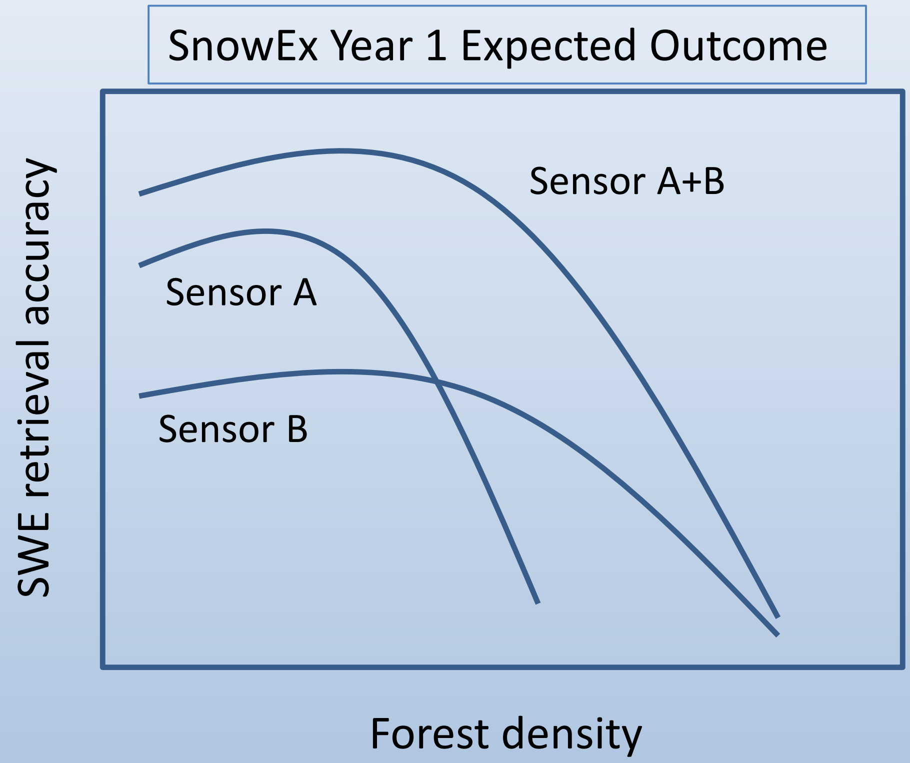
- **Each has strengths and issues when faced with the challenges of snow sensing**
  - Forests & vegetation
  - Wet snow
  - Complex terrain
  - Deep snow & shallow snow
  - Layering inside snowpacks
  - Clouds, atmospheric propagation
  - Needing density to convert depth to SWE
  - Dirty snow
  - Retrievals that need ancillary data on snow grain size, soil moisture, soil roughness, etc

Detailed list in backup

No single sensing technique works across all types of snow and confounding factors

Why SnowEx? and what we need from it

- Therefore, a global snow mission requires a multi-sensor approach
- Trade studies will be key to evaluate potential concepts
- The trade studies require multi-sensor field data (airborne + ground): SnowEx will provide
- The trade space should span the sensors, snow types, & confounding factors
- SnowEx Year 1 focused on one confounding factor: forests



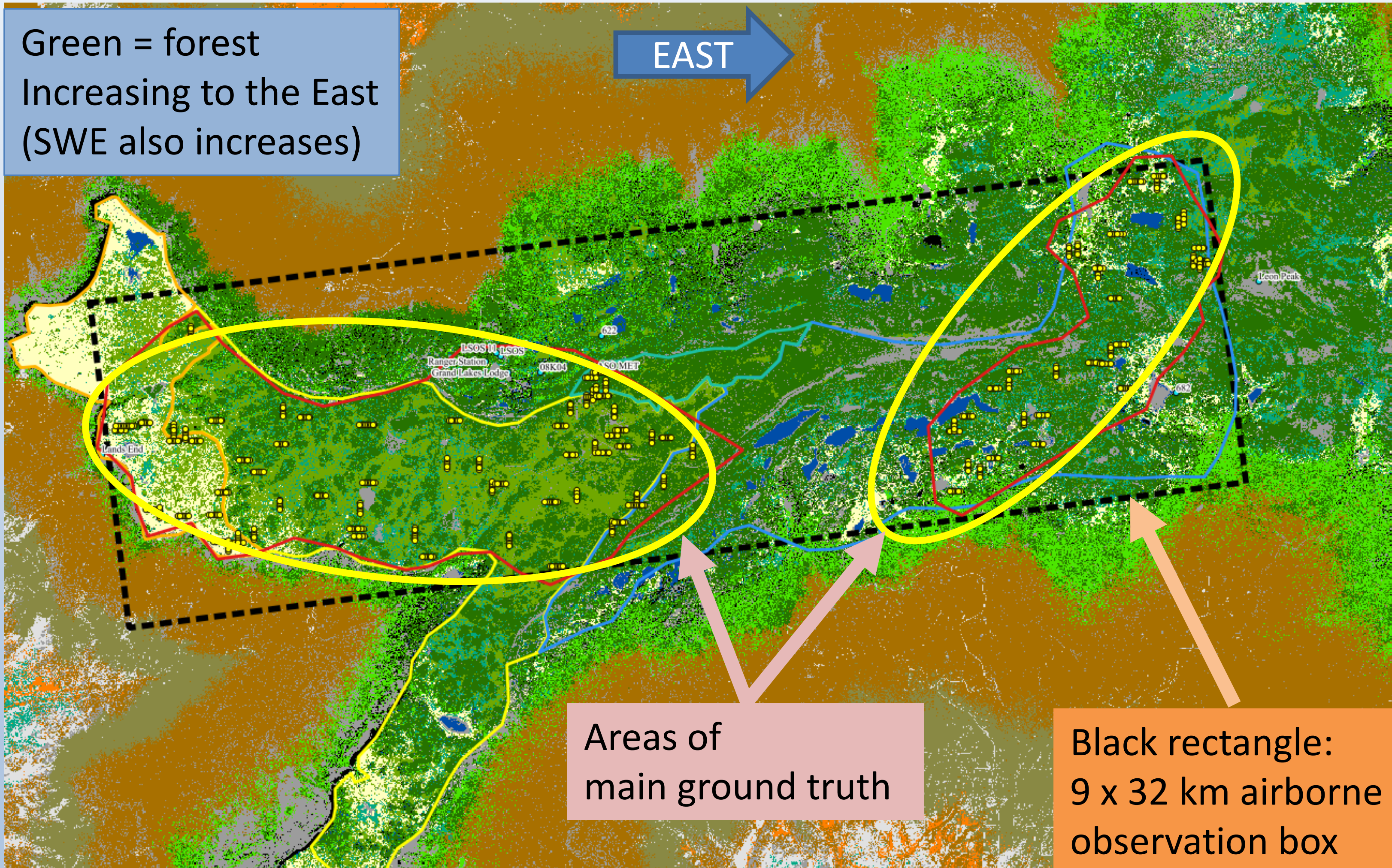
SnowEx is how we obtain input data for mission concept trade studies

Airborne
Remote Sensing

SnowEx Year 1 Location

SnowEx year 1 Location: Colorado, USA

Primary site: Grand Mesa, CO



Grand Mesa was an ideal site for the forest objectives of Year 1

Year 1 Airborne Sensors & Aircraft

CORE SENSORS

- **SnowSAR: X & Ku-band radar (ESA)**
- **CAR: BRDF & multispectral imager (GSFC)**
- **AESMIR (passive mw, from GSFC) 18 & 36 GHz (did not fly)**
- **Thermal IR/video suite**
  - **Imager (GSFC)**
  - **High-accuracy non-imaging (KT.15, from U.Washington)**
  - **Video camera (GSFC)**
- **ASO suite (JPL)**
  - **Lidar**
  - **Hyperspectral imager**

EXPERIMENTAL ALGORITHMS

- **UAVSAR: L-band InSAR (JPL)**
- **GLISTIN-A: Ka-band InSAR (JPL)**

Prototype sensor

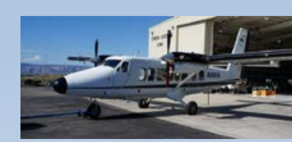
- WISM: active & passive microwave (Harris Corp IIP)

Aircraft
(flight days)

NRL P-3 (6)

King Air (5)

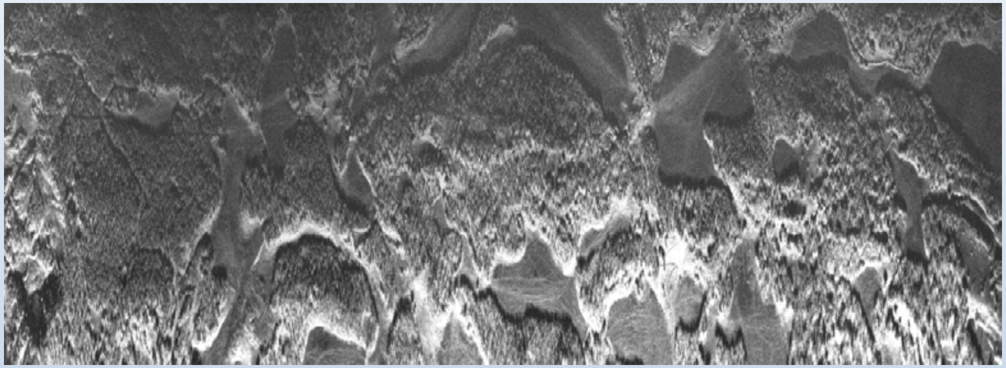
Two NASA G-IIIs (4,3)



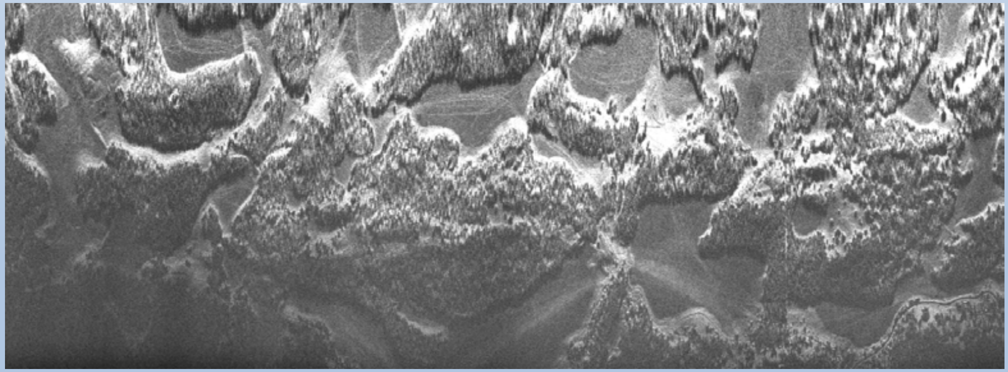
Twin Otter (3)

SnowSAR (X/Ku SAR)

- Core sensor: dual frequency SAR (X & Ku bands)
- Developed by ESA for CoReH20 effort; Operated by MetaSensing
- Multiple campaigns on different aircraft between 2011-2014
- First time installation on a P-3
- Best data set on 21st Feb
- Processing/calibration ongoing
- Pros: volume scattering retrieval, sensitive to SWE & melt, high res, topography OK, sees through clouds, no sun needed
- Questions: accuracy, saturation, wet snow, forest, vegetation, soil



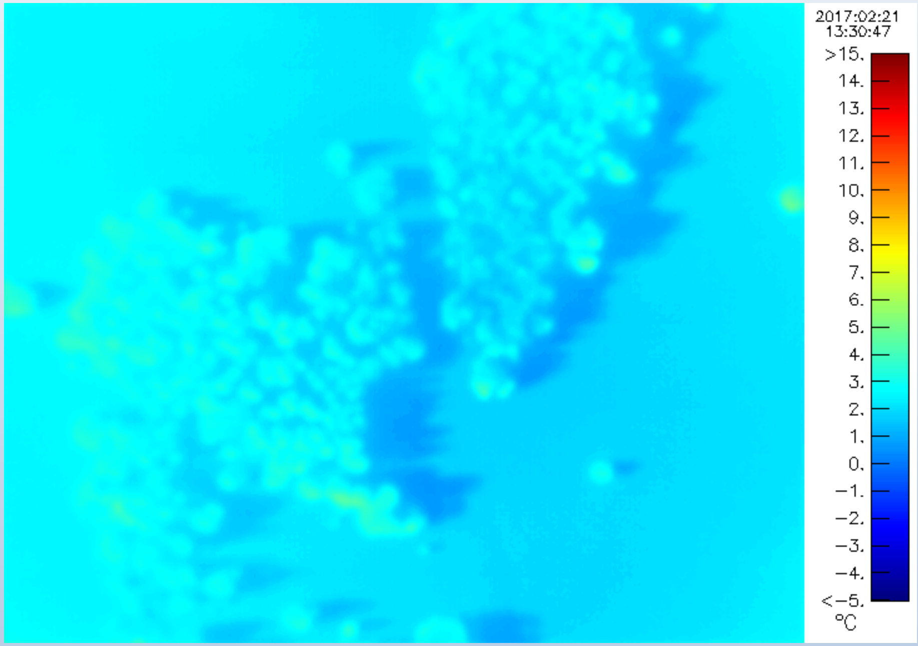
X-band



Ku-band

Thermal IR Sensor Suite

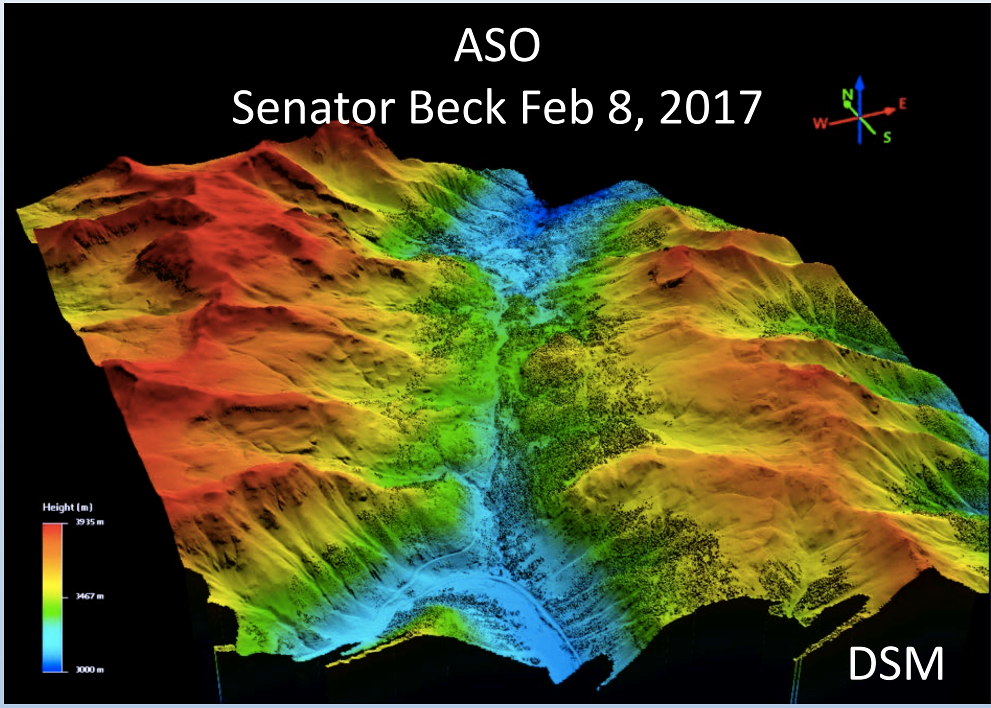
- Thermal IR Sensor Suite (IRSS) consists of two instruments and a camera
  - QWIP infrared imager (GSFC)
  - KT-15 infrared thermometer (U. Washington)
  - HD visual video camera
- IRSS Instruments were cross-calibrated with ground team field IR targets before deployment
- IRSS Instruments calibrated with handheld target before/after each flight



Example QWIP thermal IR image showing trees ~same temperature as snow in clearings [significant snow is intercepted by trees]. Shadow areas are much colder.
These data are critical for energy balance modeling studies.

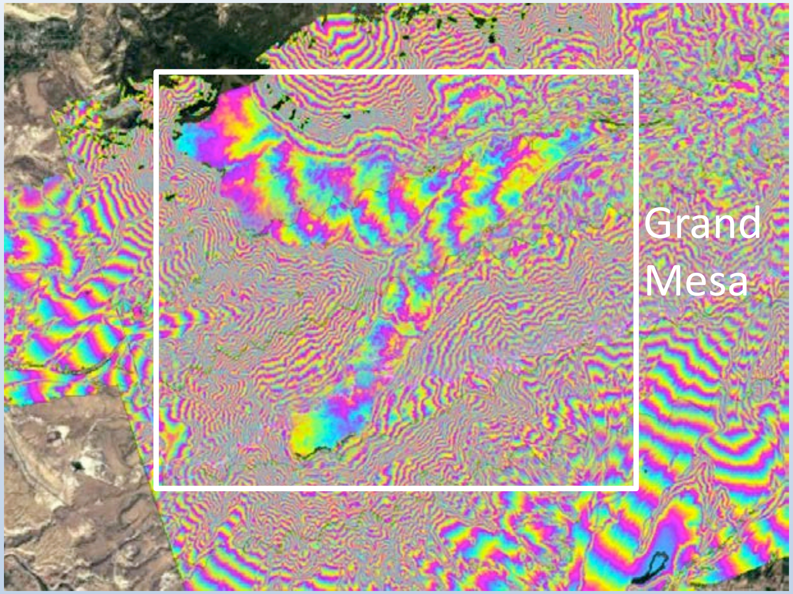
Lidar

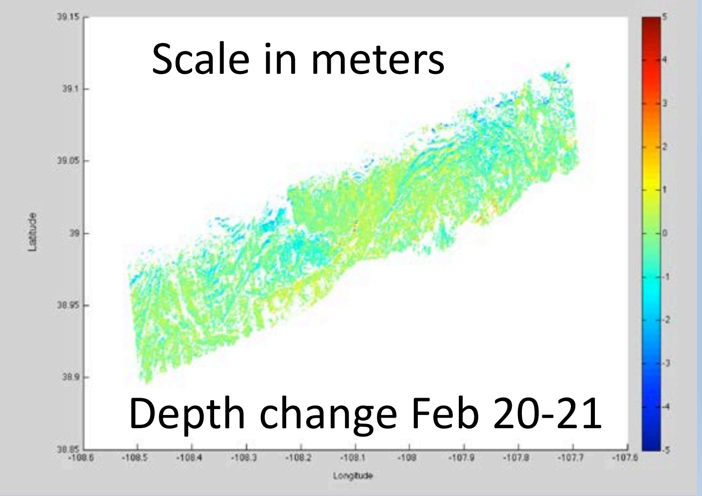
- Core sensor for SnowEx Year 1
- Fills spatial gaps in ground truth
- Airborne Snow Observatory (JPL)
- COTS sensor; mature installation
- Pros: high res, topography OK, wet snow OK, good forest penetration, wide swath (airborne), no sun needed, altimetry portion TRL 9
- Questions: requires density to get SWE (not TRL 9), snow depth resolution only ok for deep snow, clouds, swath width for spaceborne



GLISTIN-A (Ka-band InSAR)

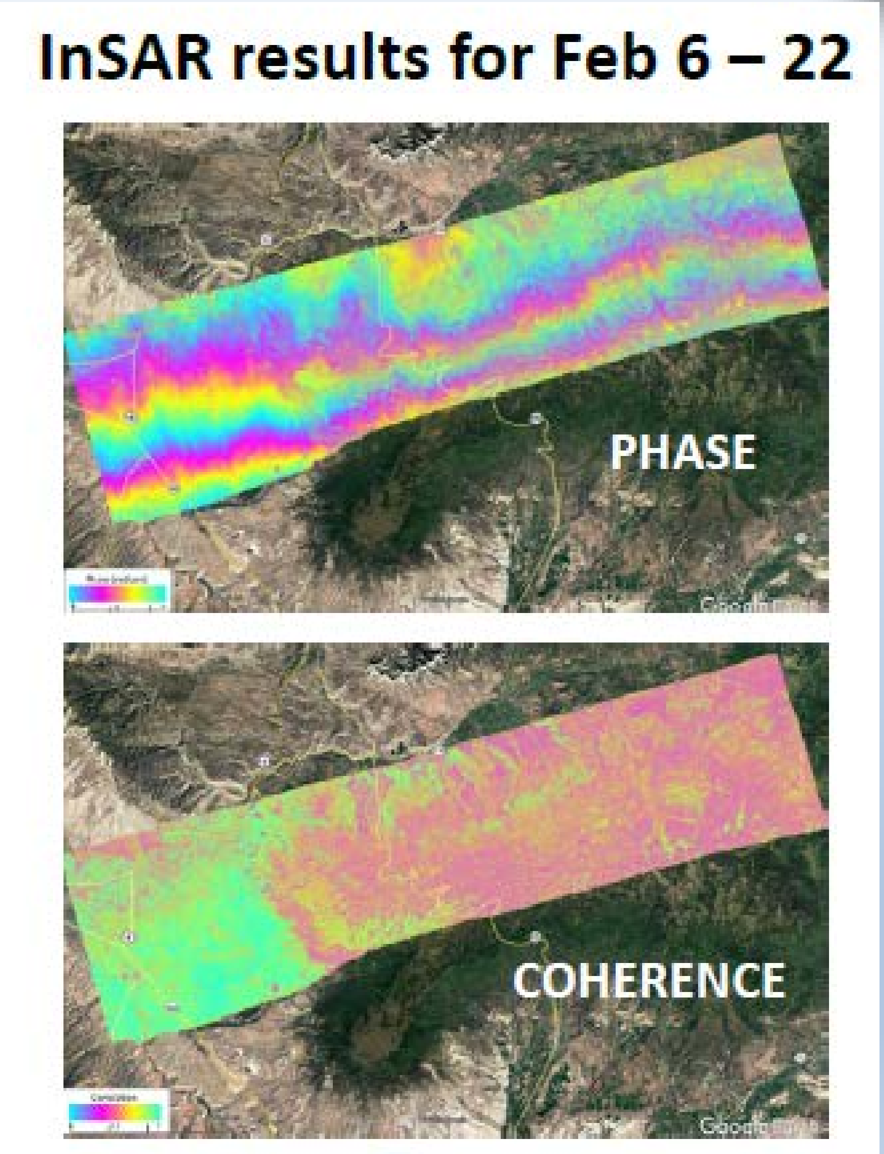
- Experimental technique
- Measures snow depth via InSAR altimetry
- Single-pass InSAR
- <u>Pros</u>: less cloud impact vs lidar, wet snow ok, topography OK
- <u>Questions</u>: penetration into snow, depth resolution, requires density to get SWE, accuracy, forest, vegetation, atmospheric correction, revisit timer, swath width, SWOT?





UAVSAR (L-band InSAR)

- Experimental technique
- Measures SWE via phase change
- repeat-pass InSAR
- <u>Pros</u>: little/no cloud impact; directly senses SWE, topography OK, sunlight not required
- <u>Questions</u>: accuracy, SWE range & precision, forest, vegetation, swath width, coherence & repeat interval, wet snow



Ground Truth

Ground Truth-the measurements

Snow depth – transcects

manual probes & MagnaProbes

Snow pits

depth

density

water equivalent

stratigraphy

grain type

grain size

snow temperature

surface roughness

snow wetness

soil temperature

soil moisture

Meteorology

5 stations - Grand Mesa

2 stations – Senator Beck

<u>Additional measurements:</u>

Snow penetrometer

Spectral reflectance

Snow casts

Soil bulk density

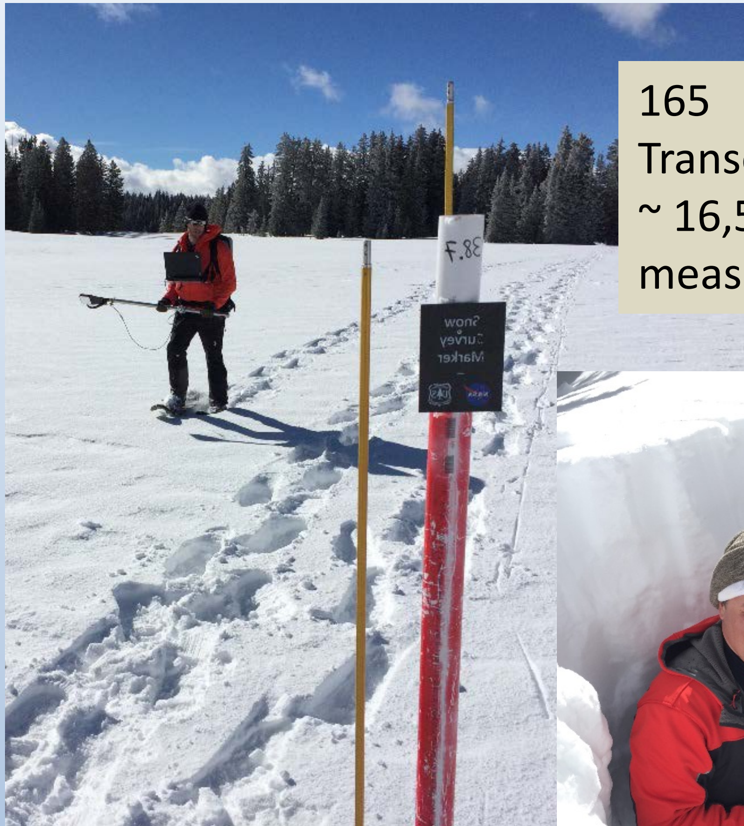
Veg biomass

Veg structure photos

Precip (solid + liquid)

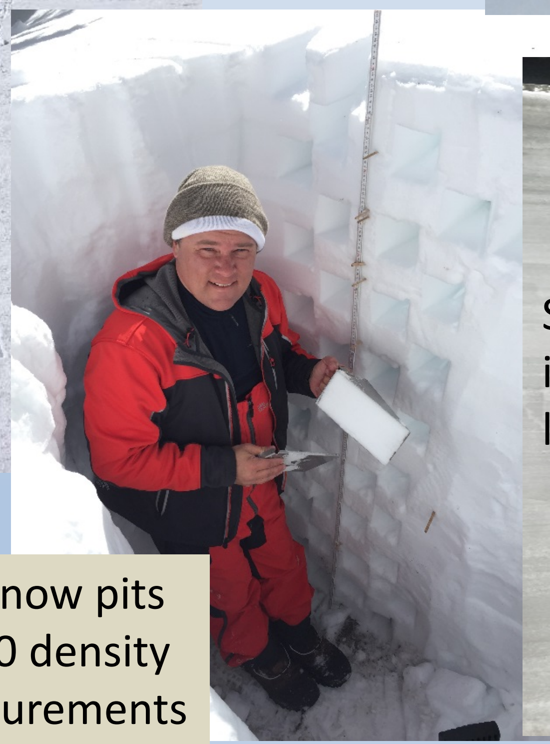
(not a complete list)

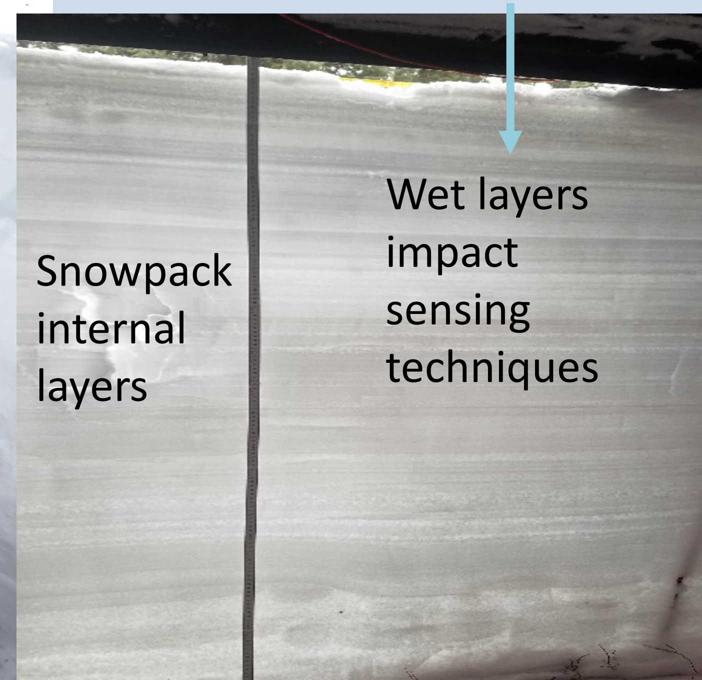
Ground Truth



165
Transects
~ 16,500 depth measurements

Unusually deep snow by Feb
And very warm → wet





Snowpack internal layers

Wet layers impact sensing techniques

3 weeks
40-50 people/wk
~100 people total

154 snow pits
~4500 density measurements

Ground Truth & Community Building


Community Training trench


Typical snow pit


Time lapse cameras


Mandatory safety training

Community building was a major component of Year 1

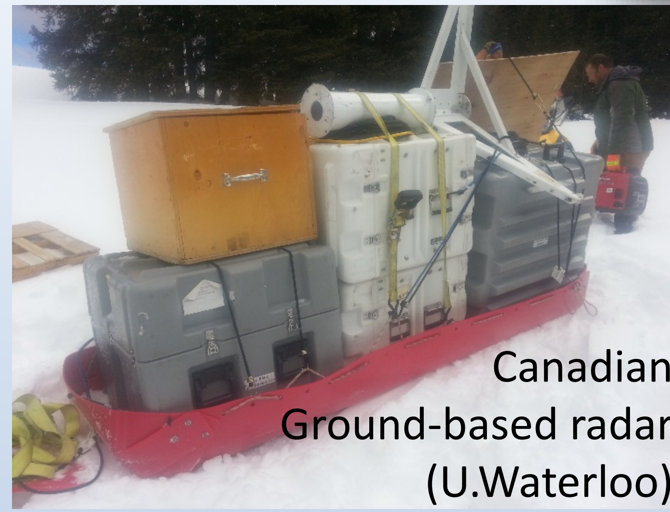
Ground Based Remote Sensing (GBRS)

Key part of Year 1 experiment design

- Similar sensors as on aircraft
- Other complementary sensors
  - more bands, different geometry, time series
- Enhanced ground truth
- Opportunities to test prototypes

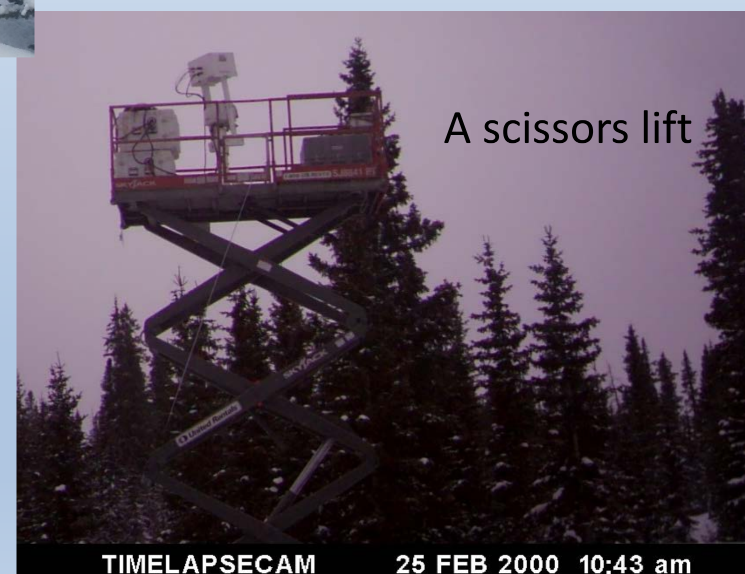
Ground-base remote sensors on…

A boom truck (U.Michigan)



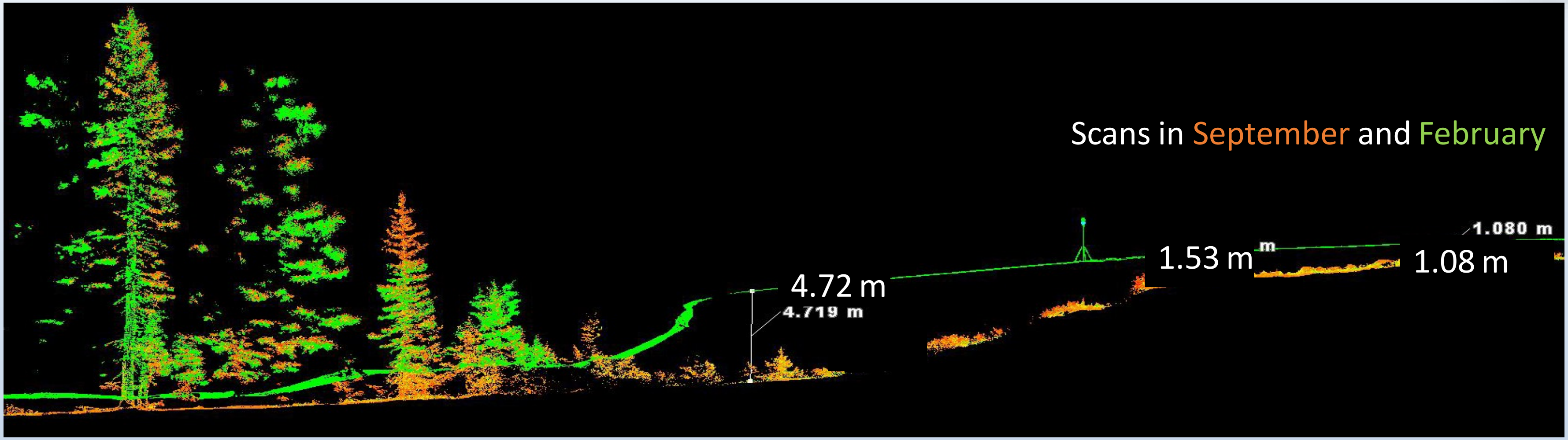
Canadian Ground-based radar (U.Waterloo)

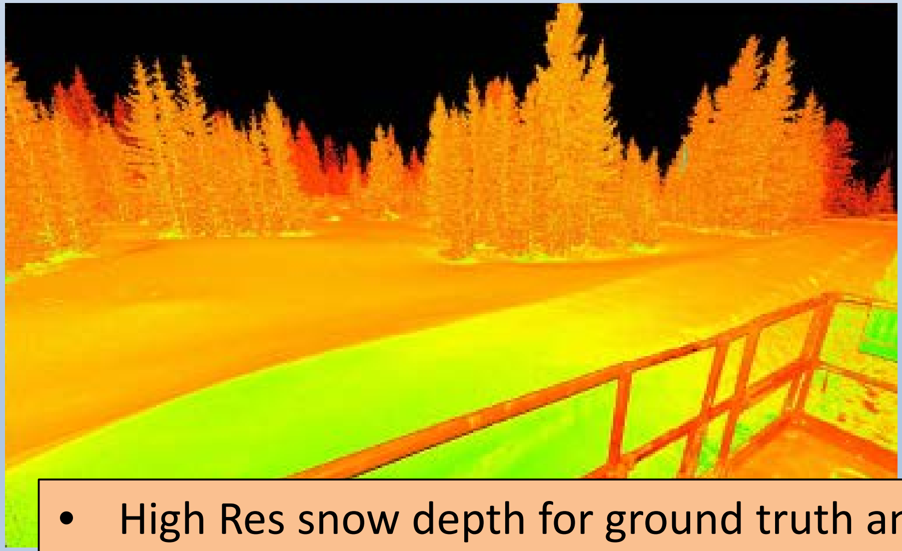
Sled towed by snowmobile (U. de Sherbrooke)

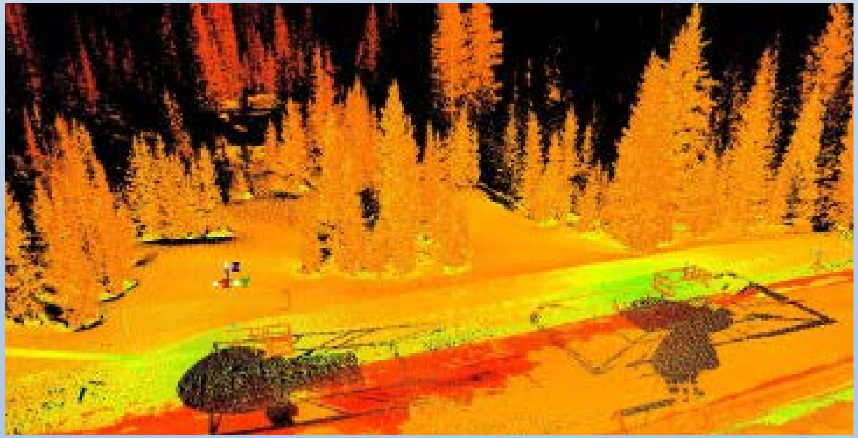


A scissors lift

GBRS Example: Terrestrial Lidar Systems





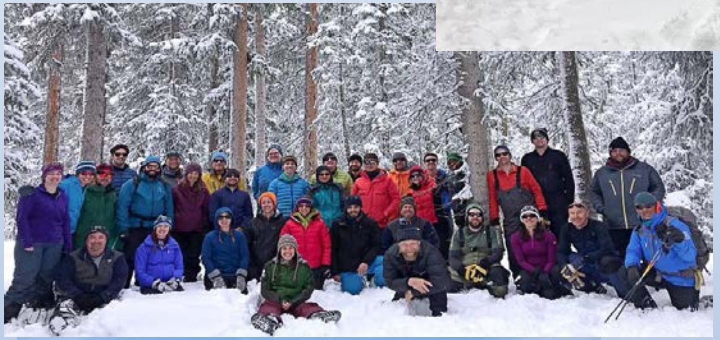


- High Res snow depth for ground truth and to answer process questions
- High Res geometry data to understand how remote sensing works in forests

Engaging the Snow Community

<u>The offer</u>:
folks who could commit a week of time were welcome to participate.

<u>The response:</u>
40-50 people x 3 weeks; total 100 participants (13 international)



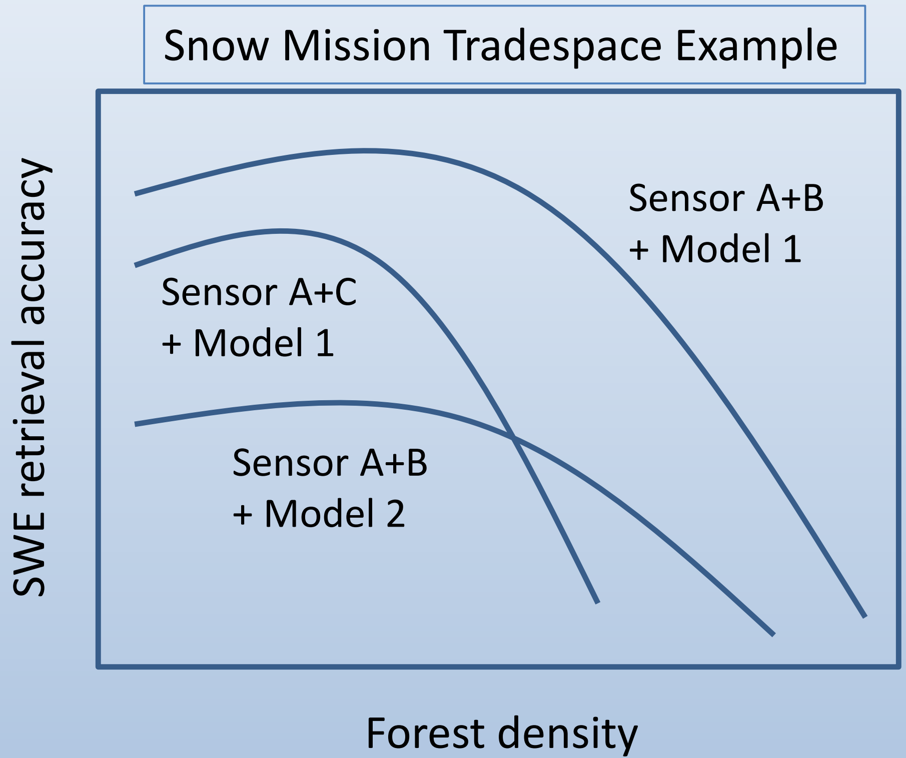
Modeling

&

Analysis

Role of Models in a Snow Mission

- Year 1 was designed to enable modeling & analysis
- Different combinations of sensors & models are available for
- Example: all high-res sensors have gaps between swaths
- Sensors-of-opportunity will come and go over the years
- Models are needed to fill gaps in space & time



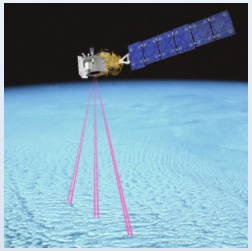
Again, trade studies will be key to evaluate potential combinations of observations + models. An international combination of sensors will be essential to a global snow mission.

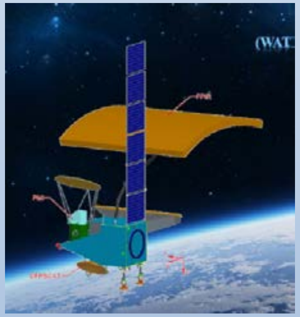
Key Trade Study Models/Tools

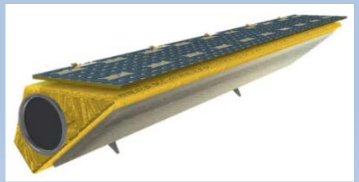
- Functional components:
  - "truth data" of snow
  - Land surface model(s) including snowpack
  - Sensor physics models
  - Satellite orbit models
  - Forward radiance models
  - SWE, depth, density, & SCA algorithms (assimilation, direct inversion, etc)
  - Evaluation tools
- OSSE (Observing System Simulation Experiment)
  - Computer model to test different mission design concepts, and to estimate their performance
  - Provides a consistent evaluation tool
- A trade study effort is underway using NASA Goddard's LIS land model + other tools

Future Snow-related Missions

- IceSat2 (NASA)
  - Global lidar, Polar orbit
- GEDI (NASA)
  - Lidar to fly on Int'l Space Station
- WCOM (China)
  - Designed for snow & soil moisture
  - active & passive microwave sensors
- EE10 snow proposal (ESA)
  - Dual-freq SAR (13, 17 GHz)
  - Active-passive retrieval w/Metop







Thoughts on a global snow mission

- Global SWE products already exist, but uncertainty is high in many regions, & current sensor mix is limited
- A broader suite of multiple sensors are required for global snow
- High resolution is desirable in some areas
  - Options: SAR & lidar, both have important limitations
  - Lidar is so far the only technique that sees through forests
- In addition, leverage existing/planned sensors
  - Passive VIS/IR from MODIS/VIIRS (for albedo)
- Cannot afford it all; international partnerships are required
  - Passive microwave from Japan's AMSR2/3, China's WCOM; Europe's METOP-SG MWI; scatterometers from WCOM; SAR from Europe's Sentinel/Copernicus
- Fill gaps in space & time with models
- Already-planned international missions plus launching 1 or 2 key missing sensors could give us a global multi-sensor snow mission

Summary

- Snow has enormous scientific and societal impacts
- The multi-sensor + model approach needed for a global snow mission requires careful trade studies
- The SnowEx campaigns are how we will collect data for those trade studies
- SnowEx Year 1 began this using forests to challenge multiple sensing techniques
  - 5 aircraft flew 9 sensors, plus 100 participants collected ground truth and >35 GBRS activities collected data at 2 sites in Colorado in February 2017
  - A unique legacy dataset was collected
- Future years of SnowEx will target science & mission concept gaps
- A global snow mission tradespace framework is being used to evaluate concept with different sensor + model combinations
- International partnerships will be essential for a snow mission

Resources

snow.nasa.gov

- NASA Terrestrial Hydrology Program Manager
  - Dr. Jared Entin, Jared.K.Entin@nasa.gov
- SnowEx year 1 organizing team contacts
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  - Dr. Charles Gatebe, charles.k.gatebe@nasa.gov
  - Dr. Do-Hyuk Kang, dk.kang@nasa.gov
- THP Snow Program Office Lead
  - Dr. Dorothy Hall, dorothy.k.hall@nasa.gov
- Int'l Snow Remote Sensing Working Group (ISWGR)
  - http://nasasnowremotesensing.gi.alaska.edu/

BACKUP

Sensing Techniques for Global Snow

Strengths:

- Lidar (altimetry): snow depth (can get SWE with density), precision OK for moderate to deep snow, very high res, forests OK, topography OK, wet snow OK, altimetry is TRL9 from space
- Ku-band SAR (volume scattering): senses SWE & melt, high res, topography OK, clouds OK, no sun needed
- L-band InSAR (phase change): senses SWE & melt, high res, topography OK, clouds OK, no sun needed, little atmospheric correction
- Ka-band InSAR (altimetry): senses depth (can get SWE with density), high res, topography OK, no sun needed, wet snow OK
- Passive microwave: senses SWE & melt, global daily coverage exists, clouds OK, no sun needed, very long record, TRL9 from space
- Multispectral: MODIS/VIIRS products exist, fSCA, albedo, grain size, moderate spatial res
- Hyperspectral: fSCA, albedo, surf grain size, mod/high spatial res
- Structure-from-Motion: extremely high res, multiple commercial satellites exist, moderate TRL

Sensing Techniques for Global Snow

Issues:

- Lidar (altimetry): clouds, depth precision not good for shallow snow, swath width (coverage), accuracy of density estimate to get SWE (not TRL 9), forests
- Ku-band SAR (volume scattering): algorithm maturity, coverage, saturation?, forests, needs ancillary data on soil, may need active-passive joint constraints, wet snow
- L-band InSAR (phase change): algorithm maturity, coverage, SWE range & precision, forest, vegetation, swath width, coherence & repeat interval, wet snow
- Ka-band InSAR (altimetry): algorithm maturity, coverage, atmospheric correction, penetration into snow, requires density to get SWE, accuracy, forest, vegetation, atmospheric correction, revisit time, swath width, SWOT?
- Passive microwave : resolution, saturation, forests, topography, future satellite gap
- Multispectral: needs sun, clouds, forests, surface only, moderate res
- Hyperspectral: needs sun, clouds, forests, surface only
- Structure-from-Motion: coverage, clouds, needs sun