NASA’s Experiences with Microwave Radiometers from Ground to Space

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Introduction/Outline

• NASA Goddard
• Satellite radiometer example
• Ground-based radiometer example
• Airborne radiometer example
• Field campaign example
• Conclusion
NASA/GSFC Passive Microwave Imaging Capabilities 1-600 GHz

Earth Science Interest Areas

Microwave Measurement Bands

Sat missions with overlapping measurements

<table>
<thead>
<tr>
<th>Band GHz</th>
<th>L 1.4</th>
<th>C 6</th>
<th>X 10</th>
<th>K 18</th>
<th>K 23</th>
<th>Ka 36</th>
<th>W 89</th>
<th>150/166</th>
<th>G 183</th>
</tr>
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</table>

GPM

GCOM-W/AMSR2

SMAP

Aquarius

SMOS

SCLP

DMSP/SSMIS

ATMS

ATMS (NPP & JPSS)
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
- 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
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
Comparison of J1 Pre-Launch, NOAA-20 on-orbit, SNPP on-orbit

ATMS Sensitivity (NEDT)

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

Multiply by 1.54 to convert these TVAC Cal values to on-orbit values

I.Osaretin, MIT LL
Repeatability (Hysteresis)

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

Ch 1-4

Ch 9-12

Ch 21 NEDT

Ch 22 NEDT

Ch 21 accur

Ch 22 accur

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

C.Smith/ NASA GSFC
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).
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

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

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

\[
\frac{\Delta G}{G} = \frac{T_{pink}}{T_{sys}}
\]
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.
S-NPP vs N-20 $\Delta G/G$

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

$\Delta G/G = \frac{T_{pink}}{T_{sys}}$
ATMS Inter-Channel Correlation

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

S-NPP on-orbit

N-20 on-orbit

N-20 pre-launch

N-20 Noise Correlation Much Better 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**
Results show that the NOAA-20 ATMS reflector has much lower emissivity than S-NPP.

NOAA-20 ATMS Ka-band RFI Test

- 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

NOAA-20 ATMS Antenna Temperature (TDR) Ch.18 183.311±7.0 GHz QH-POL
UTC Date: 2017-11-29

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

**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
Airborne

- NAST-M
- SLAP
- AESMIR
- Aircraft considered
NAST-M airborne mw sounder

Proteus Configuration

Built by colleagues at MIT
Scanning L-band Active Passive (SLAP): Goddard’s airborne simulator for SMAP

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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

Motor (non-rotating, inside)

Instrument (rotating, outside)

ESTAR calibration box Lives again!

3/28/2018

Kim et al, microRad at MIT
SLAP overall configuration
maximize re-use, simulate SMAP

Antenna
- Aquarius diplexers
- SMAP Digital Back end
- Radiometer w/SMAP front end
- radar

Spinning assembly

Non-Spinning
- Operator interface
- Aircraft Nav & Attitude sensor
- AESMIR motor controller
- AESMIR motor
- Power supplies
- SLAP/AESMIR controller

New build
- Use AESMIR
- From Aquarius
- From SMAP
- COTS

3/28/2018
Kim et al, microRad at MIT
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

12/5/2014 Kim et al, SED seminar
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

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

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- 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)

Secondary SnowEx site: Senator Beck Basin (SB)

Tertiary SnowEx site: Fraser Forest (FF)

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

AFRC G-III base: AFRC (KPMD)

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

P-3 base: Peterson AFB (KCOS)

2/26/18 NASA HQ
Primary site: Grand Mesa, CO

Green = forest
Increasing to the East
(SWE also increases)

Areas of main ground truth

Black rectangle: 9 x 32 km airborne observation box

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-IlIs:** (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
CAR/BRDF Grand Mesa

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

Example image

Example BRDF

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

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
- **Pros**: less cloud impact vs lidar, wet snow ok, topography OK
- **Questions**: penetration into snow, depth resolution, requires density to get SWE, accuracy, forest, vegetation, atmospheric correction, revisit timer, swath width, SWOT?

Grand Mesa

Scale in meters

Depth change Feb 20-21
UAVSAR (L-band InSAR)

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

Additional measurements:
  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

Community building was a major component of Year 1

Mandatory safety training
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)

Sled towed by snowmobile
(U. de Sherbrooke)

Canadian Ground-based radar
(U. Waterloo)

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

Scans in **September** and **February**

![Lidar Scan Images]

2/26/18 NASA HQ
Engaging the Snow Community

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

The response: 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

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