SI-Traceable Calibration of Satellite Microwave Radiometers

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Outline

Background (what)

- SI-traceable Microwave Radiometer calibration

Motivation (why)

- NWP, FCDR

Technology (how)

- NIST blackbody target

Standards

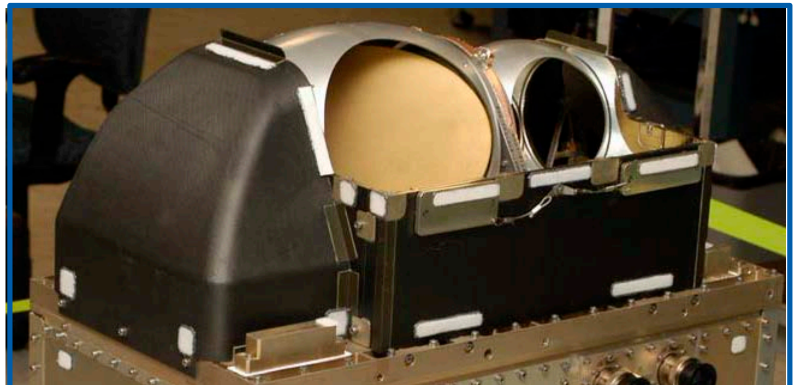
Status & Future Plans

CAVEAT

- Ongoing work !!
- “The answer” not completely known

Satellite MW Radiometer Cal Example

Example: ATMS



On-board Blackbody target

Cosmic MW Background

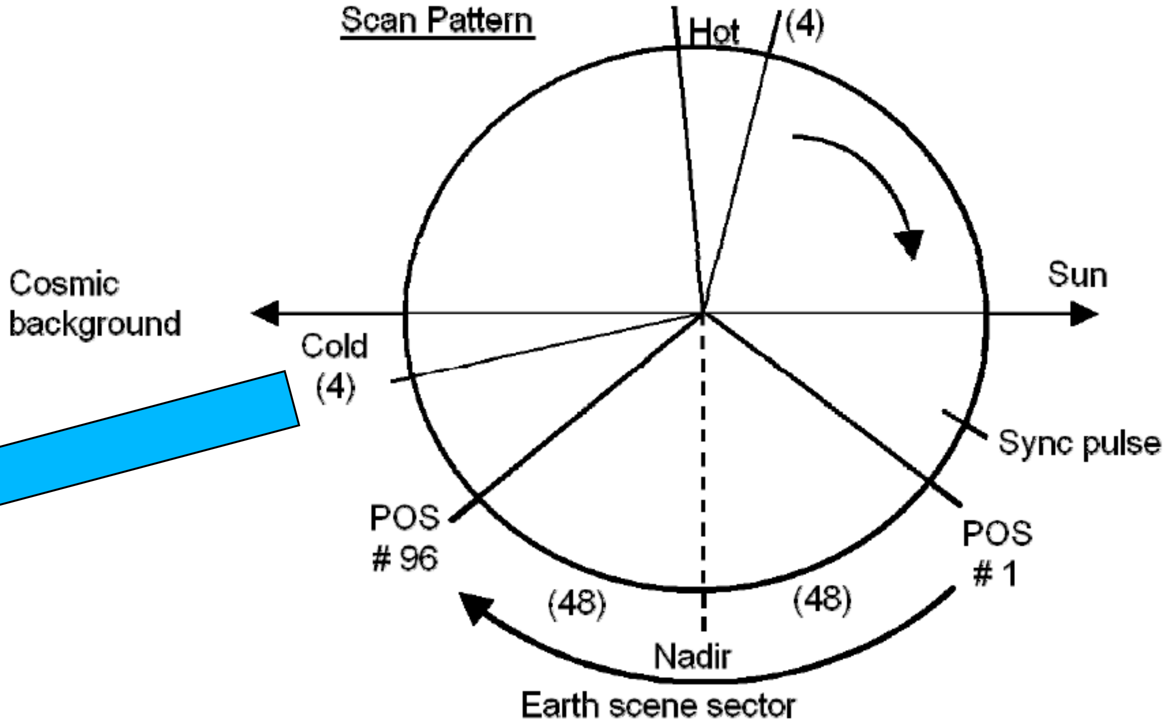


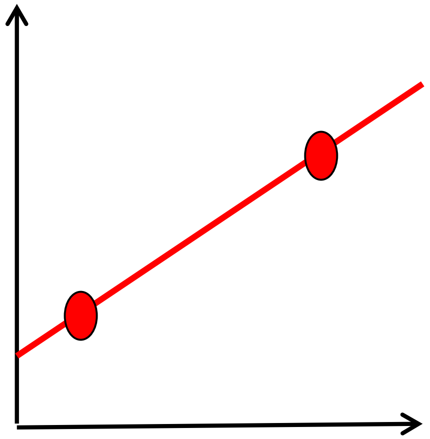
Figure 6. Scan sequence (flight direction is toward the reader)

Typical MW Radiometer TB Calibration

Typical black body used to calibrate satellite MW radiometers: 2D array of pyramids

(highly simplified version)

- Build your radiometer as linear as practical
- Point it at 2 calibration targets (1 hot, 1 cold) to determine the cal curve (a line)
- Cal targets are typically black bodies with emissivity ~1, so TB = physical temperature



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What “SI traceable” **is *not***

- Traceability implies a rigorous uncertainty assessment—true
- Using an SI unit as the standard provides a well-defined reference –true
- Your measurement will have unusually good accuracy—not necessarily
- In other words, just because you know the size of your error bars very well, doesn’t guarantee that the error bars are small

SI-traceable *inter-calibration* of Satellite MW Radiometers

- My *personal* forecast (so not NOAA or NASA policy): future sounder obs will need to combine smallsats + anchor sounders like ATMS, MWS
- Example: GPM constellation—"X-cal" effort has harmonized TBs with respect to one member radiometer (GMI)
- According to NIST, this is inter-*comparison*, not inter-*calibration* because the reference (GMI) isn't traceable to a *standard*
- Adding traceability to a standard would make it inter-*calibration*
- Traceability to a SI standard would be SI-traceable intercalibration
- Traceability to a standard implies absolute calibration
- Traceability to which SI unit?

GNSS-RO and Tb Standards

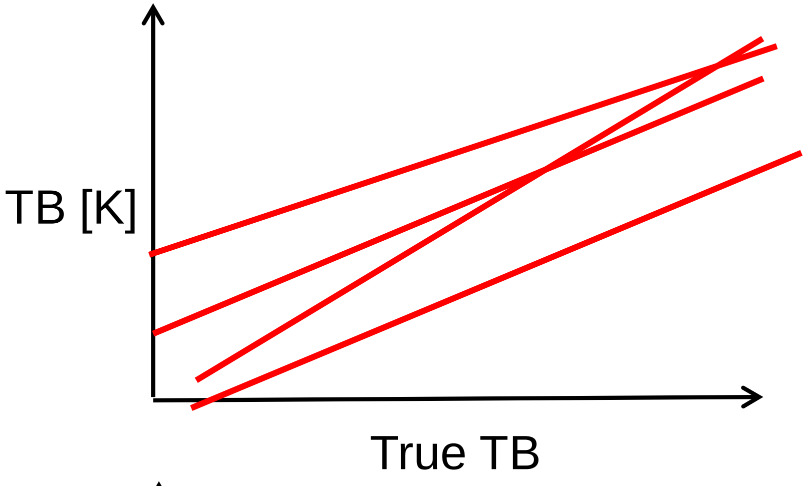
- GNSS-RO is SI-traceable through *frequency* standards.
  - Connected to atmospheric Temperature & Humidity via density & refraction modeling
  - Relies on 1-2 GHz signals chosen for low sensitivity to atmosphere
  - Spatial coverage: best altitude range 8-25 km, 300 km horizontal resolution, ~1 km height resolution
  - Creates reliable long-term RO data record
- MW Radiometry can be SI-traceable with *TB* standards.
  - More direct connection to atmospheric Temperature & Humidity via radiative transfer
  - Relies on 18-183 GHz bands chosen for high sensitivity to atmospheric temperature & humidity
  - Finer horizontal resolution, similar vertical resolution, wider altitude range
  - Creates reliable long-term Tb data records
- Comparable uncertainties achievable: 0.1--1 K (single retrieval)
- Strengths & limitations are complementary

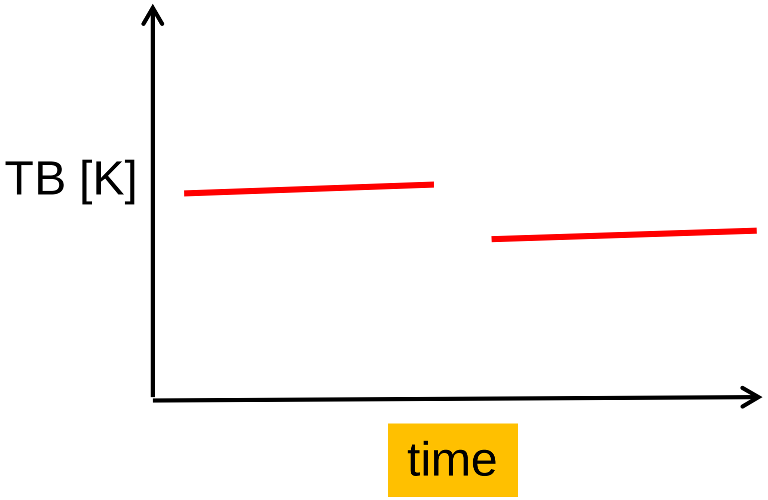
Motivation

- Inter-calibration for constellation systems
- Absolute TB calibration
- Benefits to NWP and FCDRs
- What is not addressed by SI-traceable TB cal?

Benefit to Constellation Systems

- Constellation systems need TB inter-calibration
- Example: anchor sounders + smallsat sounders
- Pre-launch inter-calibration can reduce burden on post-launch inter-cal
- Still want post-launch inter-cal to handle issues like footprint matching, but the portion due to just TB inter-cal would be well-quantified by SI-traceable TB calibration
- Post-launch traceable inter-cal also appears possible, which would extend traceability to on-orbit
- Pre- or post-launch inter-cal would provide immunity to temporal gaps





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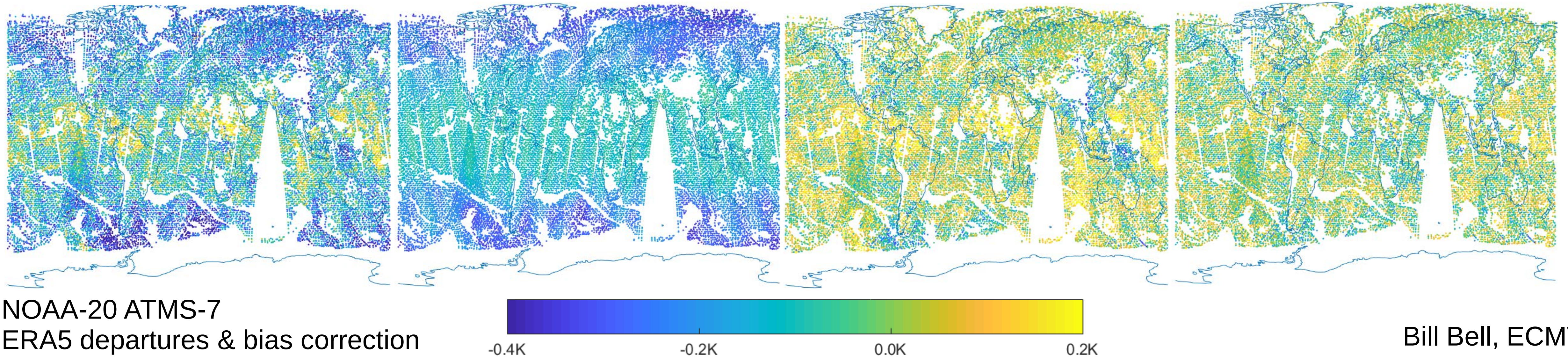
Benefit to NWP forecasting

- NWP & climate models subtract biases
- Bias sources include:

1) Radiometer sensor
2) Radiative transfer model (RTM)
3) Forecast model

- Bias corrections are larger than forecast model errors
- Bias from RTM & forecast models (#2 & #3) are often artificially assigned to sensor bias (#1) in order not to disturb the models
- This is unphysical
- Impedes progress in actually fixing the models (thus presumably improving forecasts)

The potential benefits of improved radiometric calibration for NWP and climate reanalysis



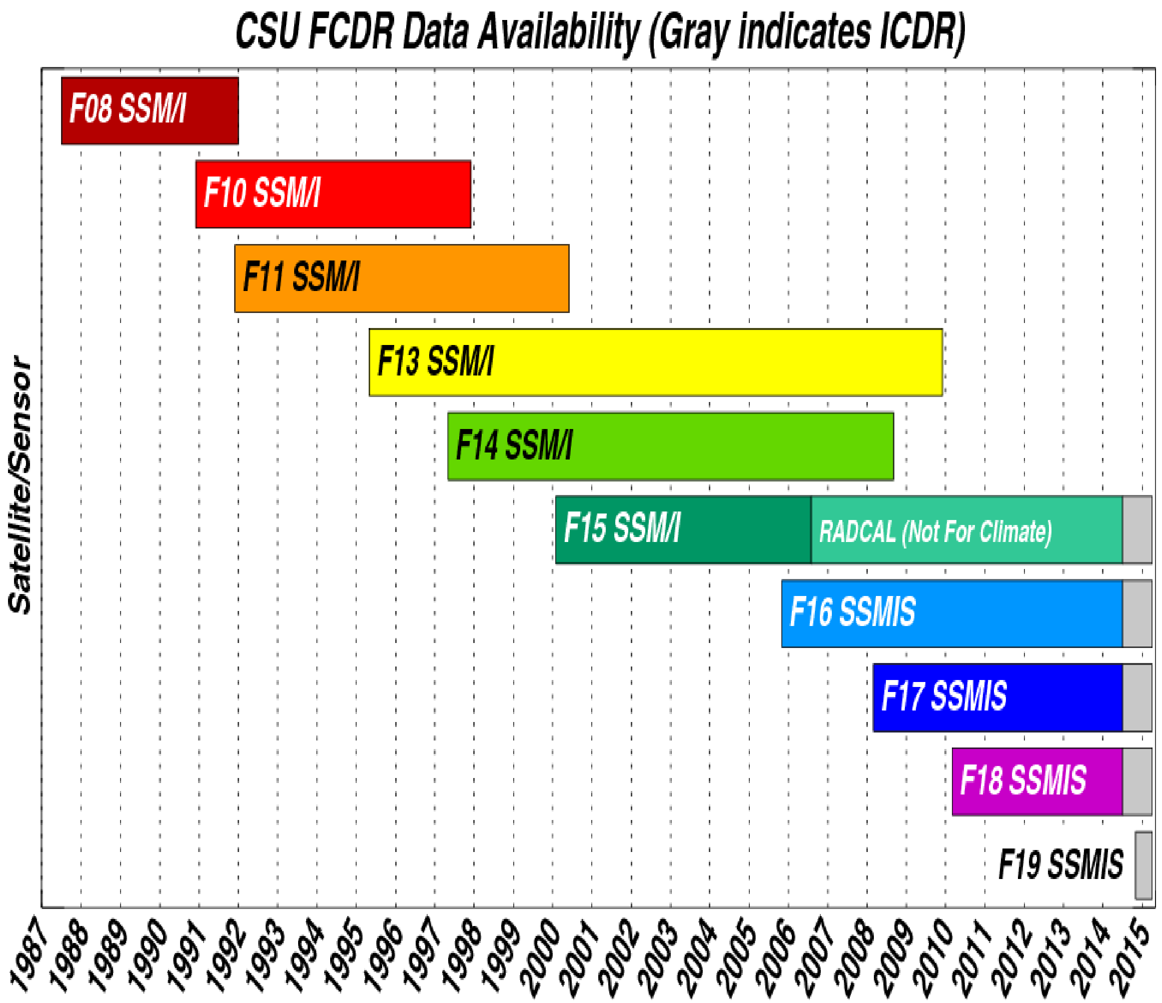
NOAA-20 ATMS-7
ERA5 departures & bias correction

Bill Bell, ECMWF

- Forecast model errors are ~0.1K for mid-trop. T- sounding channels
- Bias corrections (parametrised, accounting for radiometric & spectral biases, RT & forecast model biases) are larger
- Improved, traceable, absolute radiometric calibration would help:
    - Partition & bound the contribution due to radiometric uncertainties
    - Reduce the magnitude of residual biases being assimilated
    - Reduce analysis uncertainties (as RT model and forecast model biases are also, inevitably, reduced in time)

Fundamental Climate Data Records (FCDRs)

- Focus on TB FCDR
  - decades-long time-series of TB
- TB FCDR is foundation for various geophysical retrievals
- Used to look for climate trends
- Need to remove calibration jumps when transitioning sensors
- Or bridging gaps
- Should help separate calibration drifts from real climate trends



Pre-launch *traceable* TB calibration would help attribute uncertainties properly & better quantify them

What SI-traceable TB Cal Does Not Address

- Careful! Total TB = f(footprint, scaling, amplitude)
  - Traceable TB cal helps quantify the amplitude uncertainty
  - Still need other techniques to address the effects of the footprints & scaling
  - What is addressed via harmonization or homogenization and what is addressed by SI-traceable TB cal is TBD

The Technology of Traceable TB Calibration

- NIST blackbody target
- Traceable calibration methodology
- Formal standards
- Upcoming satellite mw radiometers

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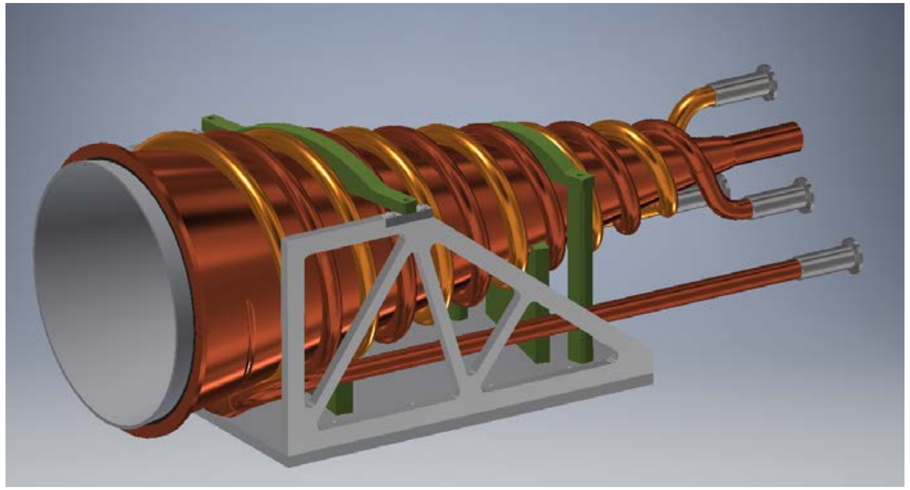
NIST Blackbody Calibration Standard

Broadband passive microwave blackbody

- NIST primary standard; traceable to SI kelvin
- 18-220 GHz design frequency range
- Result of Derek Houtz's PhD thesis



Design requirements:

- Maximize emissivity
- Minimize temperature gradients
- Variable temperature operation
- Minimize IR radiation effects
- Compatible with ATMS (2 targets: 12 & 23 cm dia.)

Hollow Cone geometry

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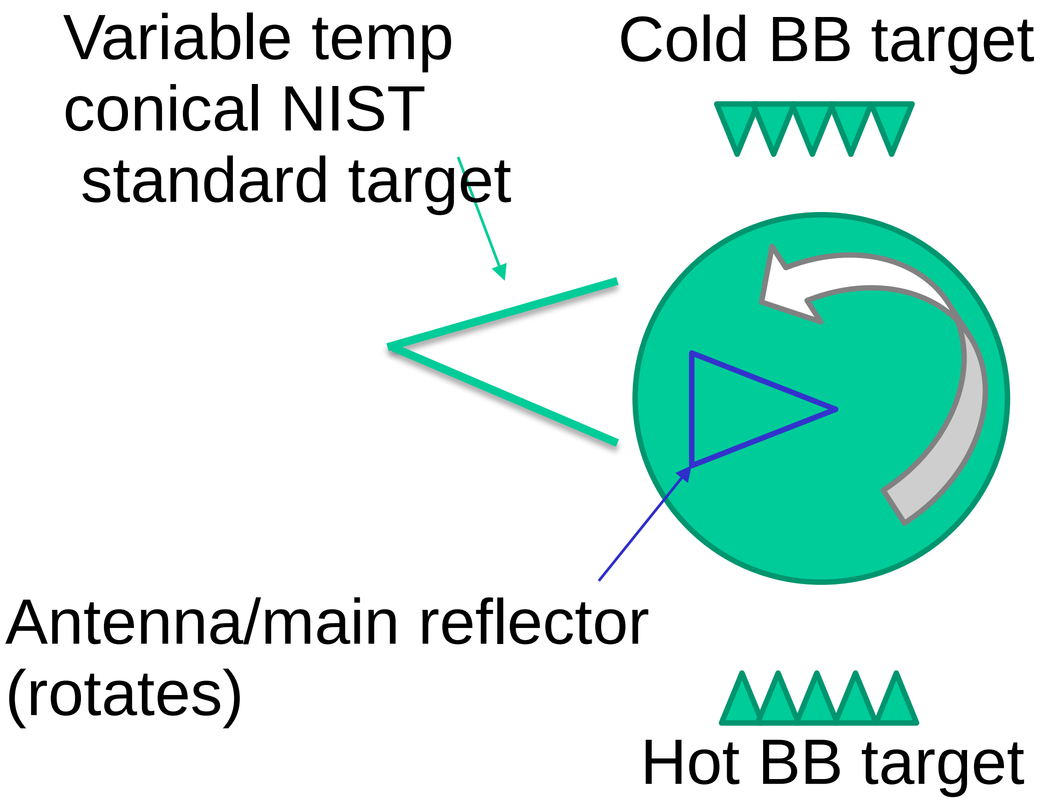
Traceable Calibration Methodology



Basic methodology:

- Alternately viewing reference target(s) while adjusting new target until radiometer raw response (counts) matches
- Results in transfer of cal to new target/system
- Status: additional engineering work needed
  - Thermal uniformity
  - Temperature range
  - Temperature sensors
  - Vacuum compatibility
  - adjust for coupling geometry

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Formal Standards for MW Radiometer Calibration

ISO 20930:2018--approved

Space systems — Calibration requirements for satellite-based passive microwave sensors

IEEE Geoscience and Remote Sensing Society (GRSS) has just started to explore whether to create an IEEE standard for calibration of all microwave radiometers (including ground & airborne)

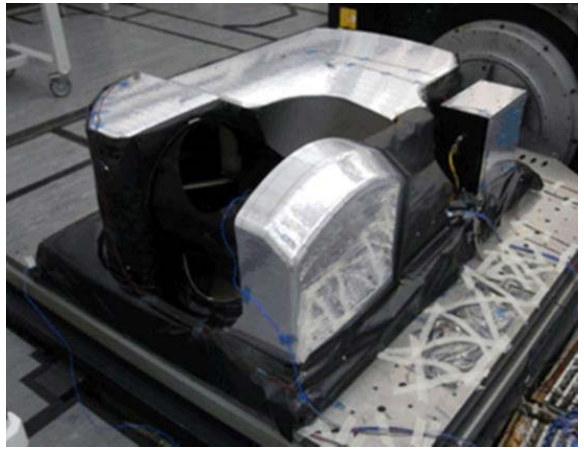
Potential Opportunities to Calibrate Future Satellite MW Radiometers

- Metop-SG radiometers (particularly MWI, MWS)
- ATMS beginning on JPSS-3 or 4
- AMSR x ?
- Cubesat radiometers
- Other future sounders & imagers

Radiometers under development at ESA

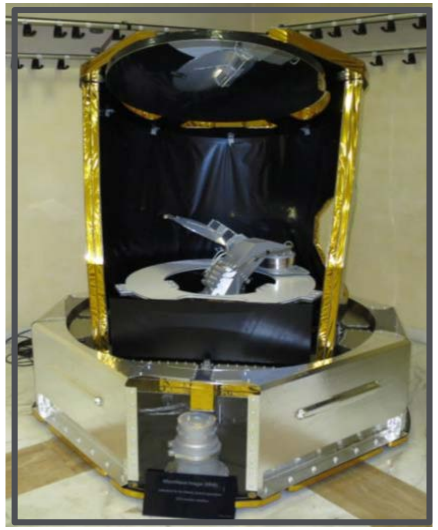
Microwave Sounder (MWS)

24 channels, 23 GHz -230 GHz
155 kg, 190 W
1m x 1.5m x 0.6m



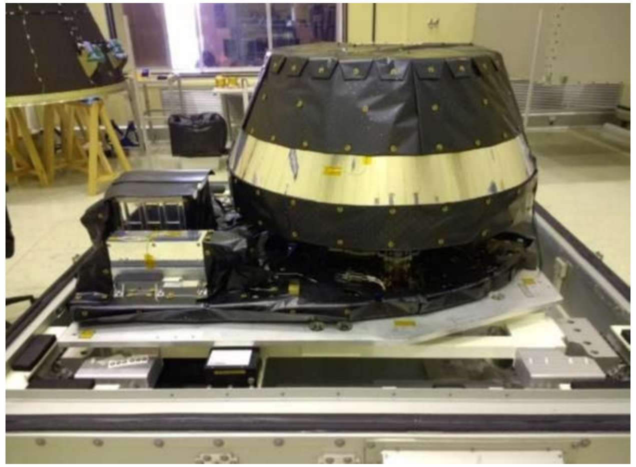
Microwave Imager (MWI)

26 channels (18.7 to 183 GHz)
285 kg (150 kg rotating), 250 W
2m x 1.4m x 1.4m



Ice Cloud Imager (ICI)

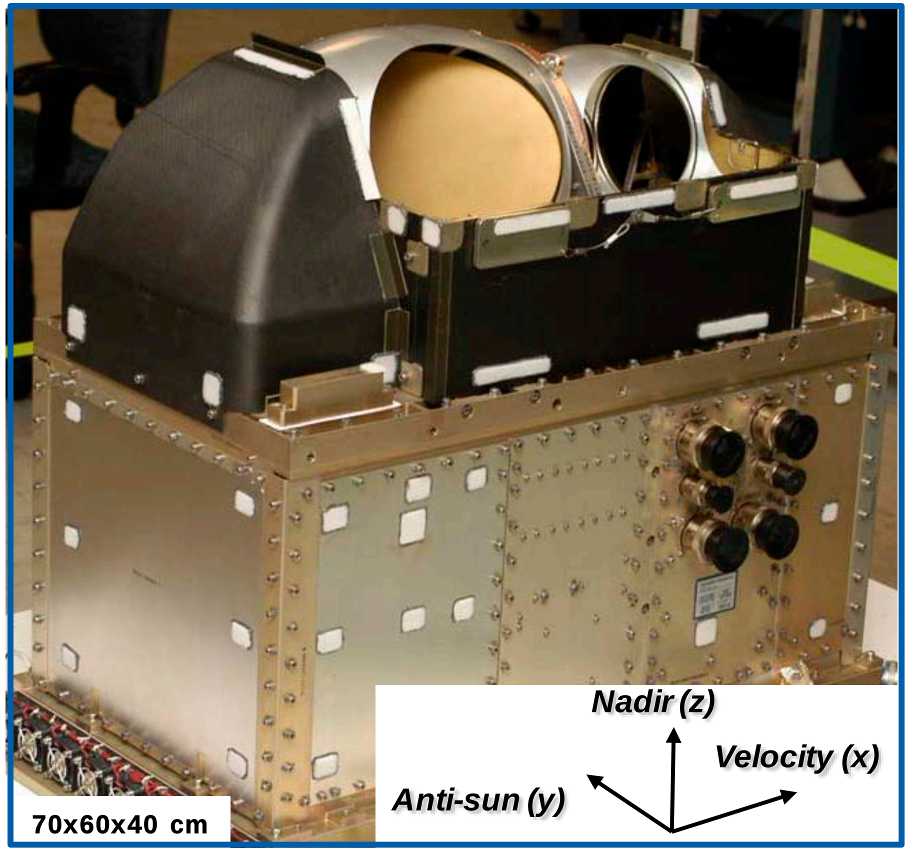
13 channels (183 to 664 GHz)
175 kg (68 kg rotating @45rpm),130 W
1.3m × 1.6m × 0.8m



3 flight models each will be launched between 2022 and 2036, providing operations at least until mid-2040's
MWS and MWI could benefit from SI traceability as similar instruments are operational or planned

Ville Kangas, ESA

Radiometers under development at NASA



ATMS

on

JPSS-2/3/4

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Status and Future Plans

Status:

- NIST prototype conical blackbody standard for TB has been designed/fabricated for 18-220 GHz
- Enables traceability to SI-kelvin & incorporation of rigorous standards-level quantification of Type A and Type B uncertainties
- Physical blackbody standard would enable rigorous pre & post-launch inter-calibration of constellation systems plus long time-series records (e.g., FCDRs) including gaps
- Absolute TB calibration would permit more realistic NWP uncertainty allocation (eventually leading to better forecasts) & enhance our ability to generate FCDRs from TB observations
- New standard ISO 20930 for satellite MW radiometer calibration

Future Plans:

- Additional development and analysis work on conical BB target; demonstrate practical calibration transfer to satellite instrument (ATMS?)
- Possible use with future Metop-SG radiometers and/or ATMS on JPSS-3 or 4
- IEEE standard being considered for MW radiometer cal (all MW radiometers, not just satellite)

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May 20, 2019
World Metrology Day

- Basic definitions of fundamental SI units will be updated
  - All 7 fundamental SI units will be quantum-based
- Example expected outcomes:
  - SI kilogram definition will go from a metal block to quantum-based
  - SI kelvin definition will become entirely quantum-based
  - https://www.bipm.org/en/measurement-units/rev-si/

Thank you!

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