NASA's Experiences with Microwave Radiometers from Ground to Space

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NASA Goddard Space Flight Center
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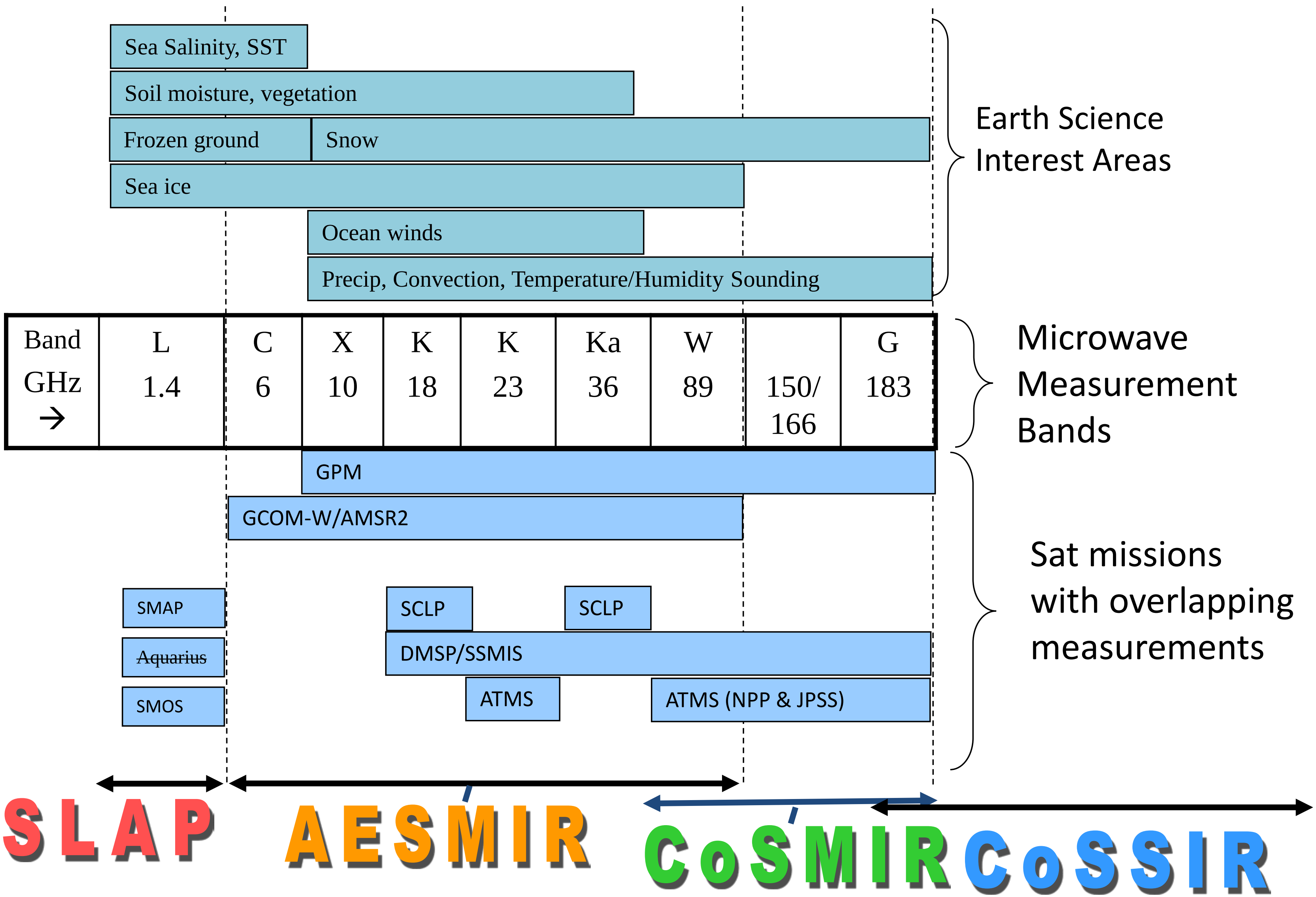
NIMS seminar
Jeju, Korea

Introduction/Outline

- NASA Goddard
- Satellite radiometer example
- Ground-based radiometer example
- Airborne radiometer example
- Field campaign example
- Conclusion

E.Kim 9/15/15

NASA/GSFC Passive Microwave Imaging Capabilities 1-600 GHz



Satellite

- **ATMS 23-183 GHz**
- **SMAP 1.4 GHz**
- **SMOS 1.4 GHz**
- **AMSR2 6-89 GHz**

Outline

- ATMS background
- Pre-launch (TVAC) testing
- Post-launch (commissioning) activities
- Conclusions & future activities
- 1st light image

ATMS timeline

Earliest spaceborne microwave sounders

- Mariner 2 – Venus
- Cosmos 243/384 -- sounding + imaging (USSR)
- 1972/75 – NEMS/SCAMS sounders on Nimbus 5/6 conceived here on MIT campus (Staelin/Rosenkranz), earliest US Earth sounders
- …(skipping several generations of sounders)…
- 1990s— ATMS conceived as replacement for AMSU-A/B, MHS

1st ATMS

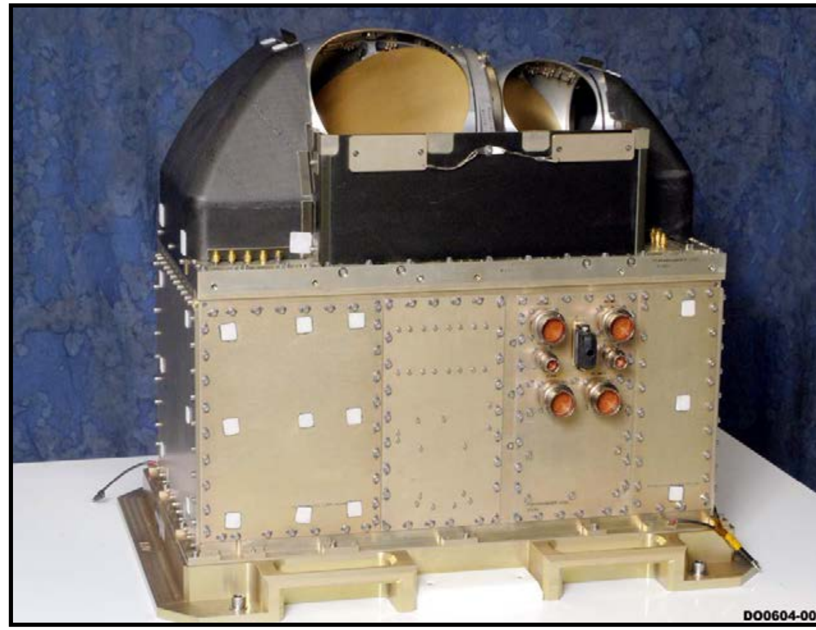
- 2011 October-- 1st ATMS launched on S-NPP (still operating)

2ND ATMS

- 2017 February – pre-launch calibration (*instrument* TVAC)
- 2017 April-May – JPSS-1 *satellite* TVAC
- 2017 Nov 18 – JPSS-1/NOAA-20 Satellite Launch
- 2017 Nov–2018 Feb – post-launch commissioning
- 2018 March 7 – NOAA-20 Handover from NASA to NOAA

ATMS at a glance

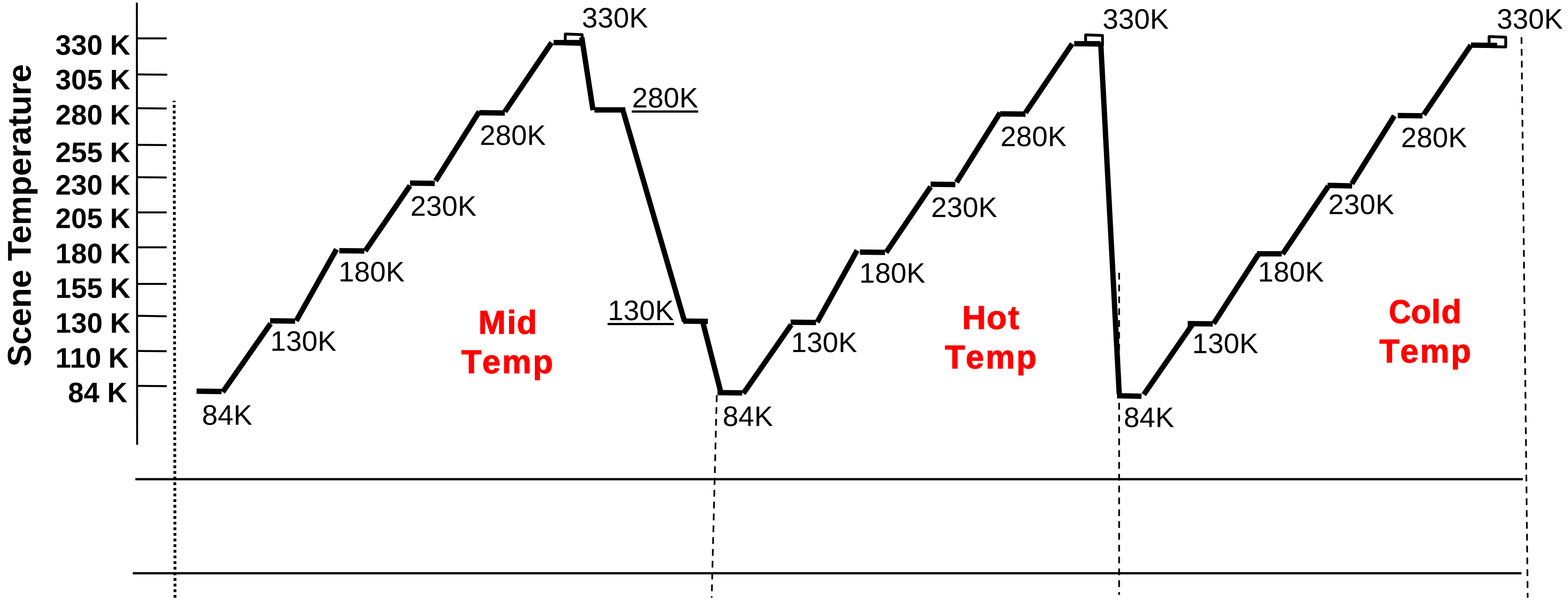
- 22 channel microwave sounder
- Frequencies range from 23-183 GHz
- Total-power, two-point external calibration
- Continuous cross-track scanning, with torque & momentum compensation
- Orbits: 824 km; sun-synch 1330 LTAN
- Thermal control by spacecraft cold plate
- Contractor: Northrop Grumman
- New US operational sounder series
- Sounders provide highest-impact observations for NWP models



Northrop Grumman

Pre-Launch Cal

- Performed at 3 instrument physical temperatures
- Spans range of possible on-orbit conditions
- 6 scene TBs each
- Measured in thermal vacuum chamber
- Primarily to measure non-linearity before launch
- Repeatability is also checked pre-launch



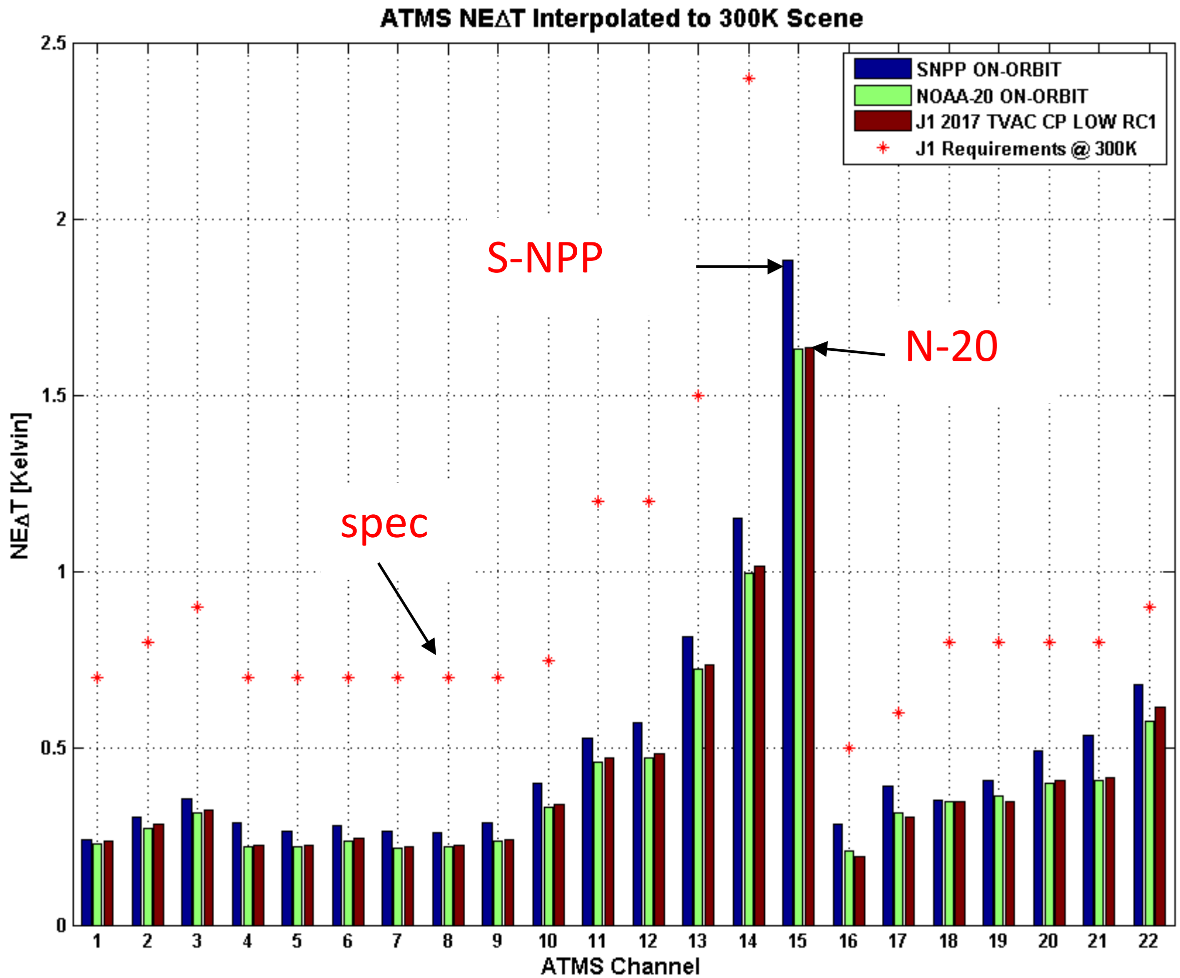
Commissioning Activities

Post-launch first 90 days (Nov 2017-Feb 2018)

- Sensitivity (NEDT)
- Noise power spectrum
- Antenna pattern/sidelobe characterization
- Scan angle bias (flat field) determination
- Reflector emissivity determination
- Ka-band RFI check
- Cold cal position selection
- Lunar intrusion mitigation
- Dynamic range
- Pointing/geolocation

ATMS Sensitivity (NEDT)

Comparison of J1 Pre-Launch, NOAA-20 on-orbit, SNPP on-orbit

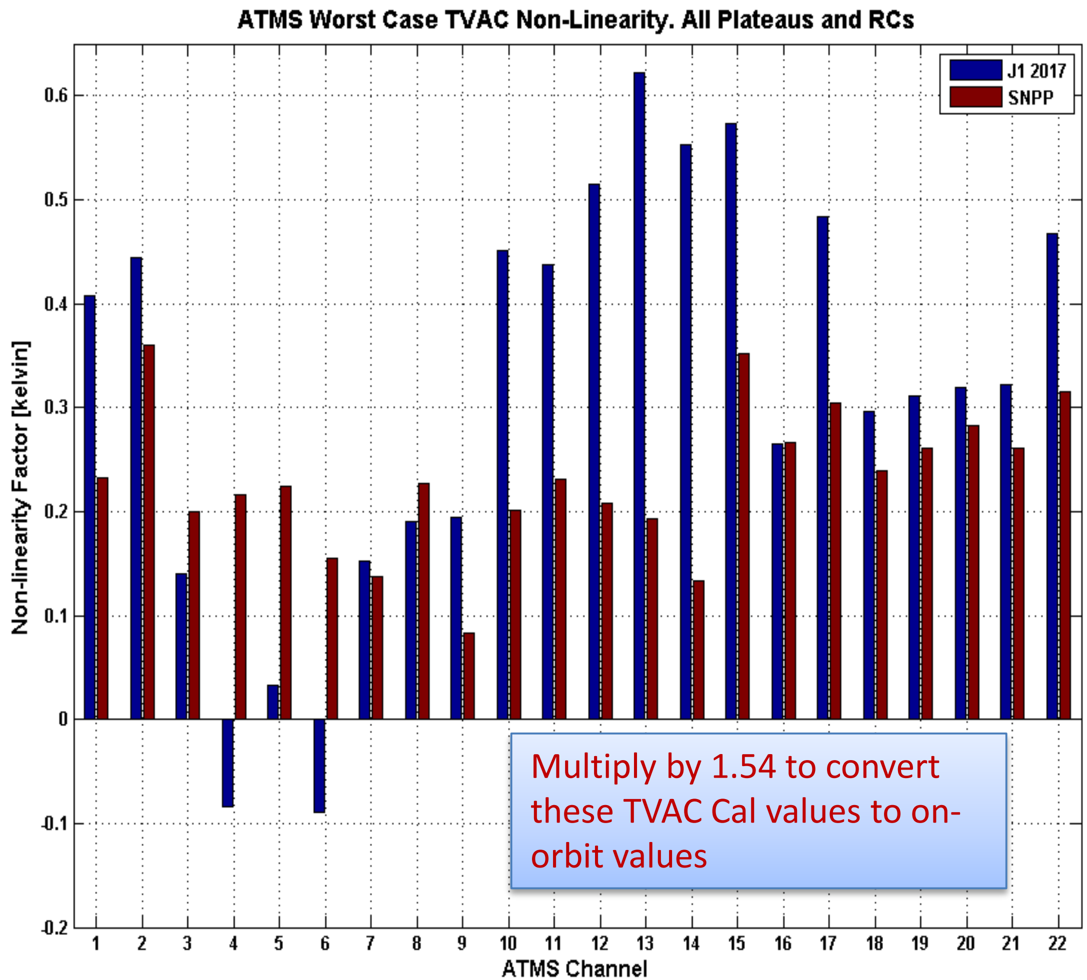


V. Leslie &
I.Osaretin,
MIT LL

N-20 NEDT on-orbit ~ same as pre-launch and better than S-NPP

Non-Linearity

- **Cannot measure on-orbit, so must measure pre-launch in TVAC**
- **13 channels show larger worst-case nonlinearity than S-NPP**
- **4 channels are about the same, 5 channels show smaller nonlinearity**
- **There is a nonlinearity correction in the ATMS TDR algorithm, so this does not affect performance of the SDRs directly**
- **But NWP models use TDRs, so residual NL is important**

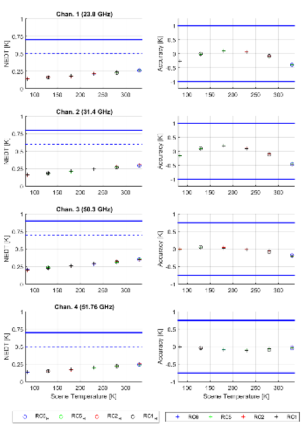


I.Osaretin, MIT LL

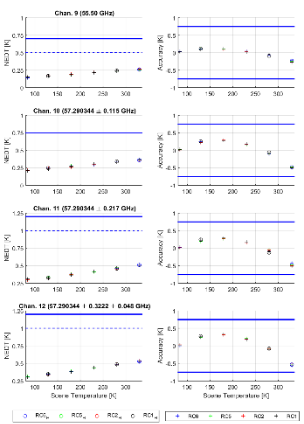
Repeatability (Hysteresis)

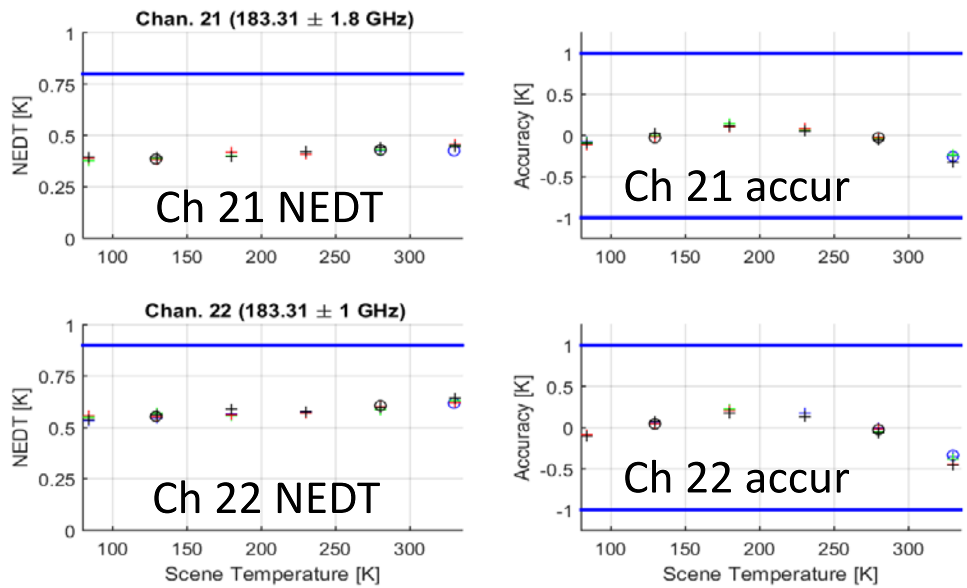
Repeated measurements (o's) are consistent with the initial measurements (+'s)

Ch 1-4

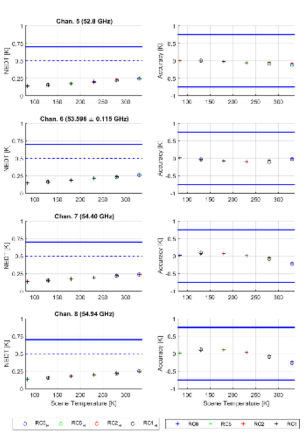


Ch 9-12

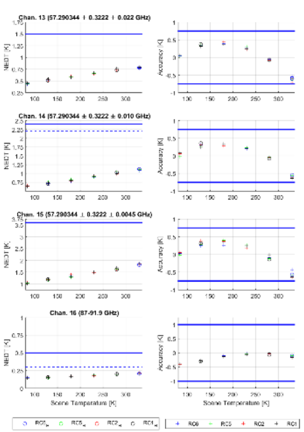




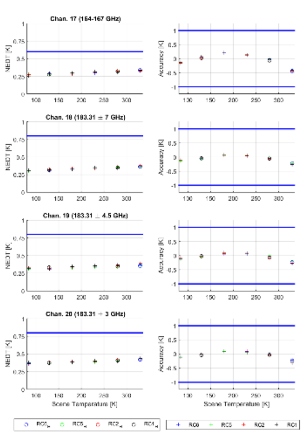
Ch 5-8



Ch 13-16



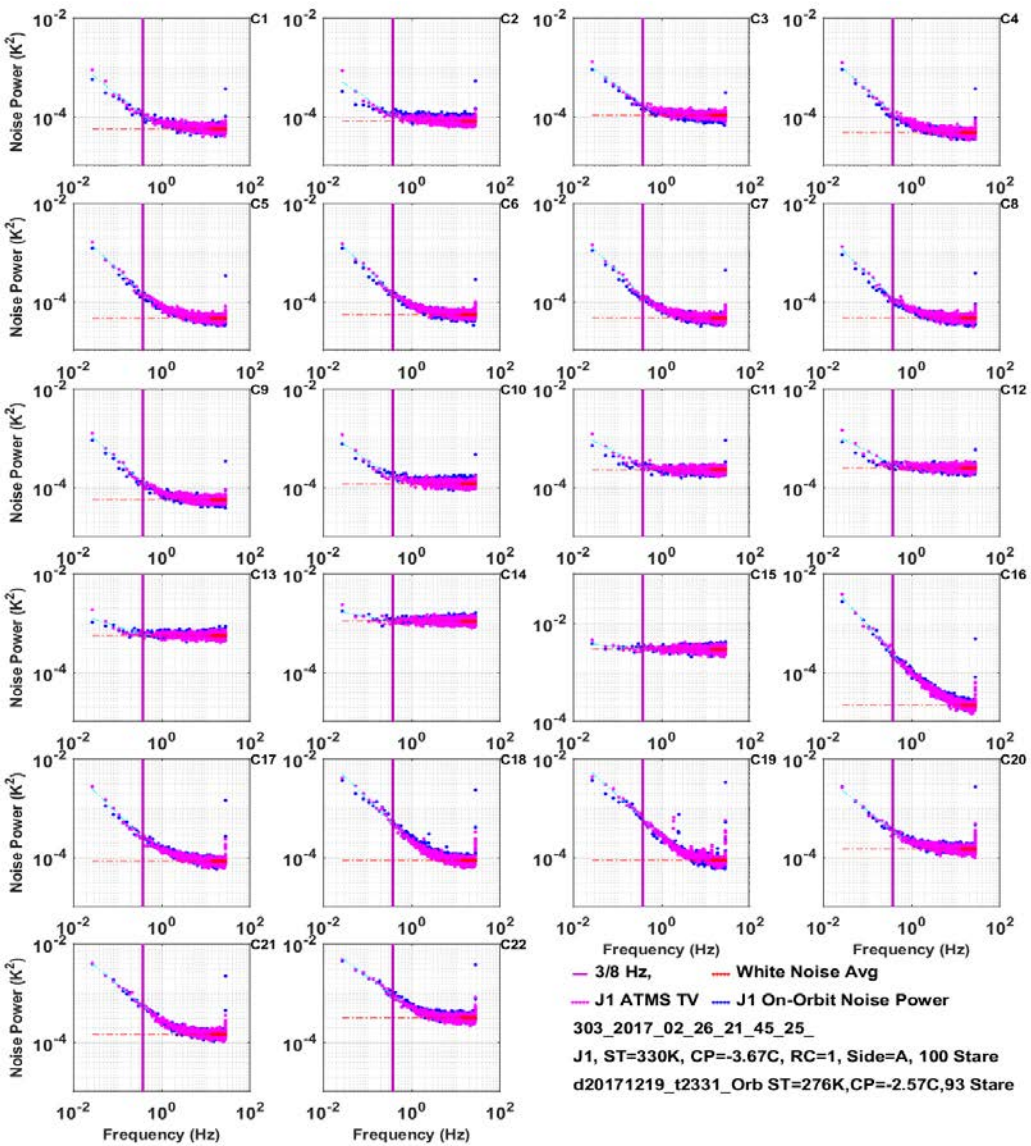
Ch 17-20



CP_Mid Hysteresis Test for 330K RC6, 130 and 280K RC1

C.Smith/ NASA GSFC

NOAA-20 TVAC versus On-Orbit Noise Power Spectra

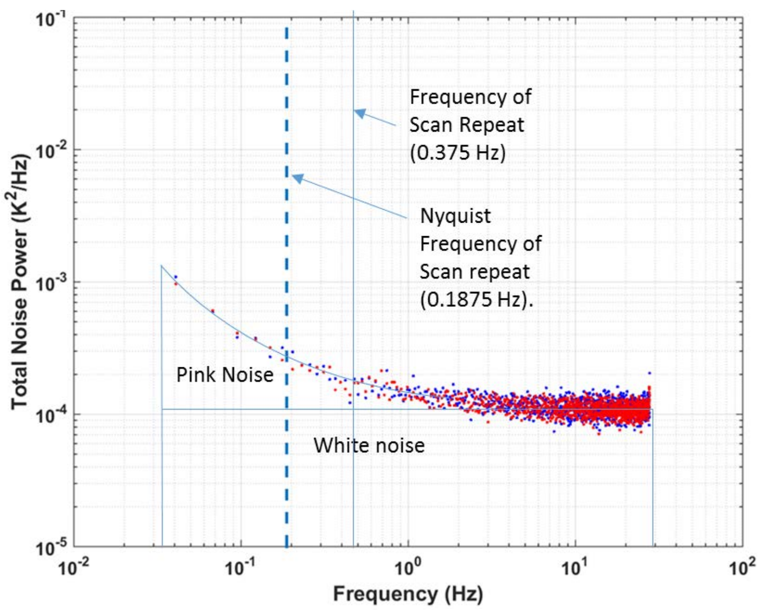


Very good agreement between Noise Power Spectra derived from very long stares at (red) TVAC scene target (330K) and (blue) On-Orbit Hot Calibration Target (276K).

J.Lyu/ NASA GSFC

Noise Power Spectra and Gain Stability ($\Delta G/G$)

- Is a measure of the excess over white noise (the “1/f” noise) that dominates the low frequency noise, and makes the “along-track” (scan to scan) NEDT larger than the “along-scan” (short term) NEDT
  - Finite $\Delta G/G$ leads to the “striping” (small scan-to-scan offsets) seen in global brightness temperature images
  - The mechanism is the long time period (relative to the single obs integration time) between cold space (ICT) observations (1 scan period, i.e. 8/3 seconds)
  - And that up to 8 scans of cold space and ICT observations are averaged before using them to calibrate the scene measurements
- This is the $\Delta G/G$ that goes into the NEDT equation



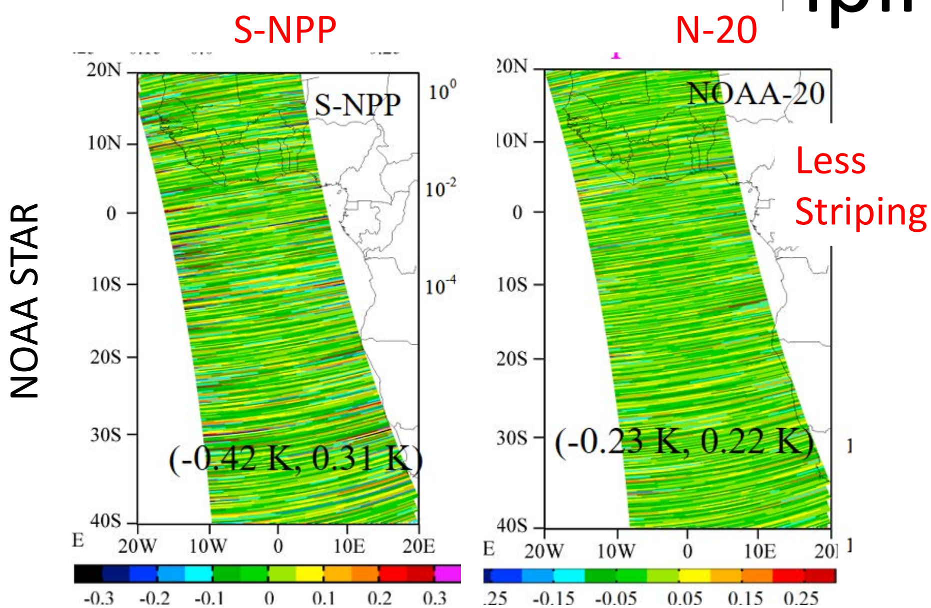
$$NEDT = \sqrt{T_{sys}^2\left(\frac{1}{B\tau_{int}} + \left(\frac{\Delta G}{G}\right)^2\right) + \Delta T_{video}^2 + \cdots}$$

$$T_{pink} = \sqrt{T_{total}^2 - T_{white}^2}$$

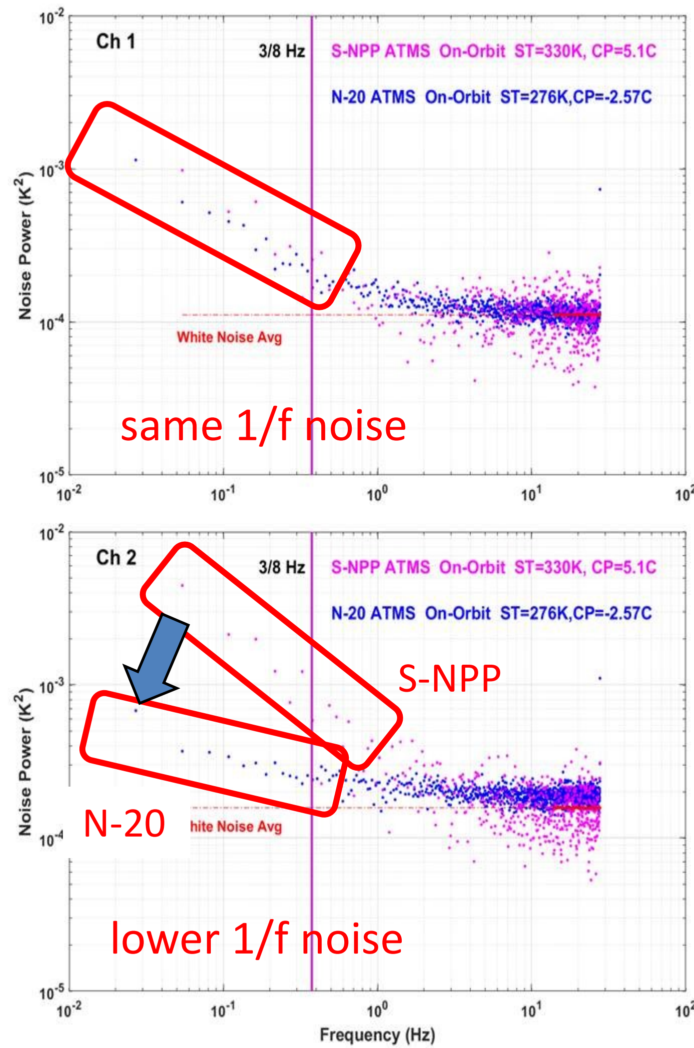
$$\frac{\Delta G}{G} = \frac{T_{pink}}{T_{sys}}$$

C.Smith/ NASA GSFC

"Striping"



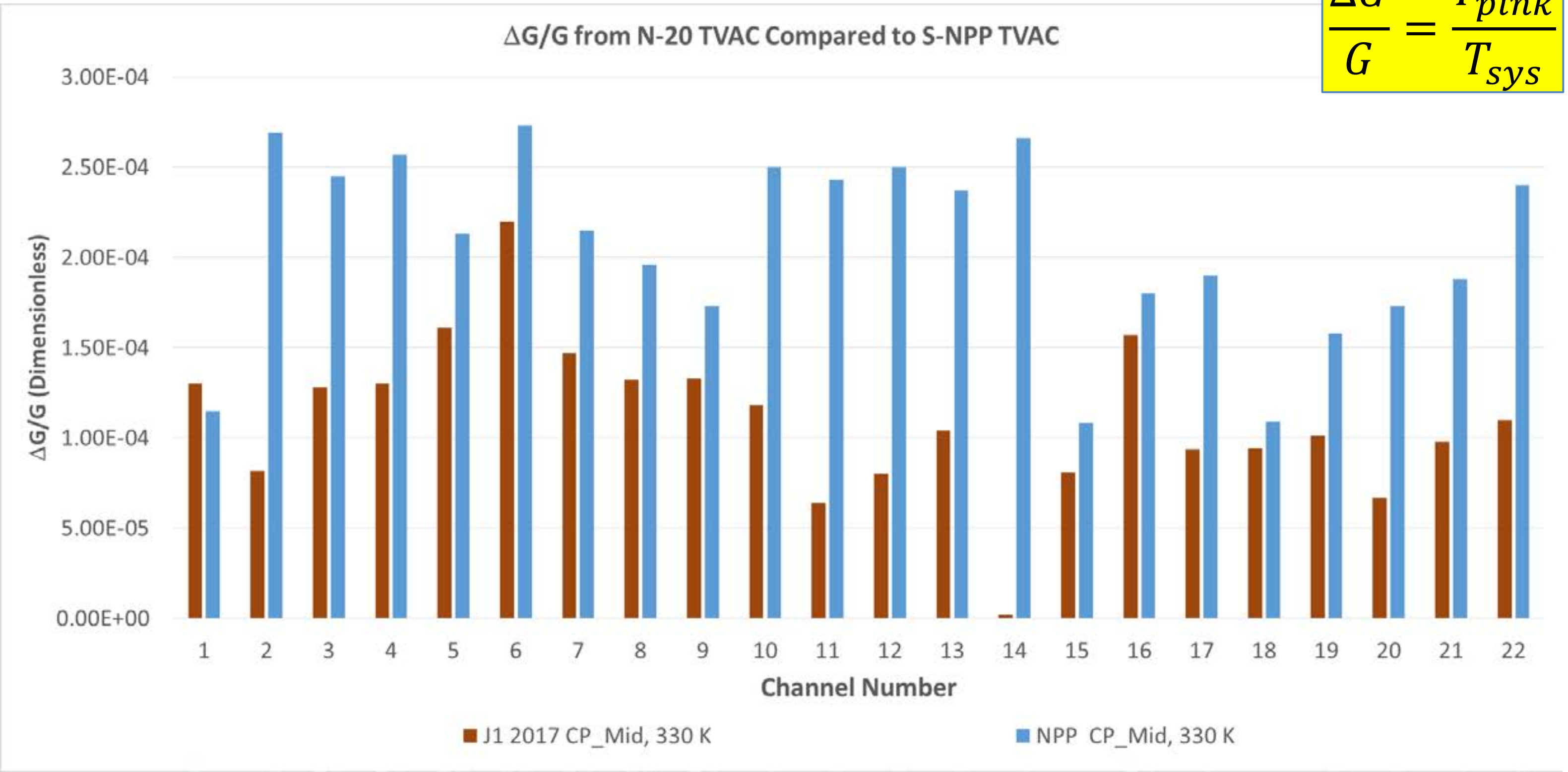
- On-orbit noise power spectra match well with Instrument TVAC results
- N-20 ATMS same or better for most channels compared to S-NPP ATMS
- Channels with < 1/f noise will have less striping



J.Lyu/ NASA GSFC

S-NPP vs N-20 ΔG/G

$$\frac{\Delta G}{G} = \frac{T_{pink}}{T_{sys}}$$



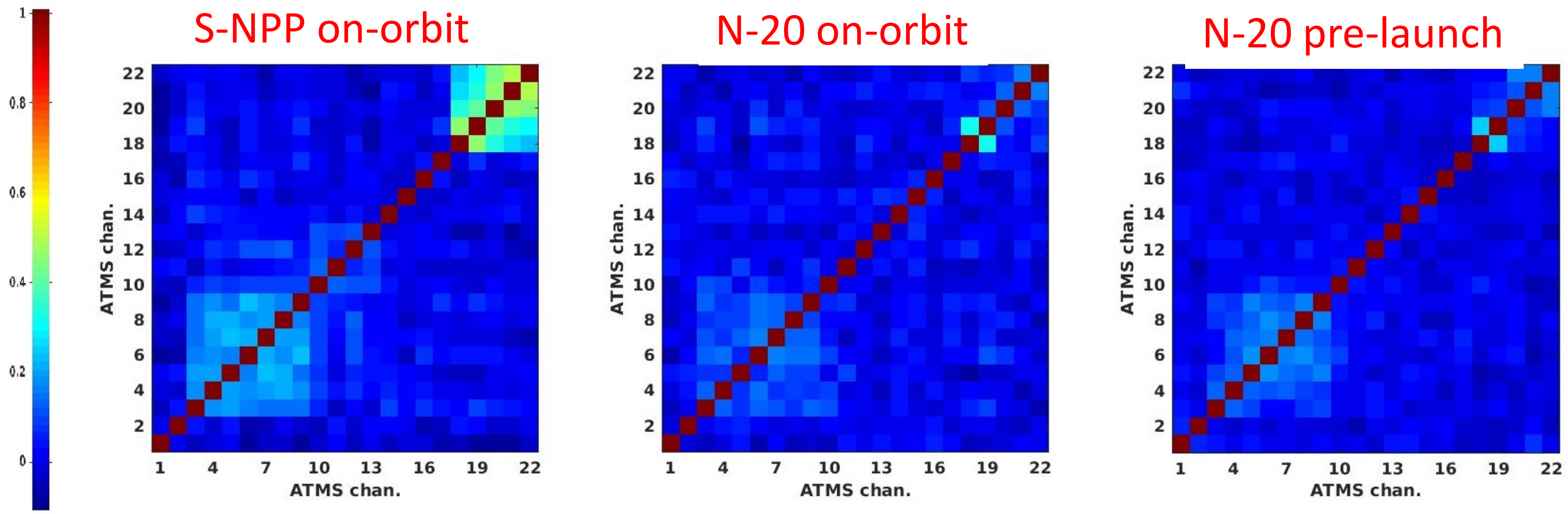
2017 TVAC CP_Mid from both N-20 and SNPP

J.Lyu/C.Smith/ NASA GSFC

N-20 ΔG/G significantly smaller than S-NPP for 19 channels
➔ significantly reduced striping for N-20 (shown on next slide).

ATMS Inter-Channel Correlation

Comparison of J1 Pre-Launch, NOAA-20 on-orbit, SNPP on-orbit

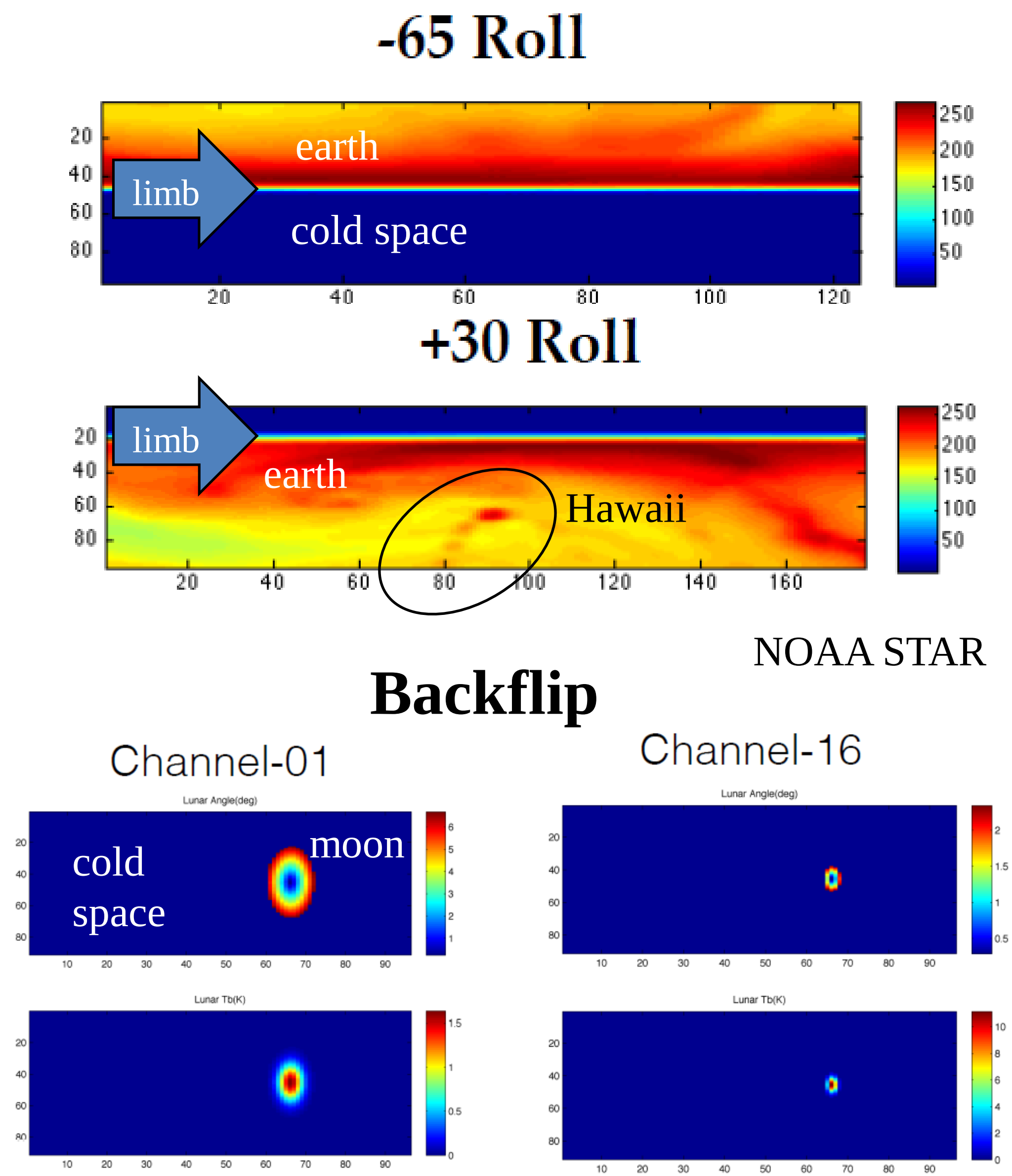


V. Leslie & I.Osaretin, MIT LL

N-20 Noise Correlation <u>Much Better</u> than S-NPP for all Channels

NOAA-20 Maneuvers

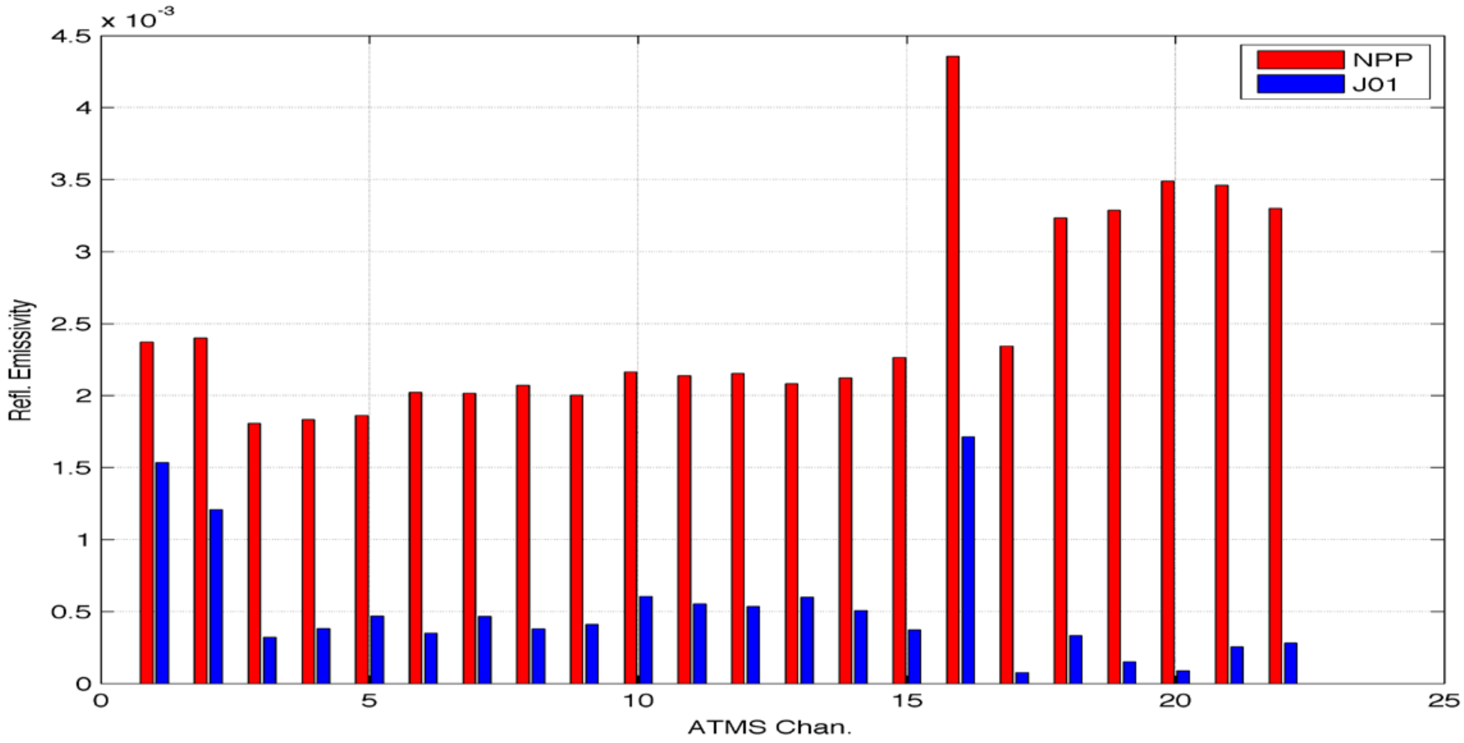
- **Rolls -65deg & +30deg**
  - Antenna pattern/sidelobe check
- **Backflip Maneuver**
  - Antenna pattern/sidelobe check
  - Sidelobe contamination characterized
  - Scan Bias (flat field) determined
  - Reflector Emissivity much better than SNPP
  - Minor lunar intrusion; no significant impact



Maneuver results good

NOAA-20 ATMS Antenna Reflector Emissivity

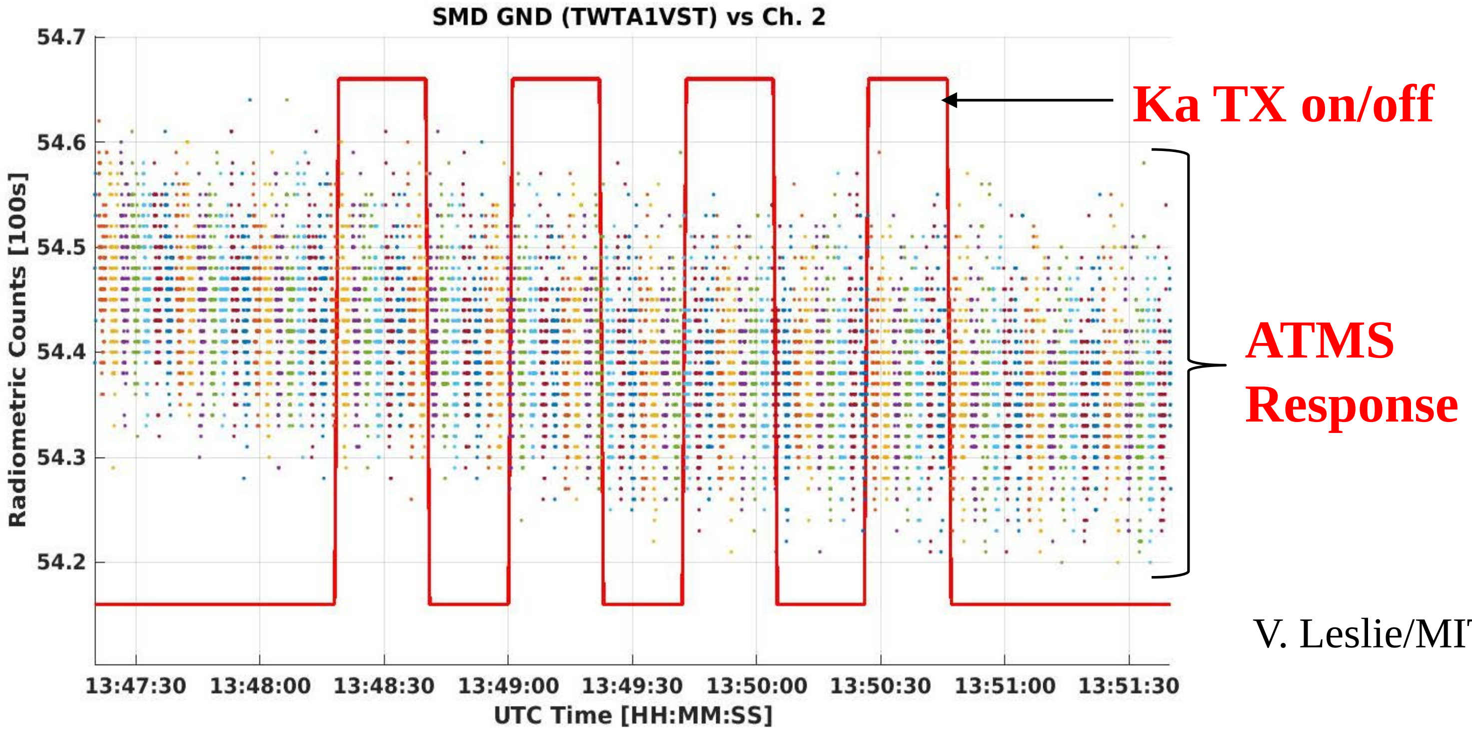
Results show that the NOAA-20 ATMS reflector has much low emissivity than S-NPP



H.Yang
NOAA
STAR

Yang, H., Weng, F. and Anderson, K., 2016. Estimation of ATMS antenna emission from cold space observations. IEEE Transactions on Geoscience and Remote Sensing, 54(8), pp.4479-4487.

NOAA-20 ATMS Ka-band RFI Test



V. Leslie/MIT LL

- NEW on N-20 satellite: Ka-band transmitters
- Qualitative check: No obvious sign of RFI from Ka transmitters so far
- Quantitative check to follow

No obvious sign of RFI from Ka transmitters so far

ATMS Conclusions

- NOAA-20 ATMS working well since activation
- NOAA-20 ATMS post-launch performance is comparable to pre-launch performance
- ATMS commissioning successful
- NOAA-20 ATMS compares well to S-NPP ATMS
  - NEΔTs stable since activation and slightly better than S-NPP
  - Inter-channel noise correlation much lower than S-NPP
  - No Ka-band transmitter RFI so far
- Characterizations nominal, and in some cases much better than S-NPP

- JPSS-2 ATMS is under construction
- SI traceable absolute TB calibration being explored (D.Houtz poster)

NOAA-20 ATMS checked out well & now operational

NOAA-20 ATMS First Light Image

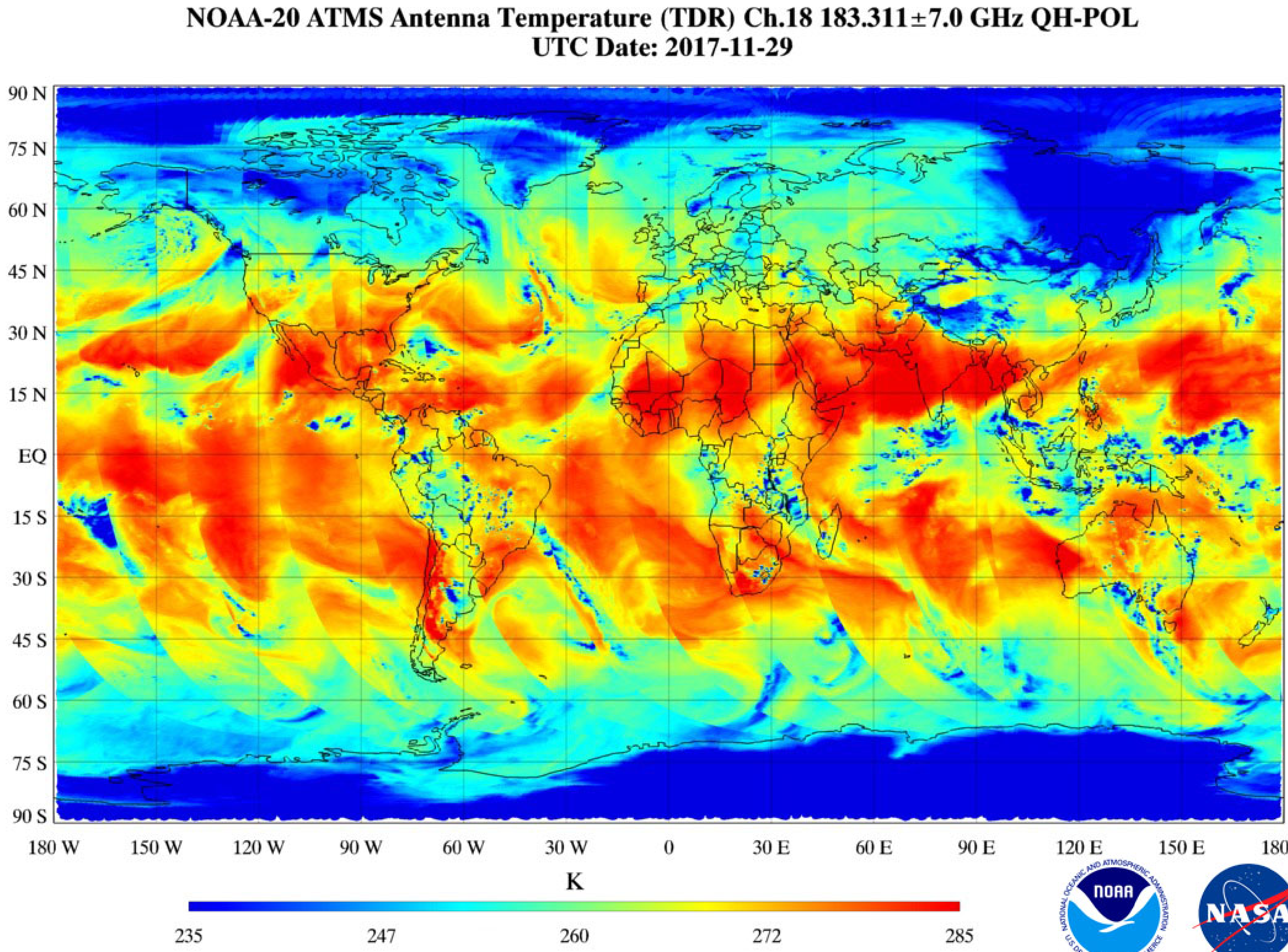


Image from NOAA STAR

Ground-based

- Looking up (atmosphere)
  - SMIR
- Looking down (soil moisture)
  - TMRS2
  - LRAD

Up-looking MW sounder

- SMiR = Scanning Microwave Radiometer
- 50, 90, 183 GHz
- Very similar to Radiometrics ‘mailbox’ radiometer
- Ground-based, aimed up
- Mechanical tilting
- Ambient & LN2 external calibration
- First deployed ~1999, still in use

Ground-based SSM/I simulator ‘TMRS2’

- Mw radiometer
- 19, 37, 85 GHz
- H & V polarized
- Ambient & cold calibration on-site
- Remote control
- 1 year in Alaska

MICROWAVE INSTRUMENTS

Peggy O'Neill
NASA / GSFC 974

Truck-mounted Radar

-- **two frequencies (1.6 and 4.75 GHz)**

-- **four polarizations (HH, VV, HV, VH)**

-- **three nadir angles (15, 35, 55 deg)**

-- **120-deg azimuthal sweep**

-- **12-m boom height**

-- **weekly measurements**

Tower-mounted Radiometer (Lrad)

-- **single frequency (1.4 GHz)**

-- **two polarizations (H, V)**

-- **five nadir angles (25, 35, 45, 55, 60 deg)**

-- **three azimuthal positions**

-- **~17-m tower height**

-- **continuous measurements**

NASA/GSFC Lrad L-band Tower Radiometer

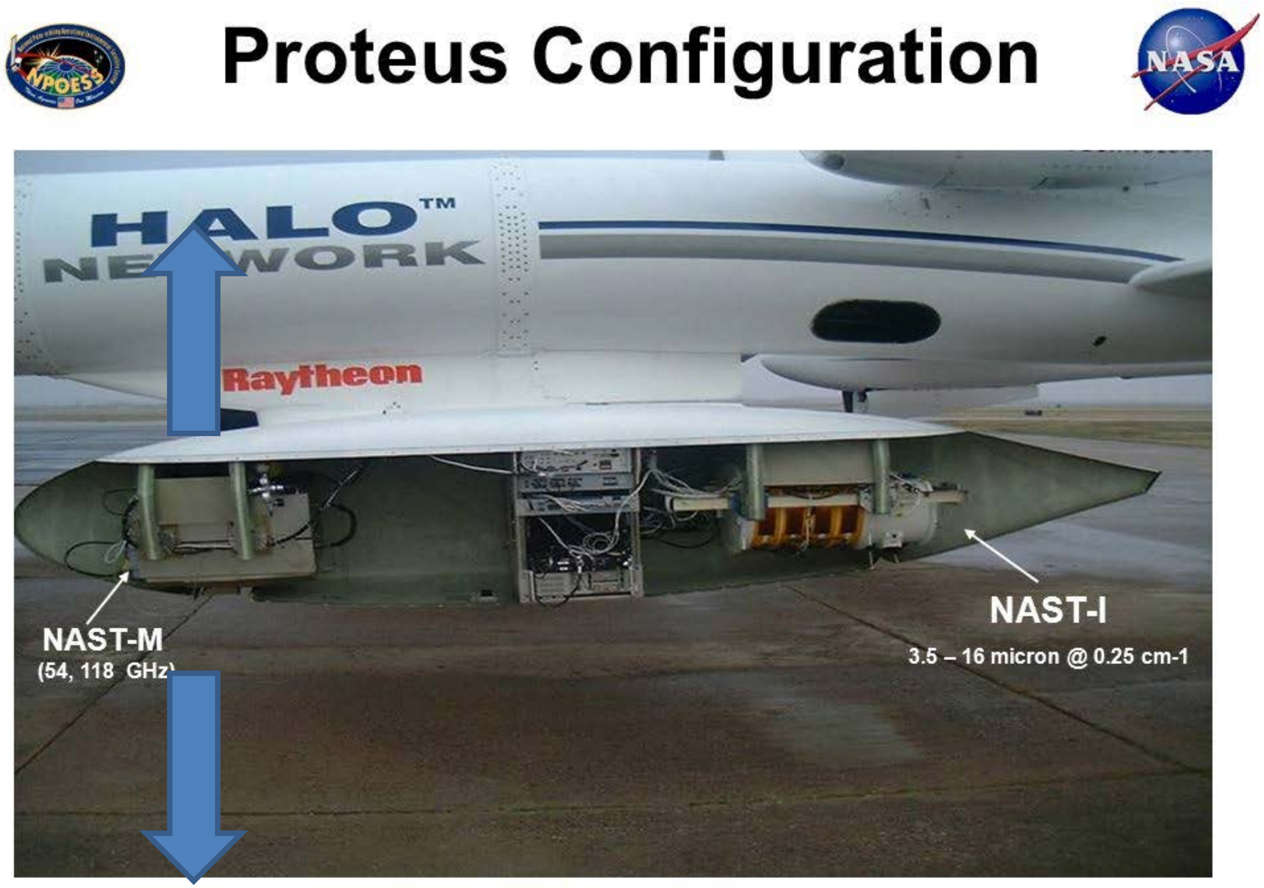
- Ground-based, 1.4 GHz, H & V-pol
- Rugged, suitable for long time series unattended observations
- Transportable 18 meter tower, easy set-up
- Automatic azimuth & elevation scanning
- 1.2m antenna (10-15 deg beamwidth)
- High-accuracy: hot/cold calibration w/each observation
- Remote control/data link
- Matched receivers
  - suitable for polarimetry
  - suitable for digital radiometry studies
- 7.5kW diesel generator or external AC power

Contact: Ed.Kim@nasa.gov +1-301-614-5653

Airborne

- NAST-M
- SLAP
- AESMIR
- Aircraft considered

NAST-M airborne mw sounder



Built by colleagues at MIT

Scanning L-band Active Passive (SLAP): Goddard's airborne simulator for SMAP

contacts
Edward.J.Kim@nasa.gov
Albert.C.Wu@nasa.gov

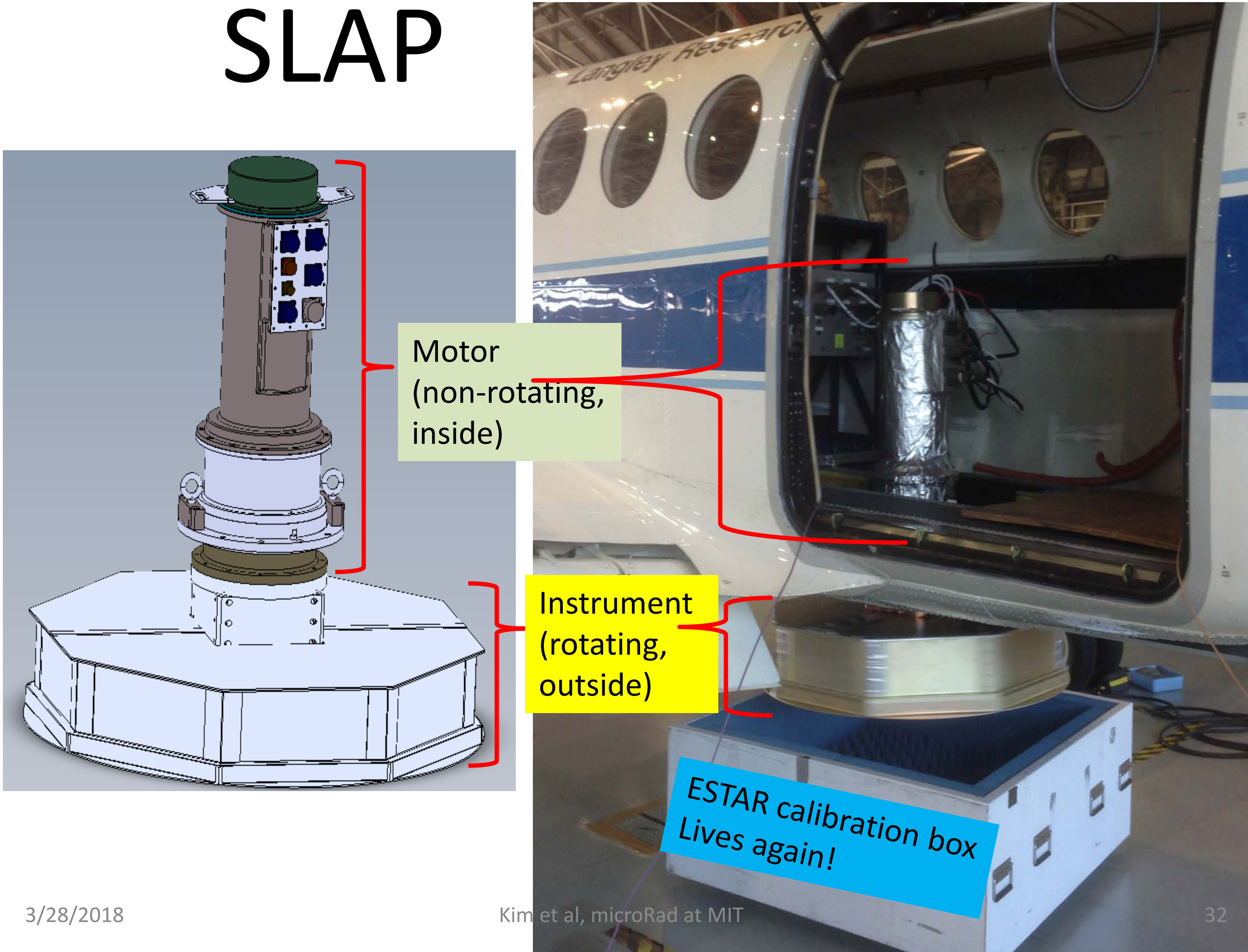
SLAP vs. SMAP

- SMAP = Soil Moisture Active Passive
- NASA soil moisture satellite
- Primary sensor = L-band radiometer
- Additional sensor = SAR for improving resolution, but radar died after 2 months
- SLAP = airborne version

Similarities

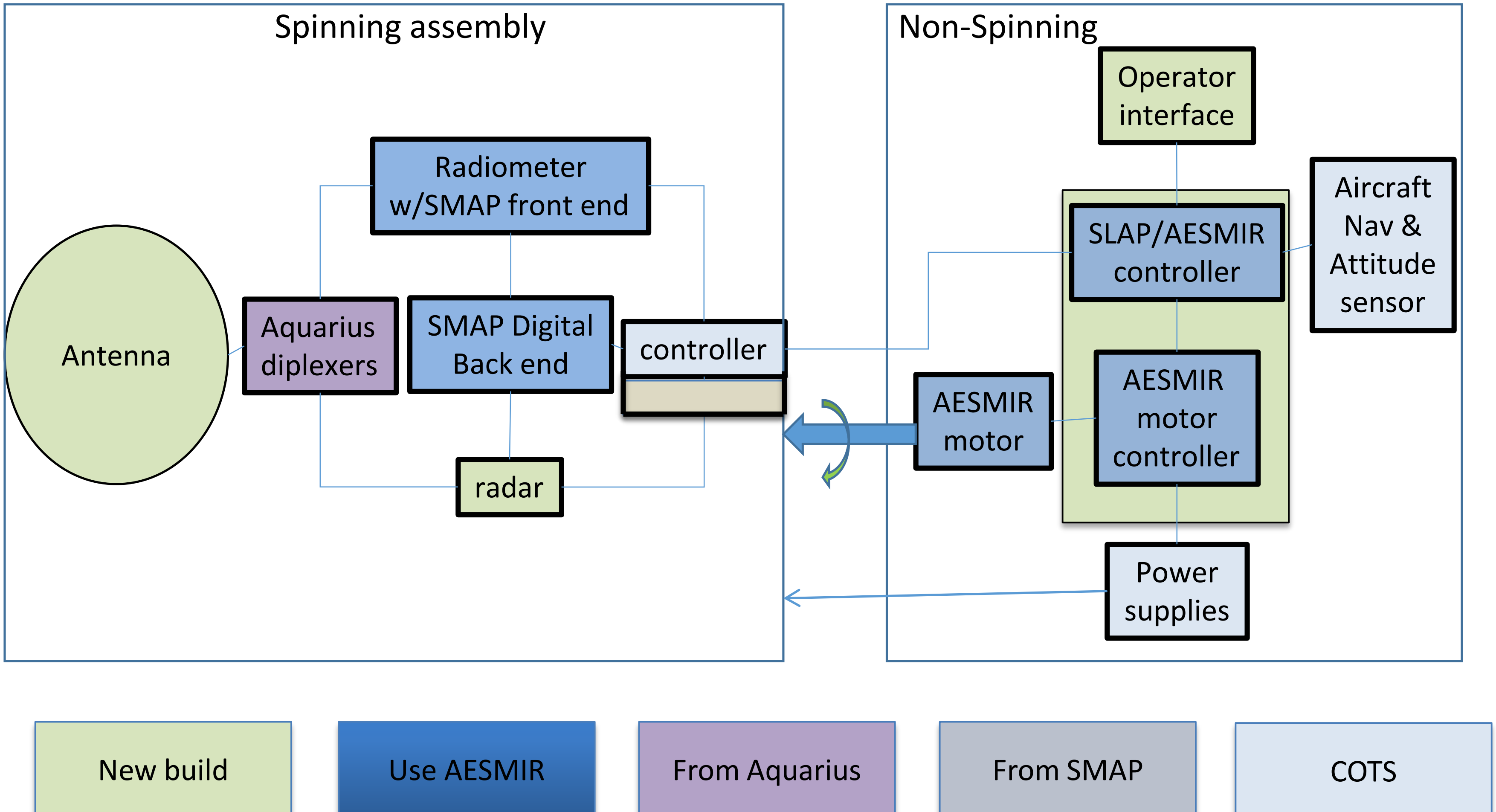
- Passive + active microwave
- Same frequencies (L-band)
- Same polarizations
- Same conical scan
- Same Earth incidence angle
- Same radiometer RFI capability
- Same basic radiometer & radar products

SLAP

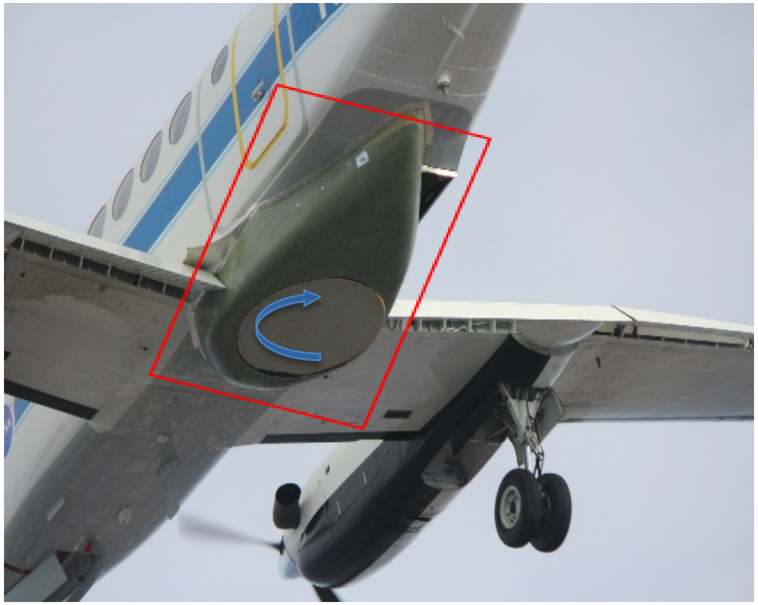

Langley Research
Motor (non-rotating, inside)
Instrument (rotating, outside)
ESTAR calibration box
Lives again!

SLAP overall configuration

maximize re-use, simulate SMAP



SLAP on NASA Langley King Air

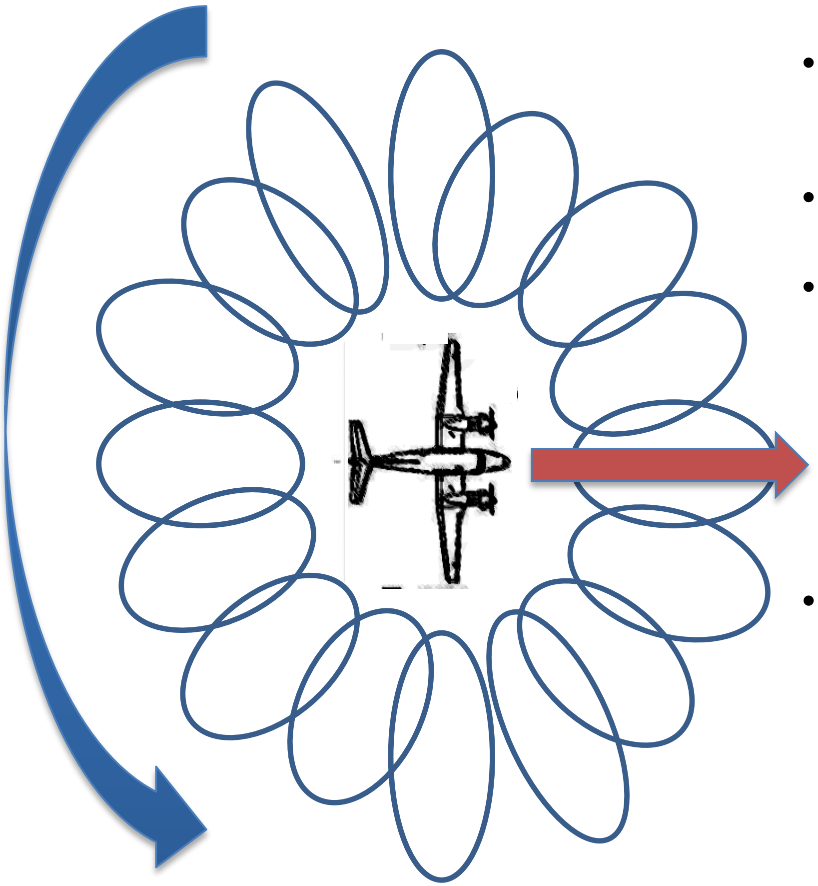


Bottom view of SLAP on NASA Langley King Air (UC-12) aircraft.

Side view

Typical aircraft operations: 190 KIAS, 4.5 hrs endurance.
1 pilot, 1 SLAP operator.

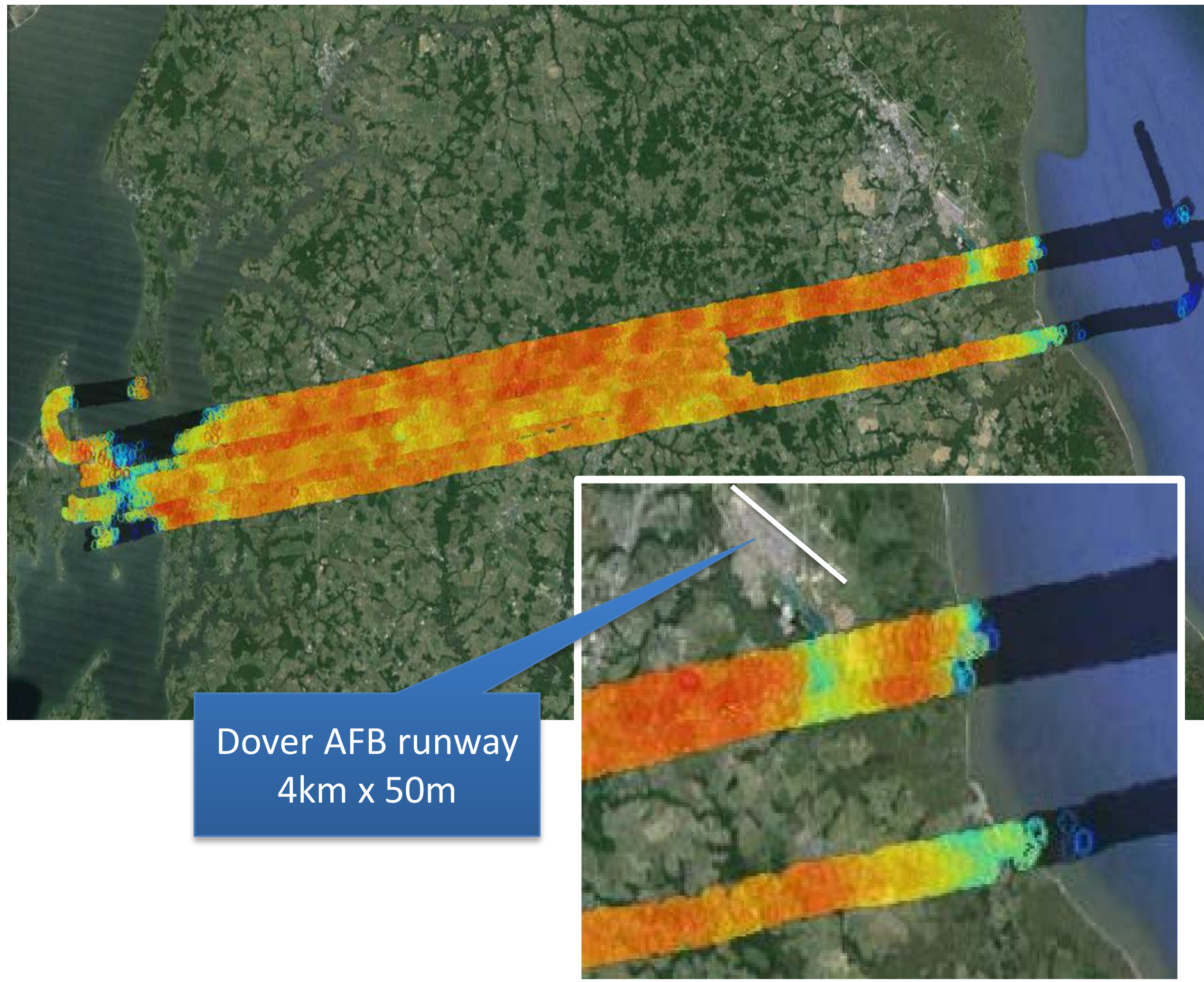
Top view of conical scan



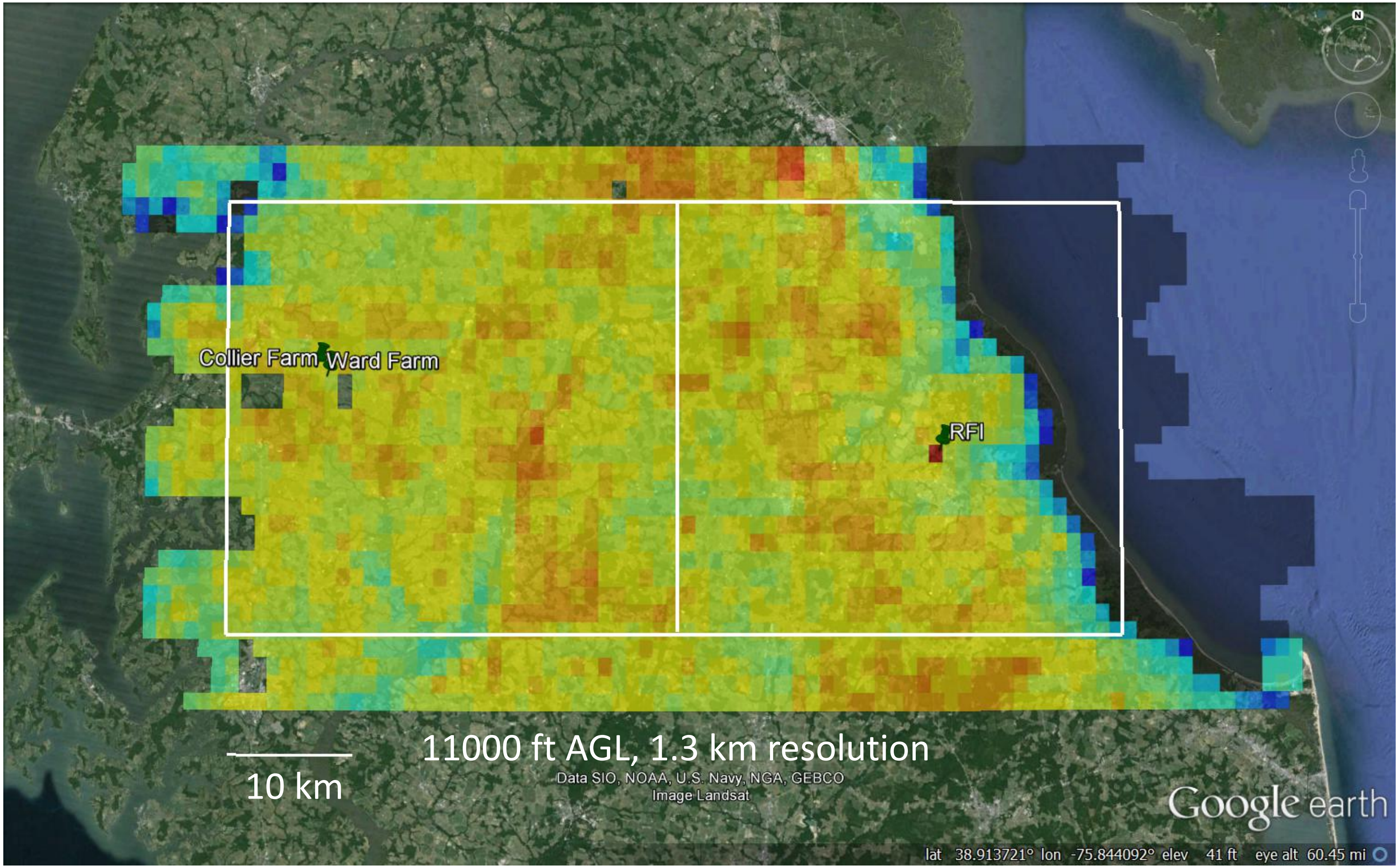
- Conical Scan rate: nominally 15 RPM, depends on altitude & airspeed for imaging without gaps
- Earth Incidence Angle 40 deg up from nadir
- Footprint size depends on altitude
  - Radar Min altitude 1500ft(457m): 200m dia.*
  - Radiometer Min alt 500ft(152m): 65m dia.*
  - Max altitude** 11000 ft(3353m): 1445m dia.
  - * geometric mean
  - ** 25000 ft if pressurized
- Full 360 deg scan yields
  - 2 looks (fore & aft) of the surface
  - 2 swath images (fore half-scan & aft half-scan)
  - different fore vs. aft readings depending on target nature

Dec 2013 Flights
High Resolution (260m) Example

- Location: Maryland Eastern shore, same flight lines as SMAPVEX'08, modified by ATC near Dover AFB
- 2 flights in 1 day (1 flight shown)
- 1st flight: low altitude (2000 ft AGL), high resolution (260m)
- ~80km long lines
- 1.4km wide swaths
- SLAP can go 4x finer (65m resolution), but swath also narrows to 350m.



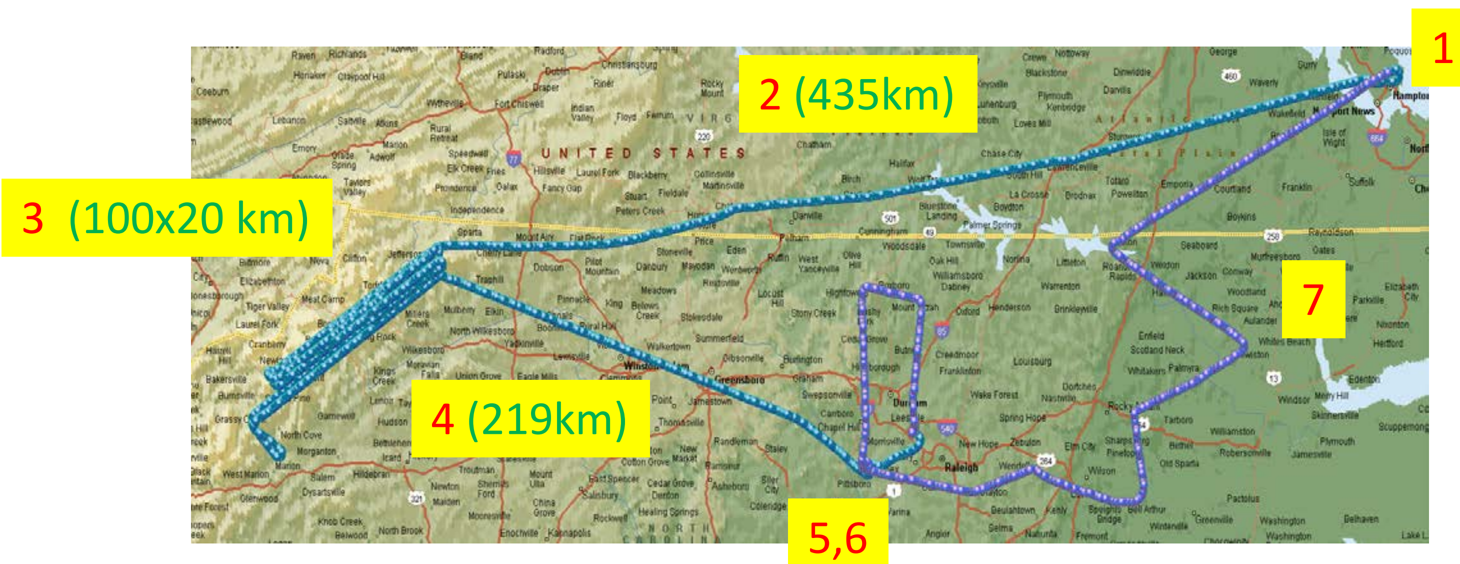
2nd flight on Dec 18, 2013—"High" Altitude
2 SMAP 36x36 km grid boxes mapped in <3hrs



May 2014 iPHEX Campaign

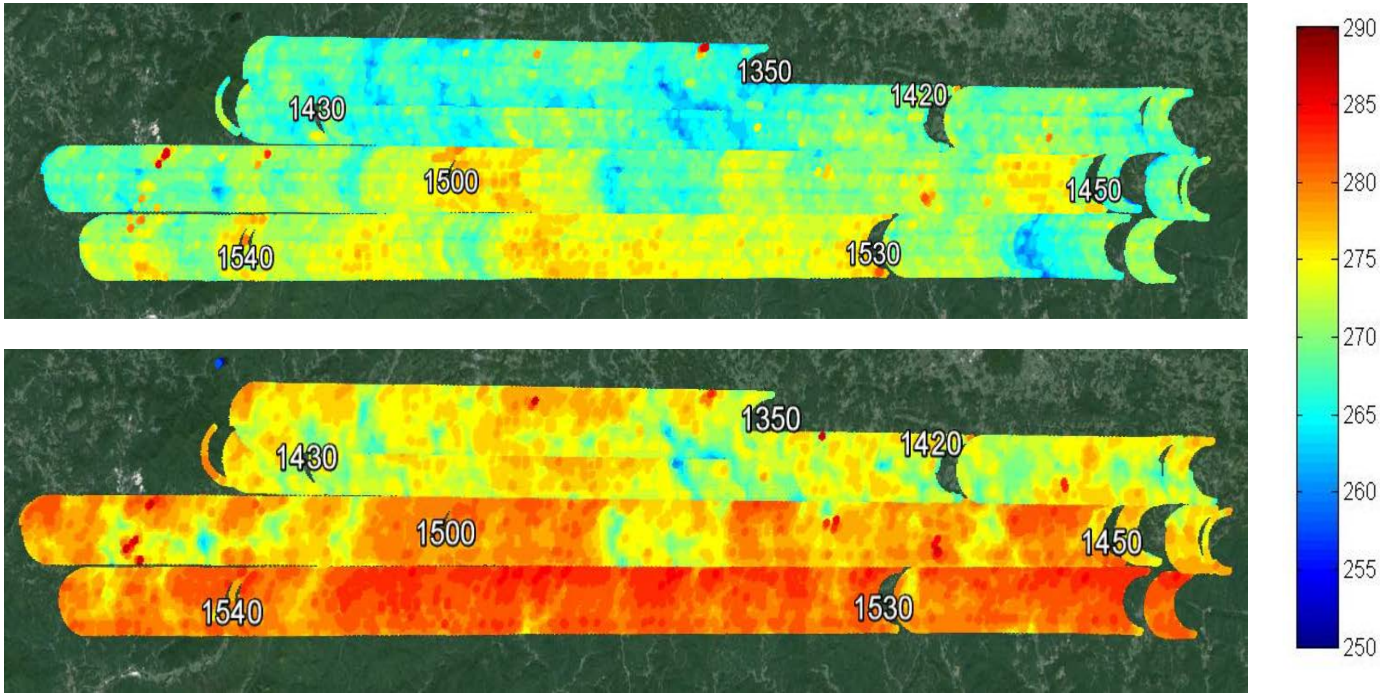
2 flights per day (~8 hrs total)

1. Aircraft takeoff/landing at NASA Langley
2. Fly to primary science target area
3. Mow the lawn at target area
4. Water cal @ Lake Jordan
5. Refuel at Raleigh-Durham
6. Water cal @ Lake Jordan
7. Overfly secondary science targets during return flight to Langley



May 21, 2014 SLAP radiometer images

Mow-the-lawn section ~ 100 x 20 km, ~centered on Boone, NC
Forested area, E-W mountain ridge divides lines, steep slope to south

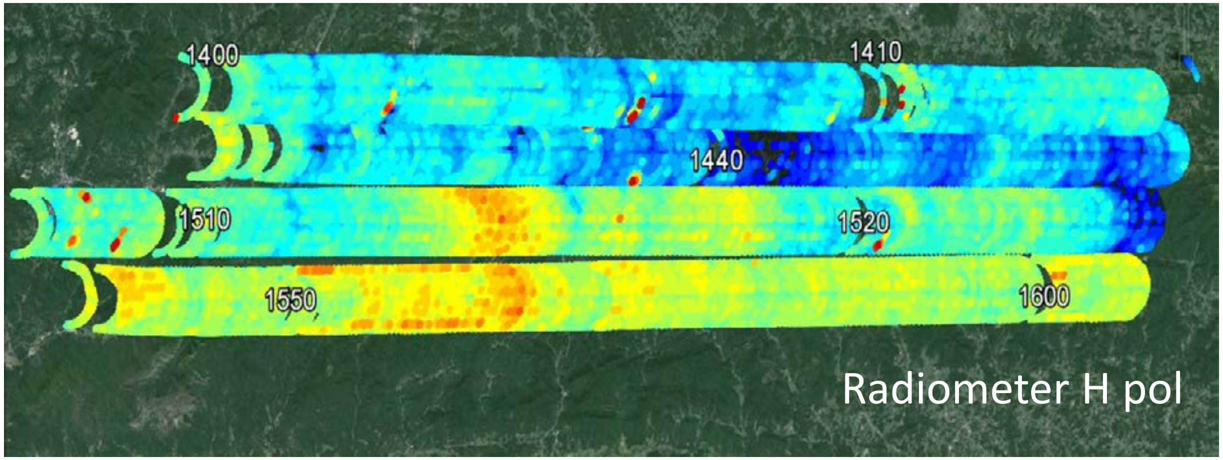


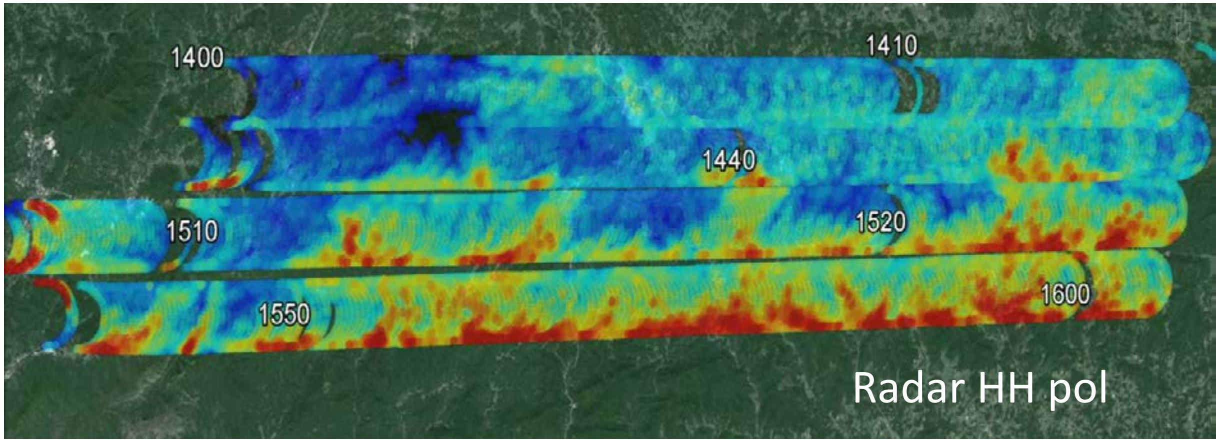
H pol
Fore half scan
SW facing lines

V pol
Fore half scan
SW facing lines

Resolution varies 200m -1km depending on terrain elevation; 2hrs elapsed time.
Isolated red spots are point RFI (color scale tops out at 290K)

May 2014 SLAP radiometer & radar for same location

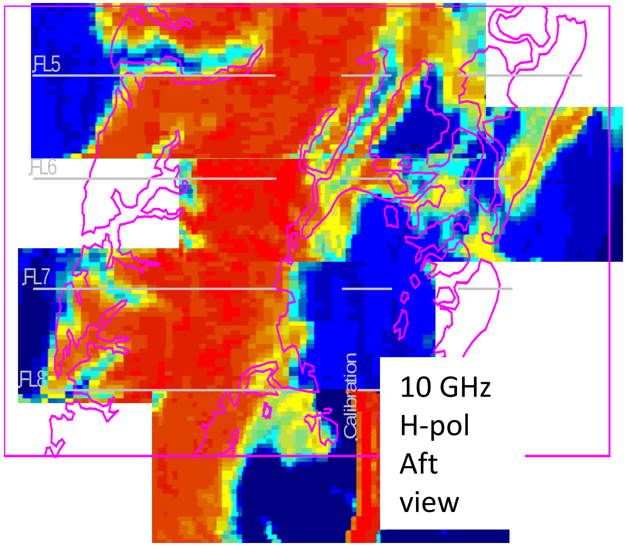


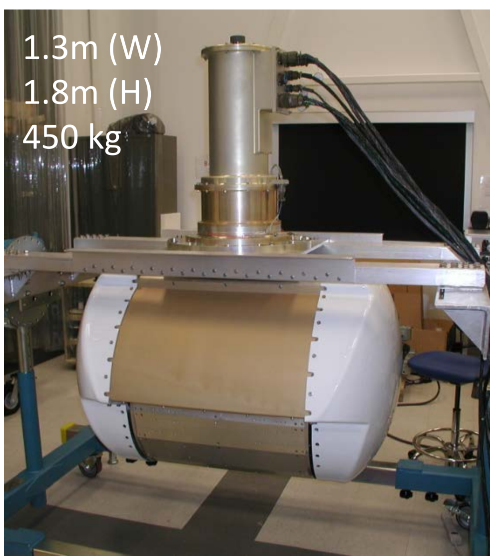


- Resolution varies
  200m -1km
  depending on elevation
- NE-facing
- Fore half scans
- Mow-the-lawn section
- ~2 hrs elapsed time
- Upper 2 flight lines
  north of ridge line
- Lower 2 flight lines
  on steep slope
- Whole domain is
  largely forested

AESMIR Airborne Earth Science Microwave Imaging Radiometer

contact: Ed Kim/NASA GSFC, ed.kim@nasa.gov, +1-301-614-5653





- Channels for snow, ice, precip, soil moisture, vegetation, ocean winds, SST, convection, temperature/humidity sounding
- All AMSR-E bands (6, 10, 18, 23, 37, 89 GHz) in a *single* scanning package + channels simulating other satellite radiometers
- Maximizes space for other instruments, science synergy, & field campaign cost effectiveness
- Flown on P-3 & C-130; compatible with other aircraft
- Programmable scanning: conical, cross-track, fixed beam, etc.
- Advanced calibration target features
- 4-Stokes capability

Field campaigns

- **SnowEx**
- **SnowEx video**

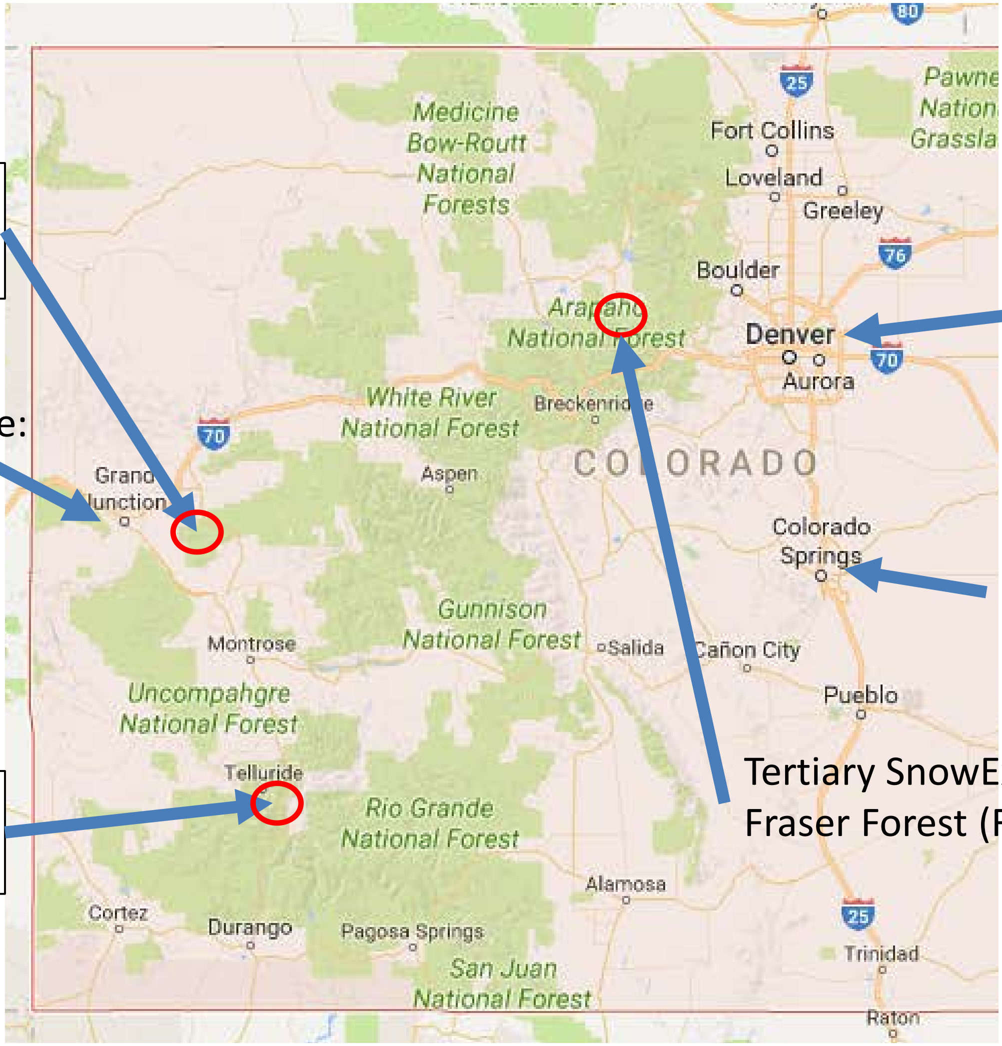
SnowEx Year 1 Sites & Aircraft Bases

Primary SnowEx site:
Grand Mesa (GM)

King Air & Twin Otter base:
Grand Junction (KGJT)

Secondary SnowEx site:
Senator Beck Basin (SB)

AFRC G-III base:
AFRC (KPMD)

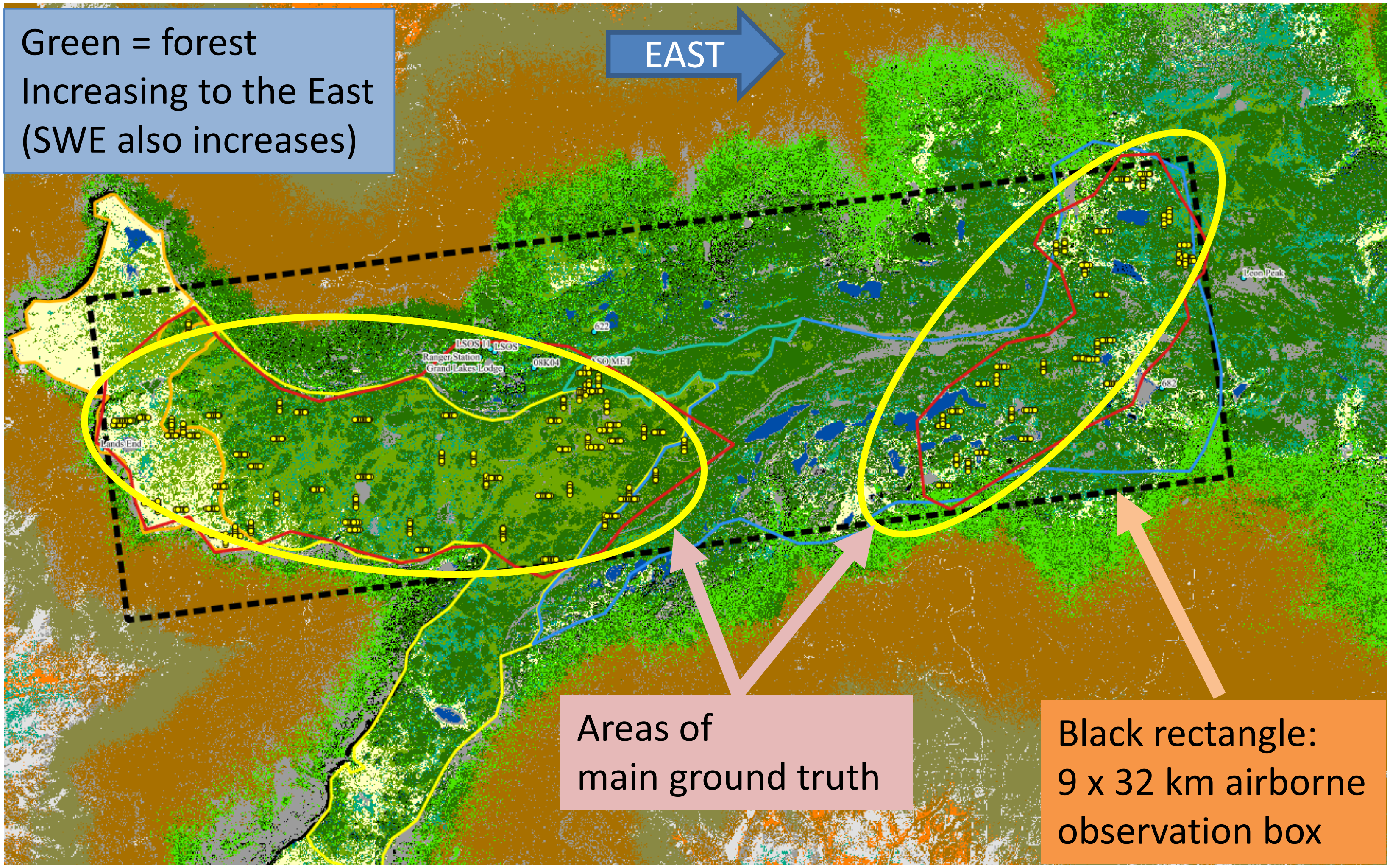


JSC G-III bases:
Centennial (KAPA)
& AFRC (KPMD)

P-3 base:
Peterson AFB
(KCOS)

Tertiary SnowEx site:
Fraser Forest (FF)

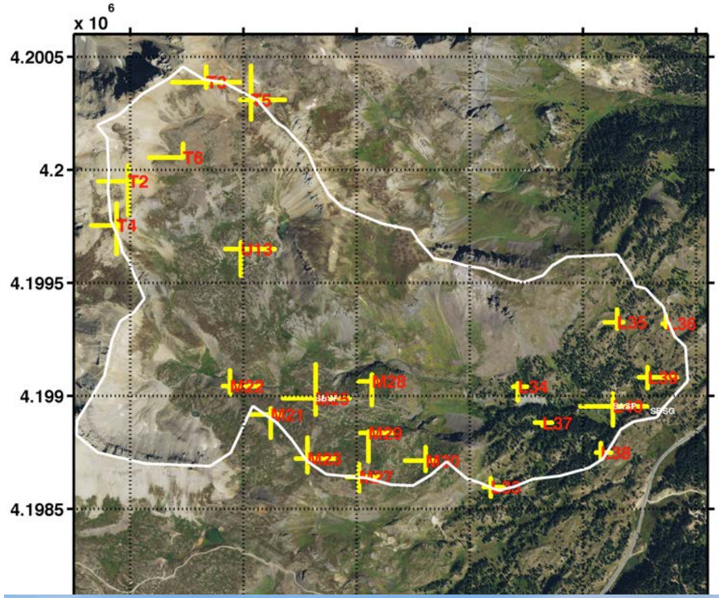
Primary site: Grand Mesa, CO



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

Secondary Site: Senator Beck Basin

- Added to provide a well-defined basin with a gauged outlet for water/energy balance studies
- Much smaller—only 3x5 km
- Same core ground truth as GM site
- 10 people; Weeks 1 & 3 only
- Airborne obs: 4 aircraft, 7 sensors
- GBRS: TLS lidar, FMCW radar, VIS/IR, Timelapse cameras, spectrometers, GPR, GPS, accelerometers, solar
- 2 energy balance met stations
- Complex topography was a ‘bonus’, not required to meet year 1 objectives



Site #2 provided a well-defined basin to address energy-balance/water budget questions

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)

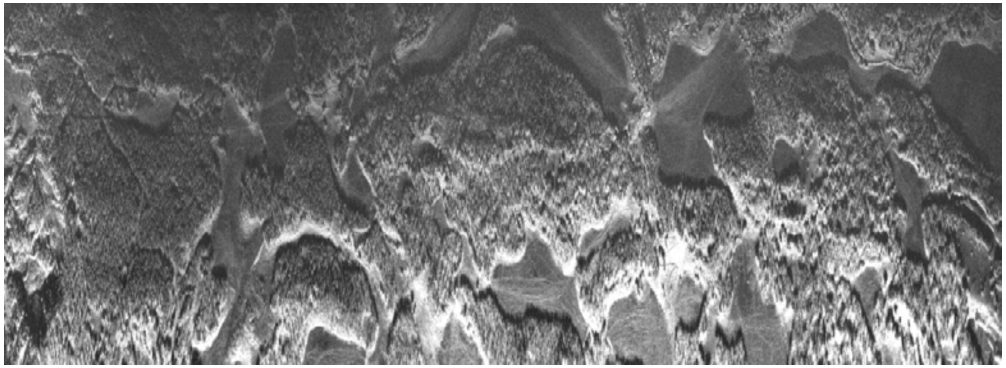
King Air (5)

Two NASA G-IIIs (4,3)

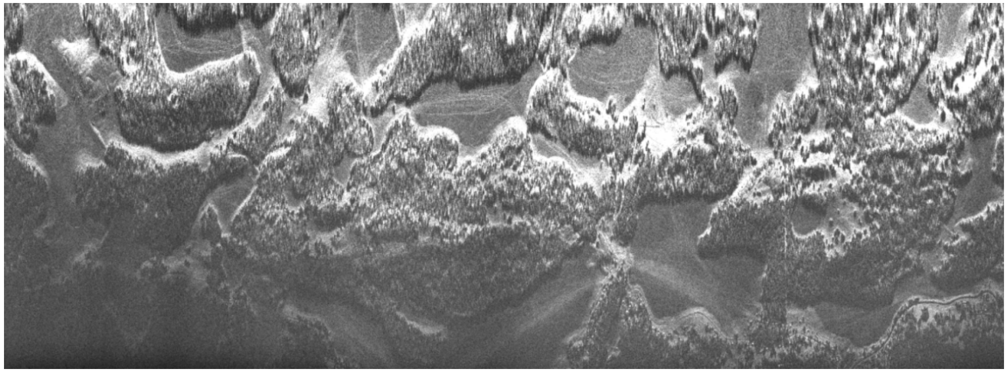
Twin Otter (3)

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
- <u>Pros</u>: volume scattering retrieval, sensitive to SWE & melt, high res, topography OK, sees through clouds, no sun needed
- <u>Questions</u>: accuracy, saturation, wet snow, forest, vegetation, soil



X-band

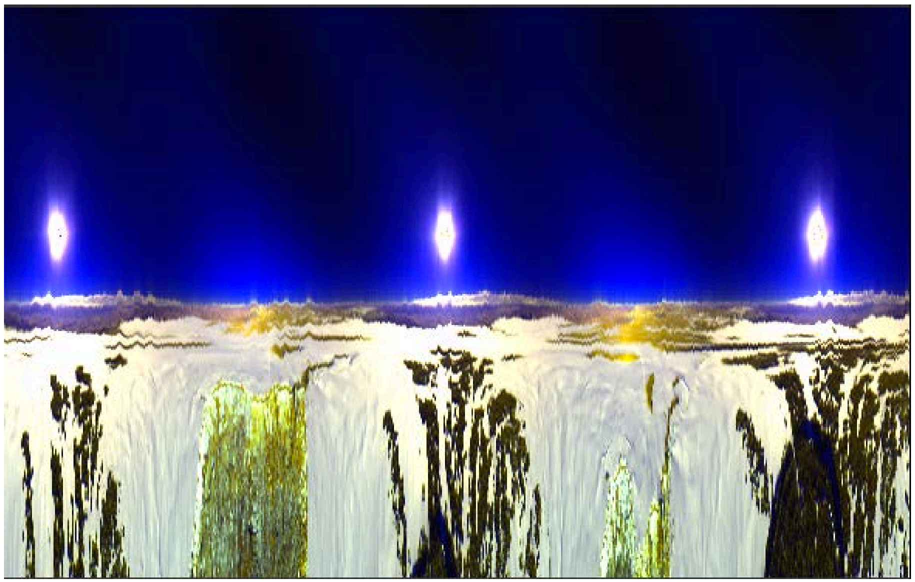


Ku-band

CAR/BRDF Grand Mesa

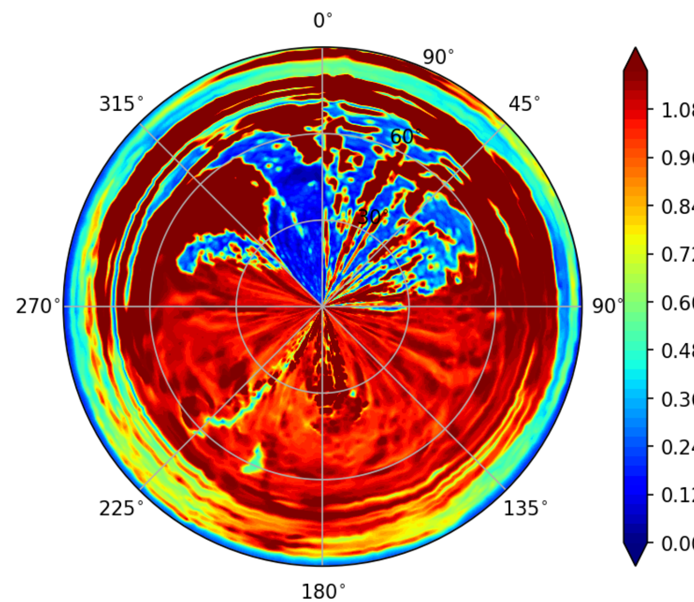
CAR = Cloud Absorption Radiometer (GSFC)
Multispectral imager & Bi-Directional Reflectance (BRDF) sensor

Example image



22:47:00UTC - 22:53:00 UTC
Feb 16, 2017

Example BRDF

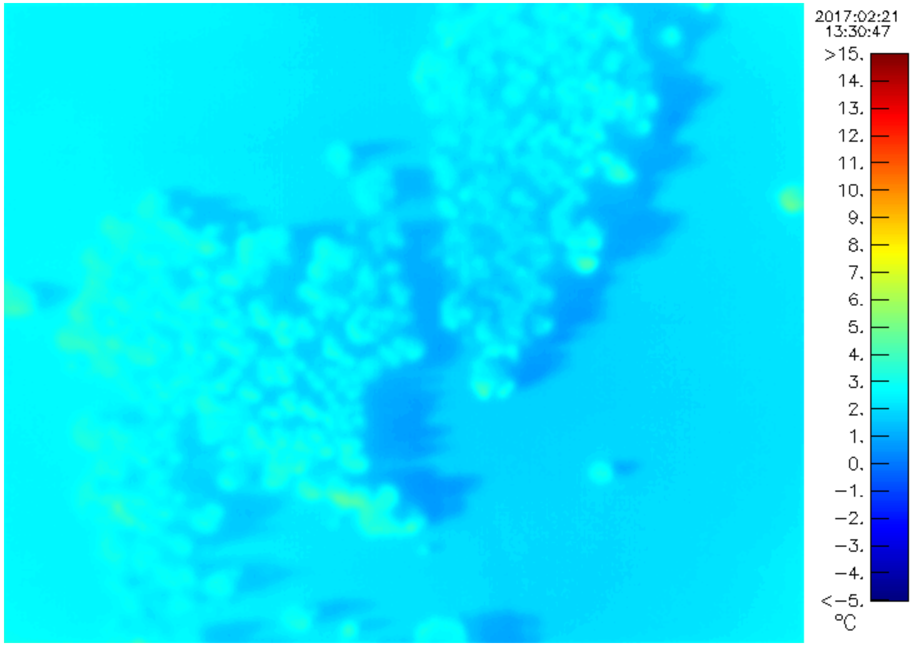


SZA = 73.70 870nm

BRDF data help decipher forest canopy effects on surface energy balance and blockage of sensing techniques by trees.

Thermal IR Sensor Suite

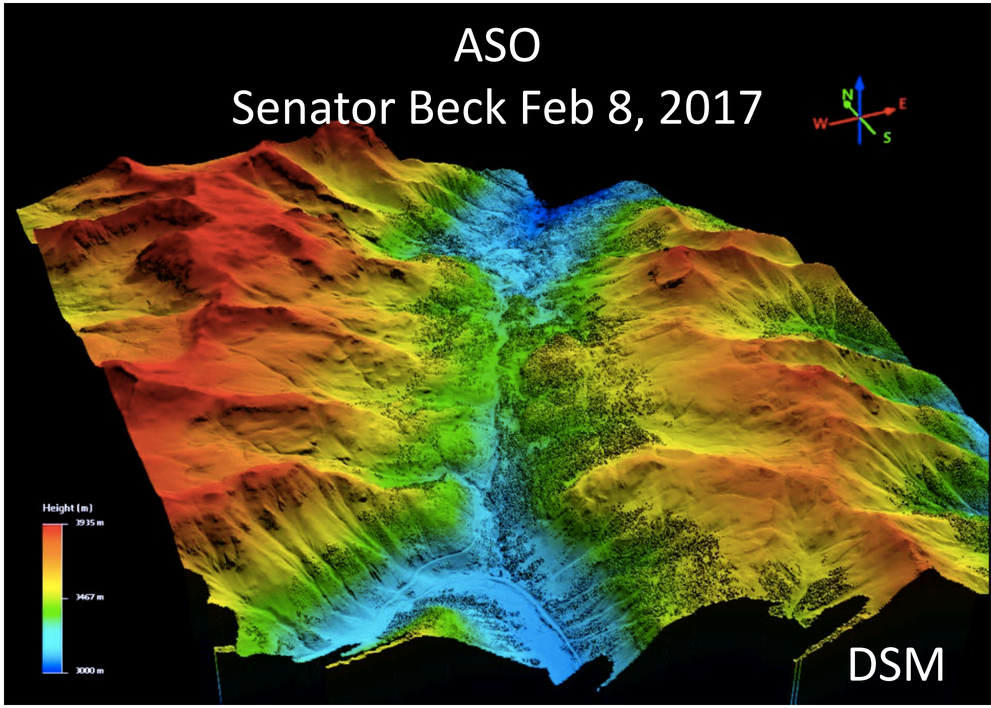
- Thermal IR Sensor Suite (IRSS) consists of two instruments and a camera
  - QWIP infrared imager (GSFC)
  - KT-15 infrared thermometer (U. Washington)
  - HD visual video camera
- IRSS Instruments were cross-calibrated with ground team field IR targets before deployment
- IRSS Instruments calibrated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

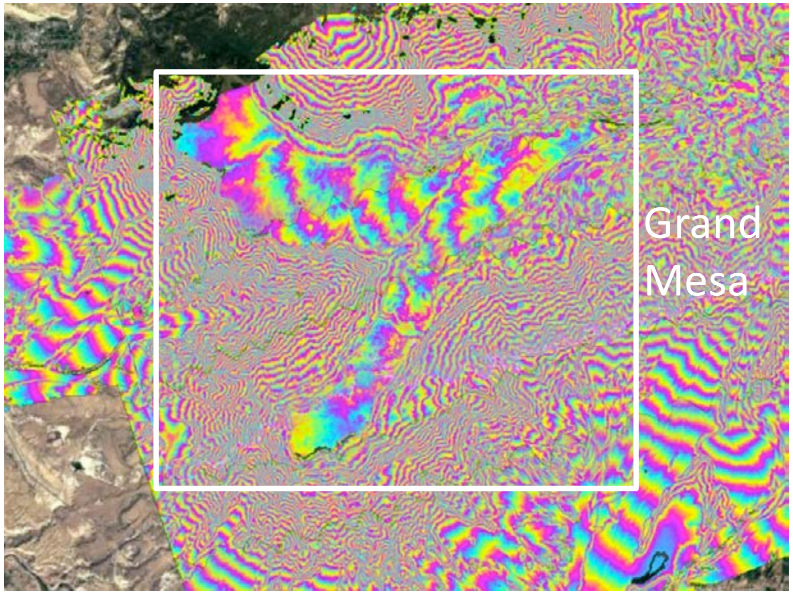
Lidar

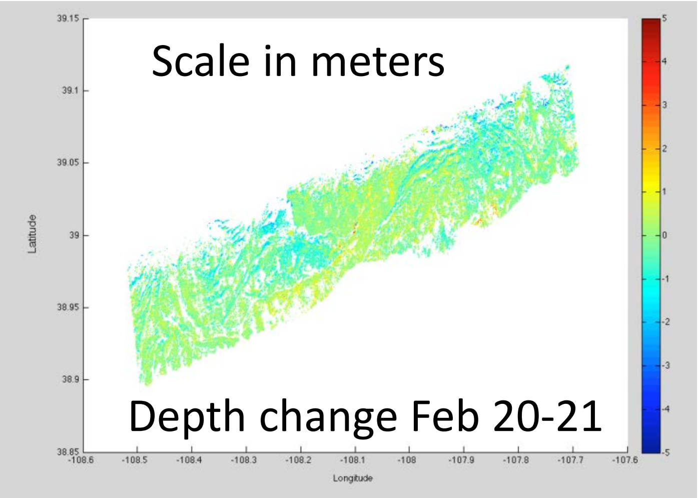
- Core sensor for SnowEx Year 1
- Fills spatial gaps in ground truth
- Airborne Snow Observatory (JPL)
- COTS sensor; mature installation
- Pros: high res, topography OK, wet snow OK, good forest penetration, wide swath (airborne), no sun needed, altimetry portion TRL 9
- Questions: requires density 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?

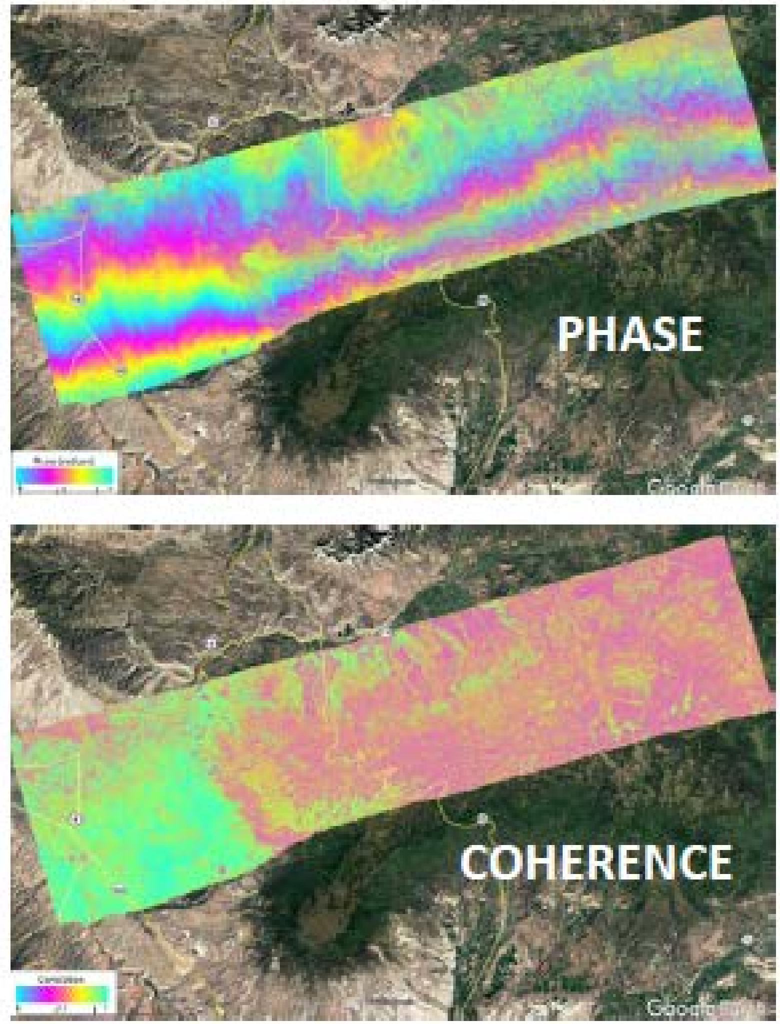




UAVSAR (L-band InSAR)

- 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

InSAR results for Feb 6 – 22



Ground Truth-the measurements

Snow depth – transects

manual probes & MagnaProbes

Snow pits

depth
density
water equivalent
stratigraphy
grain type
grain size
snow temperature
surface roughness
snow wetness
soil temperature
soil moisture

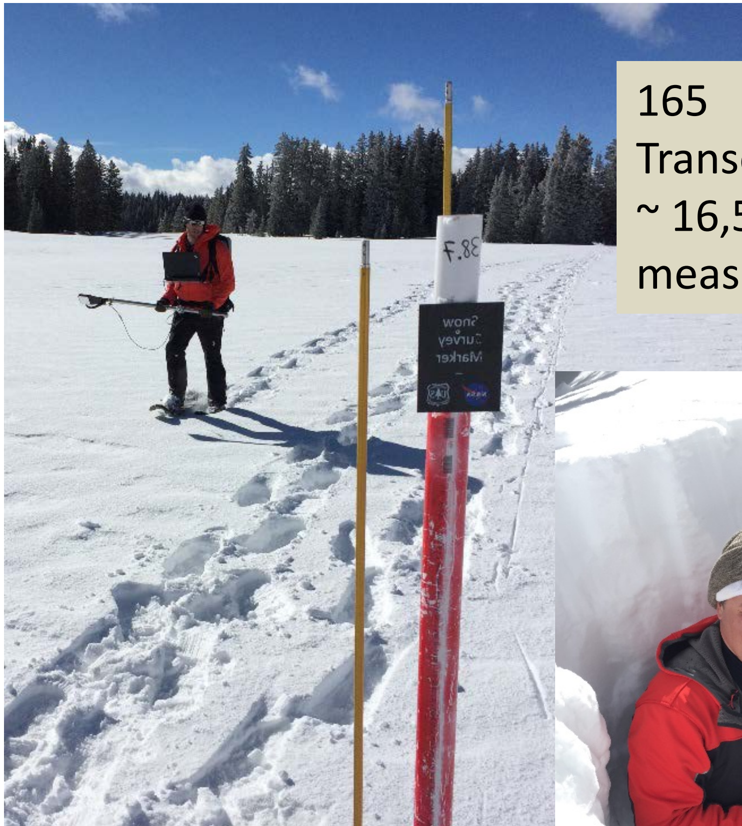
Meteorology

5 stations - Grand Mesa
2 stations – Senator Beck

<u>Additional measurements:</u>

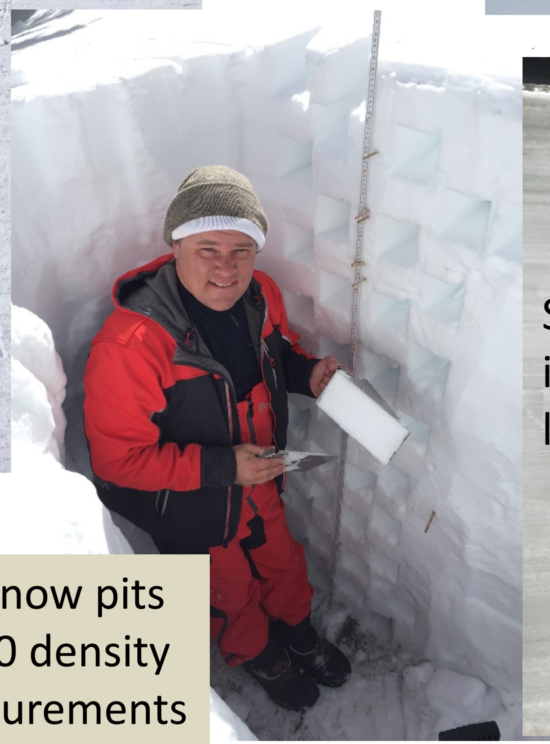
Snow penetrometer
Spectral reflectance
Snow casts
Soil bulk density
Veg biomass
Veg structure photos
Precip (solid + liquid)
(not a complete list)

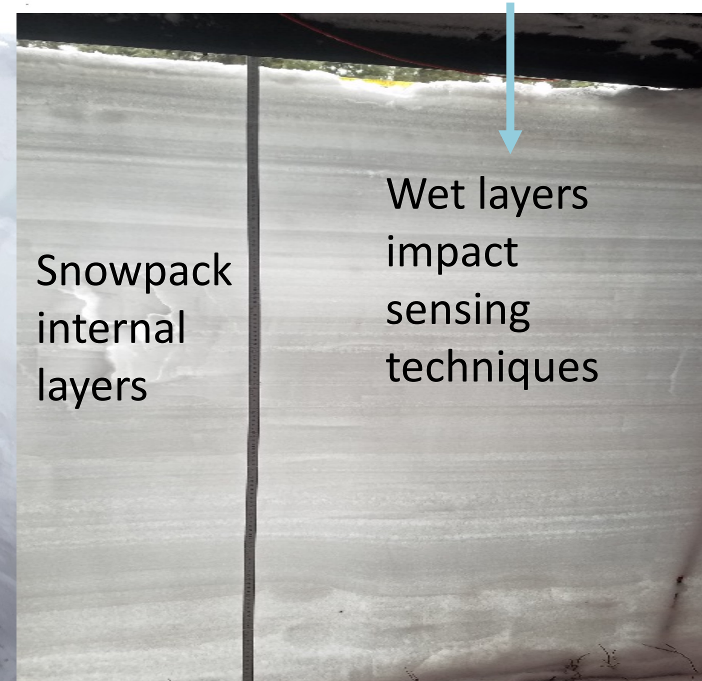
Ground Truth



165
Transects
~ 16,500 depth measurements

Unusually deep snow by Feb
And very warm → wet





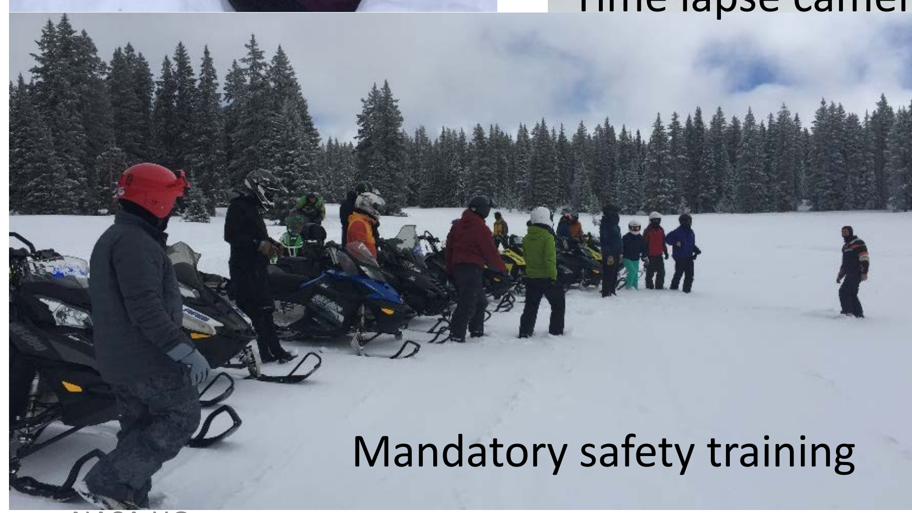
Snowpack internal layers

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 building was a major component of Year 1

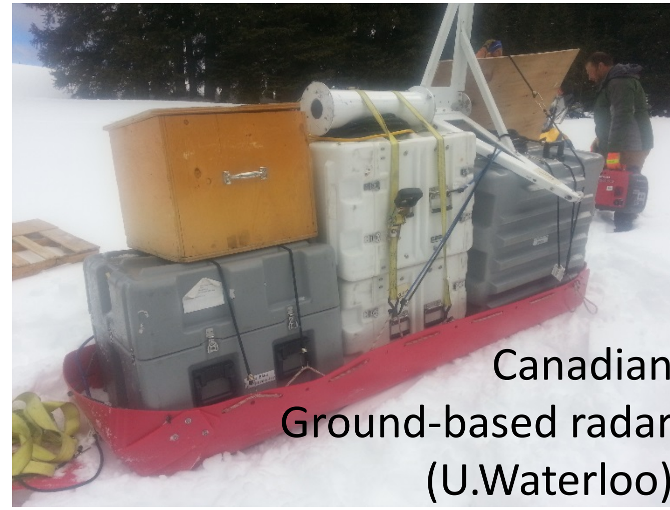
Ground Based Remote Sensing (GBRS)

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…

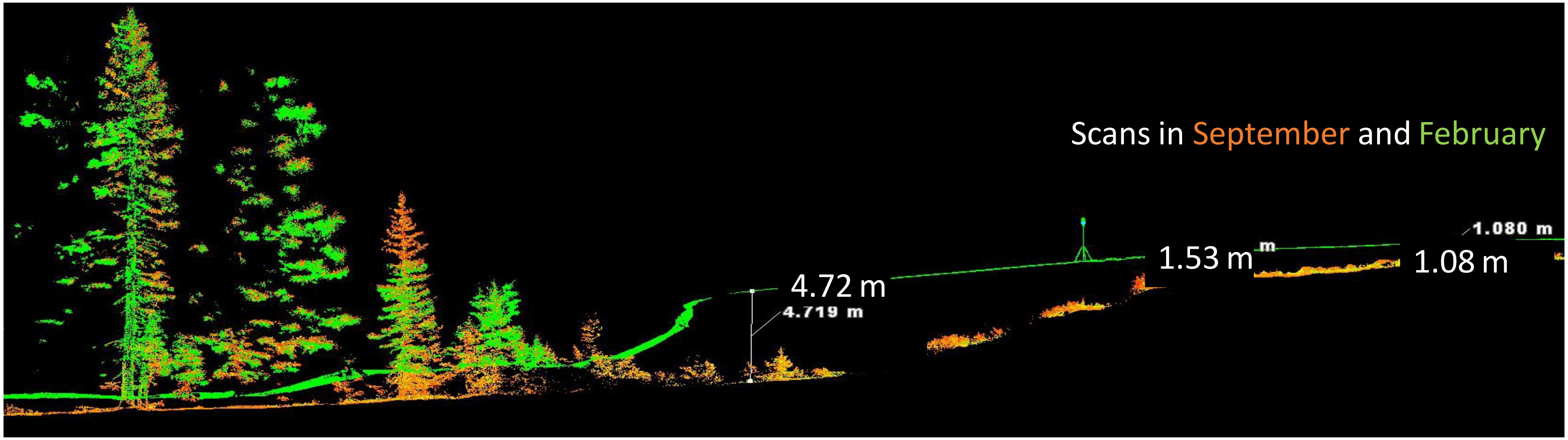

A boom truck (U.Michigan)

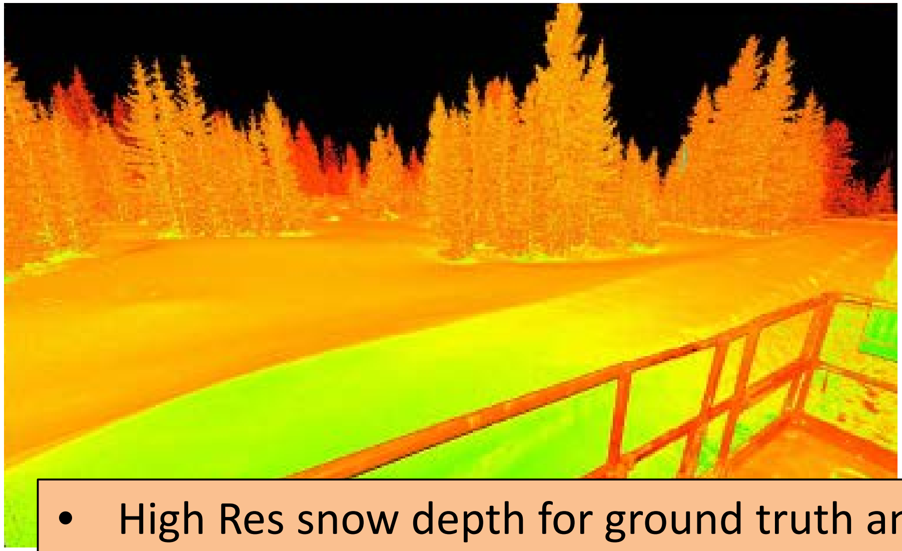

Canadian Ground-based radar (U.Waterloo)

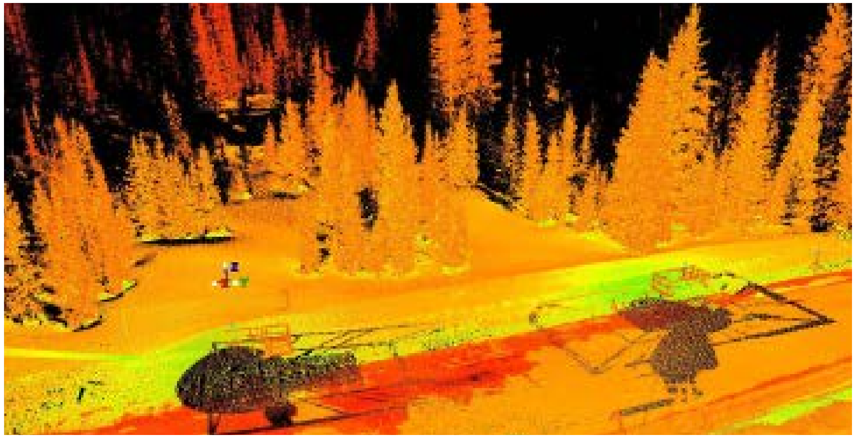
Sled towed by snowmobile (U. de Sherbrooke)

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)

SnowEx Summary

- Snow has enormous scientific and societal impacts
- These are reflected in multiple Designated and Explorer topics in the Earth Science Decadal Survey
- The multi-sensor + model approach needed for snow requires careful mission concept trade studies
- The SnowEx campaigns are how THP 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; NSIDC is the archive
  - Extensive press coverage & public outreach
- Future years of SnowEx will target science & mission concept gaps
- A snow mission tradespace framework is under construction and will use SnowEx data
- Several upcoming snow-related missions & proposals have synergies to explore: ABoVE, GPM, IceSat2, GEDI, ESA EE10
- NASA should develop a wider swath lidar

Snow Resources

snow.nasa.gov

- NASA Terrestrial Hydrology Program Manager
  - Dr. Jared Entin, Jared.K.Entin@nasa.gov
- SnowEx year 1 organizing team contacts
  - Dr. Edward Kim, ed.kim@nasa.gov
  - Dr. Charles Gatebe, charles.k.gatebe@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/

Conclusions

- Presented some examples of microwave radiometers deployed on
  - The ground
  - Aircraft
  - Satellites
- Microwave radiometers are powerful observational tools for atmosphere, land, ocean, and cryosphere
- If operated carefully, they can provide useful and unique observations

- Contact info: ed.kim@nasa.gov