SI Traceable Microwave Brightness Temperature Calibration/Inter-calibration: Benefits, Technology, and Needs

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OUTLINE

- Background and Motivation
  - Some MW calibration basics
  - Benefits of SI-traceable MW calibration
- Recent developments
  - NIST blackbody target
  - ISO standard
- Status & Future Plans

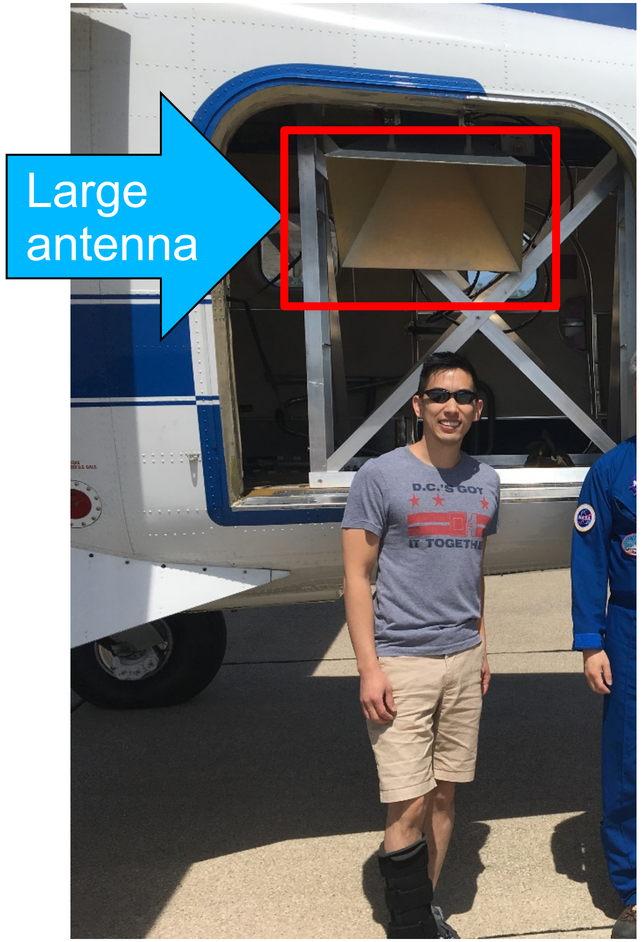
Background and Motivation

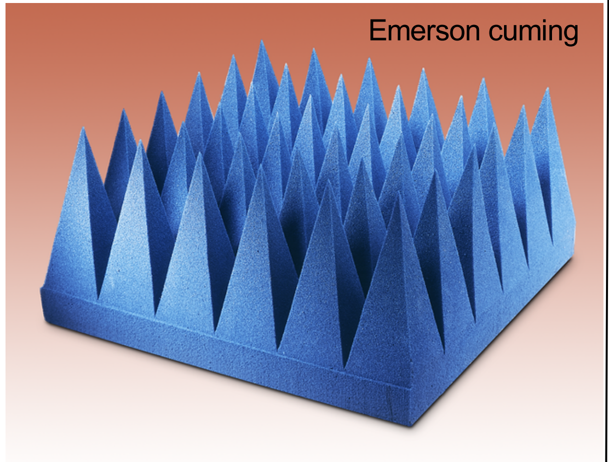
- MW radiometer calibration basics
- Benefits to NWP and FCDRs
- SI traceability
- Complementarity to GNSS-RO

Satellite Microwave Radiometer Calibration Basics

- Microwave radiometry ≈ thermal IR radiometry, but longer wavelengths & wider range
- Optical (vis—thermal IR): 0.4--12 μm (1.5 decades)
- Microwave: 1mm—1m (3 decades)
  - λ physically large → apertures can be small, e.g., 10—20 λ → diffraction not negligible → nearly everything is a source, some at 0.1% to 1% level
  - Antenna beam efficiencies typically 90—98% → sidelobes cannot be ignored
  - Antenna type/shape → practical limits on calibration strategies
- Focal plane architectures not an option
- Imaging usually by mechanical scanning of single-pixel sensors

Satellite Microwave Radiometer Calibration Basics

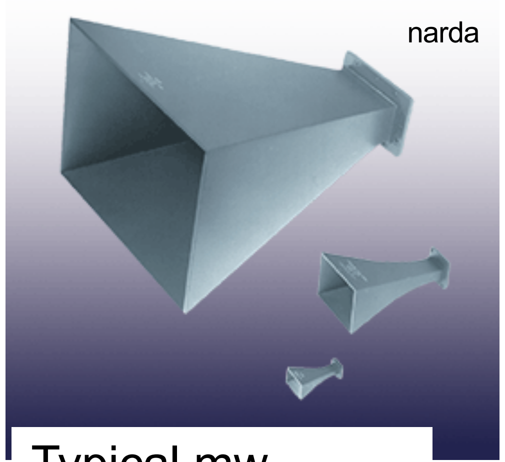




Typical anechoic chamber Microwave absorber used as blackbody: example above 80x80x35cm @1GHz

Rubber foam w/carbon particles

NIST traceable PRTs embedded in blackbody



Typical mw Horn antennas @ different bands

Horn antennas with lenses

Solid pyramidal Blackbodies of different sizes
20-200 GHz
Epoxy loaded w/iron particles
NIST PRTs

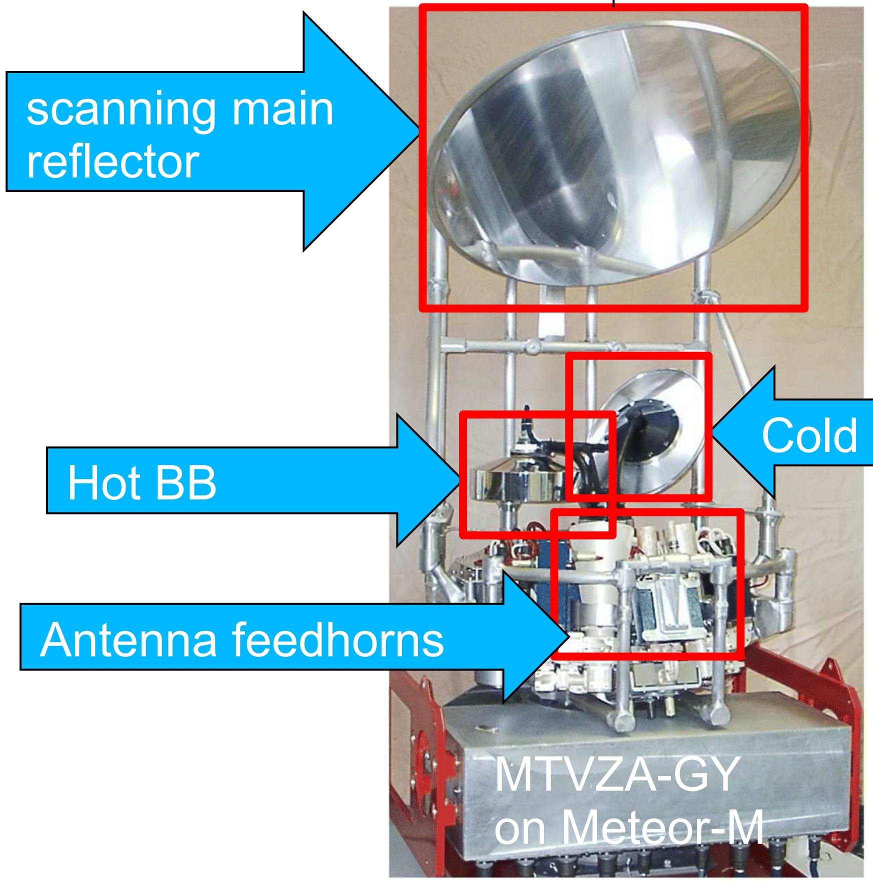
“Patch” printed circuit antenna

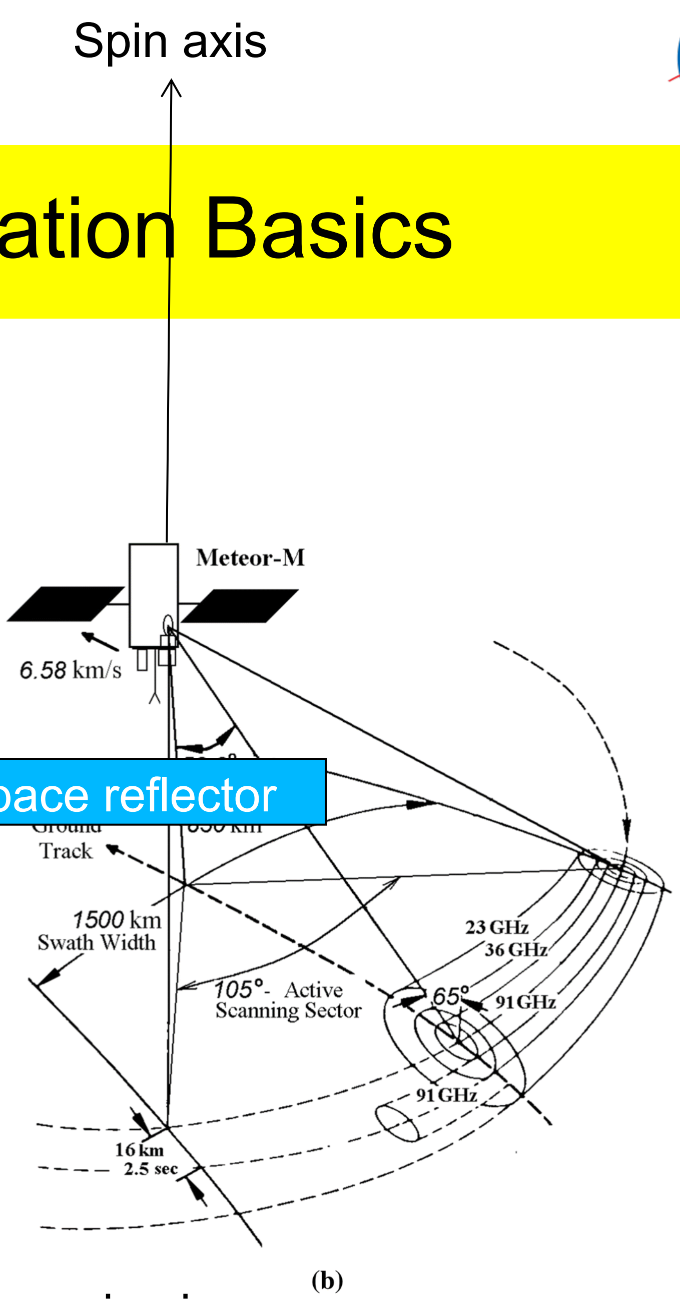
Satellite Microwave Radiometer Calibration Basics

Satellite conical scanning MW imager configuration

Calibration by on-board hot BB and cold space view

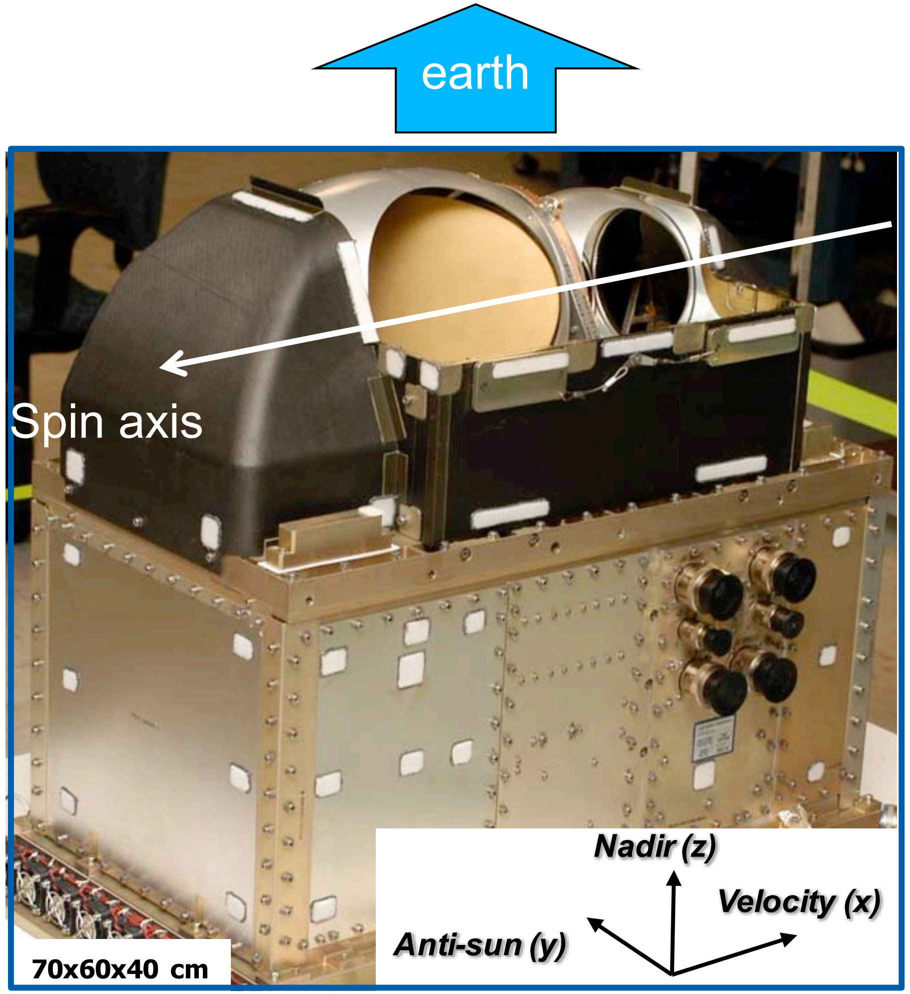
AMSR-E microwave imager on Aqua (JAXA/NASA)





Same configuration used by nearly all satellite conical scanning imagers since 1980s: SSMI,SSMIS,AMSR-E/AMSR2, WindSat, TMI, GMI, etc.

Satellite Microwave Radiometer Calibration Basics

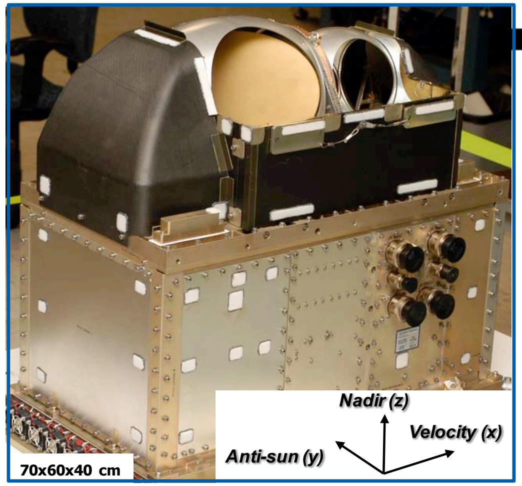


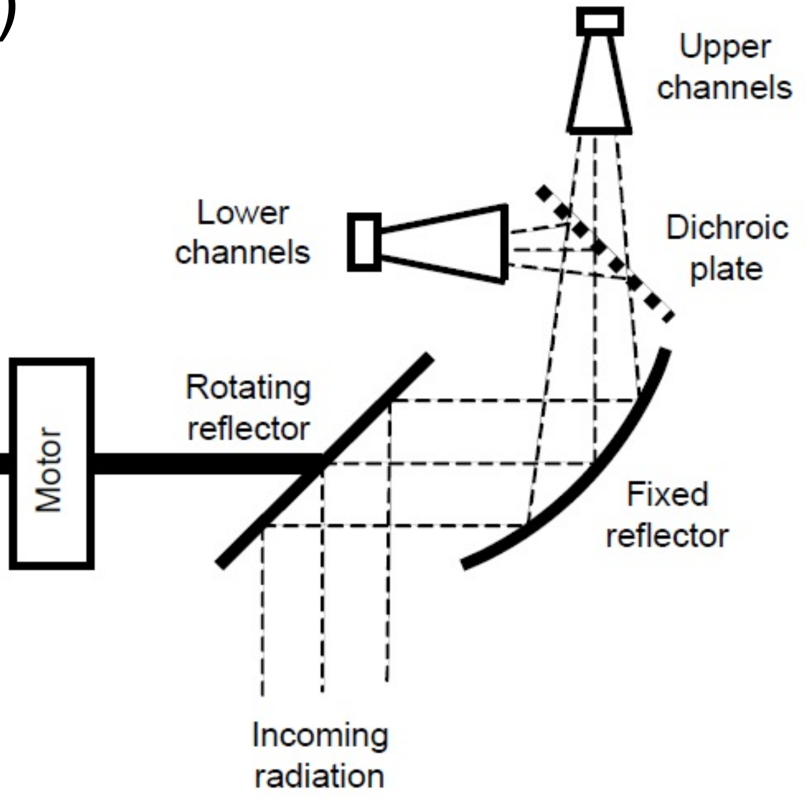
Example: ATMS

- Overall size: 70 x 60 x 40 cm; 80kg
- Rotating reflector design
- Single linear polarizations, 22 channels
- 23—183 GHz sounder
- Aperture sizes small (~ 20—30 cm)
- Beam-filling onboard cal target feasible
- Hot cal target = solid blackbody
- Cold cal target = cold space view
- Cal every scan (8/3 seconds)
- Limited thermal stabilization
- Cal combines pre & post launch meas

Satellite Microwave Radiometer Calibration Basics

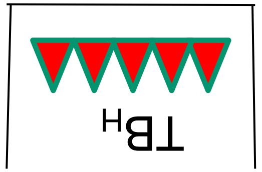
Example: cross-track spaceborne scanner (ATMS)

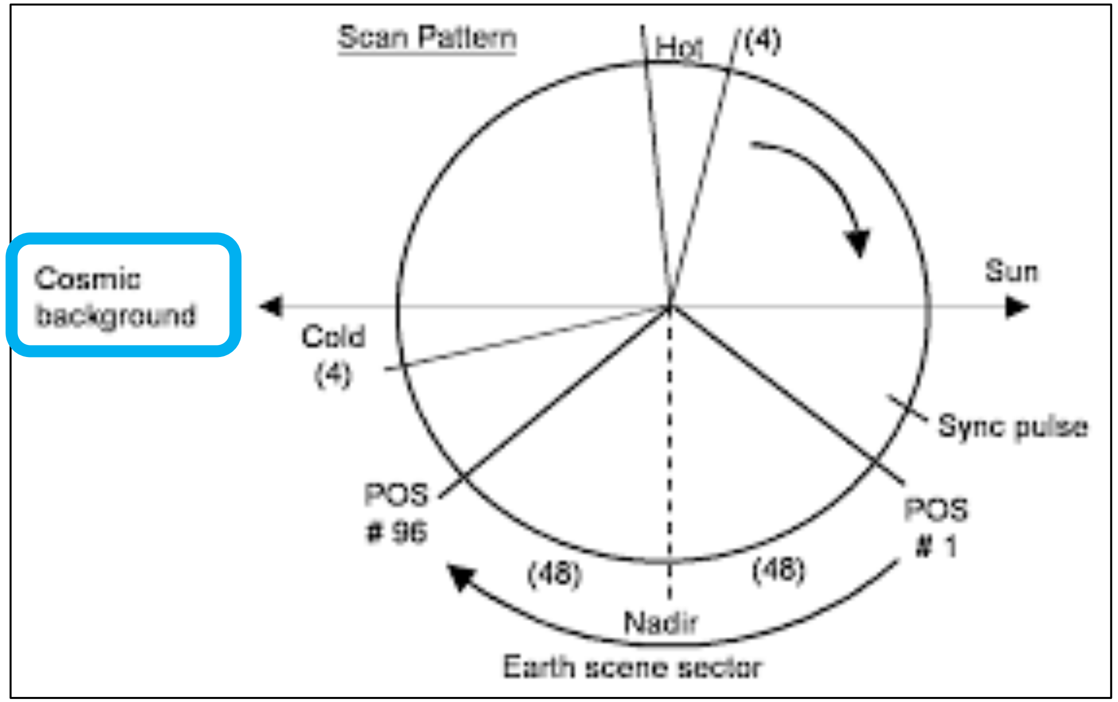




Hot BB target @T_H

Hot/cold calibration every scan (8/3 sec)





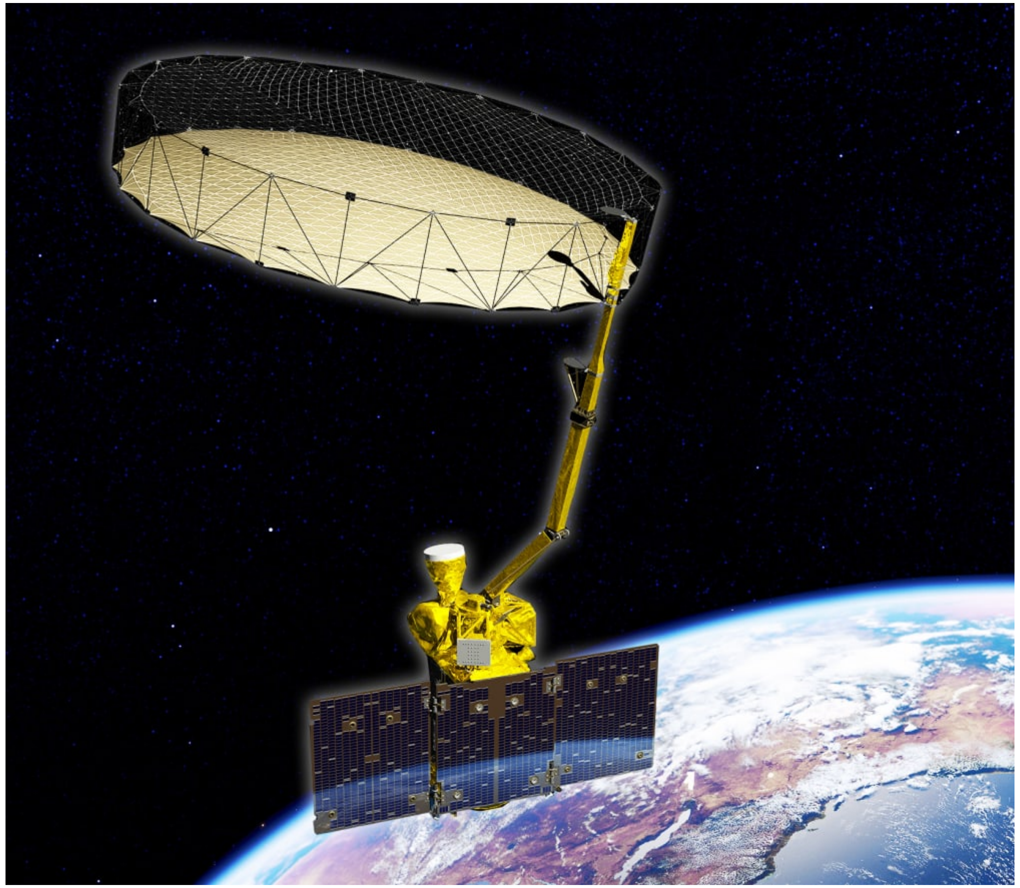
Same configuration used by nearly all satellite scanning sounders since 1970s: MSU, AMSUs, MHS, ATMS, etc.

Satellite Microwave Radiometer Calibration Basics

- Beamfilling cal targets often not practical on board satellites (AMSRx, SMAP, SSMI, etc)
- Cold space is an excellent calibration reference (primary standard), but
  - Pure cold space view is difficult to achieve; nearby on-board structures contaminate view → bias
  - Cold space cal bias can be function of Earth scene
  - Through-the-main-reflector viewing may require flipping satellite upside down → changes thermal environment
- Still need a hot cal target or reference for 2-point cal
- If not including main reflector in on-orbit cal path, hot & cold cal can be compact
- Current calibration methodology OK for current NWP purposes
- Achieving climate-level calibration (tenths of degree/decade): extremely challenging
- But any advancements could leverage the 40-year MW sounder record

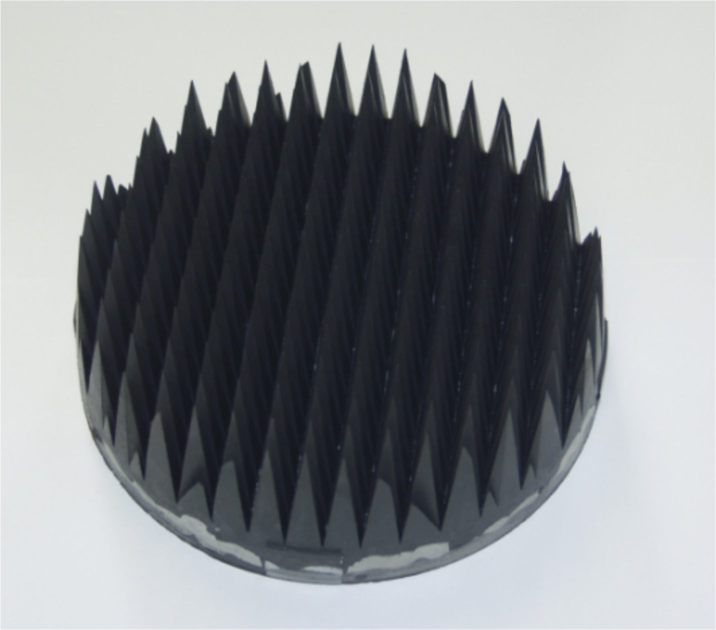
Satellite Microwave Radiometer Calibration Basics

Example: SMAP (Soil Moisture Active Passive)



- Passive @ 1.4 GHz → 21 cm wavelength
- Rotating reflector design
- Aperture diameter 6m
- Beam-filling onboard cal target not feasible
- Hot cal targets = vicarious (ocean, Antarctica)
- Cold cal target = cold space view, monthly flip
- Internal references for shorter time scales
- Active thermal stabilization
- Cal combines pre & post launch meas

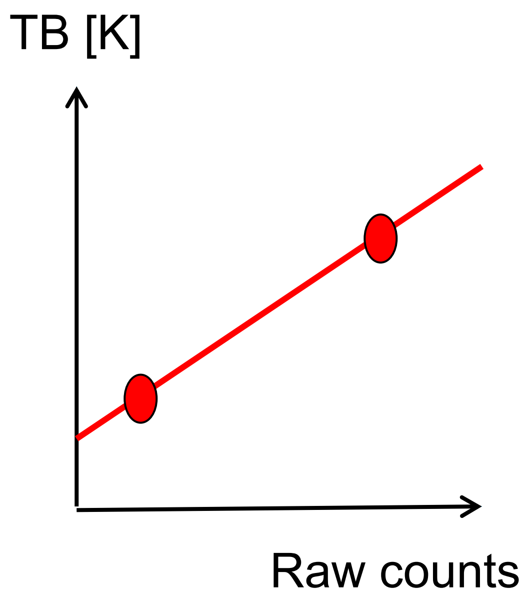
Typical MW Radiometer TB Calibration



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

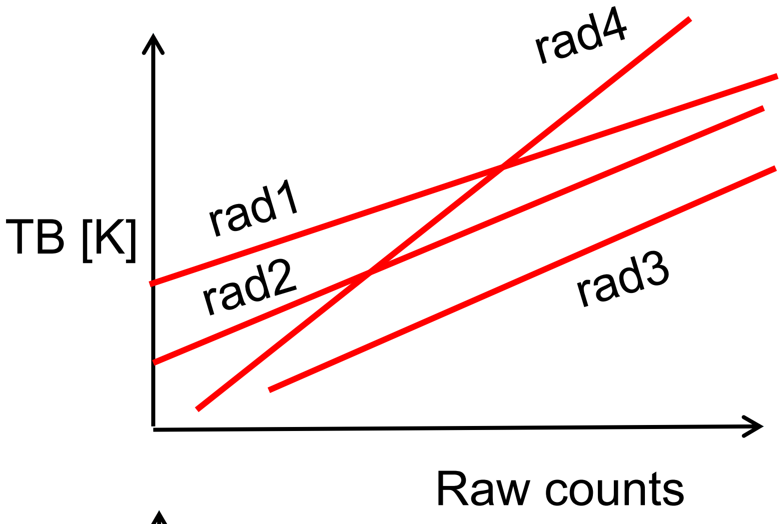
(highly simplified version)

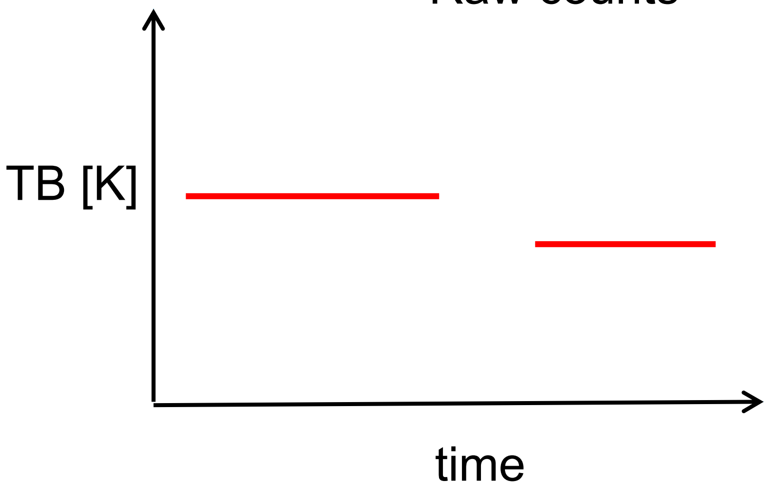
- Build your radiometer as linear as practical
- Point it at 2 calibration targets (1 hot, 1 cold) to determine the cal curve (a line)
- Cal targets are typically black bodies with emissivity ~1, so TB = physical temperature



Benefit to Constellation Systems

- Single radiometer TB calibration scenario on previous slide
- Constellation systems need TB inter-calibration
- Example: full sounders + cubesats
- 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
- 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





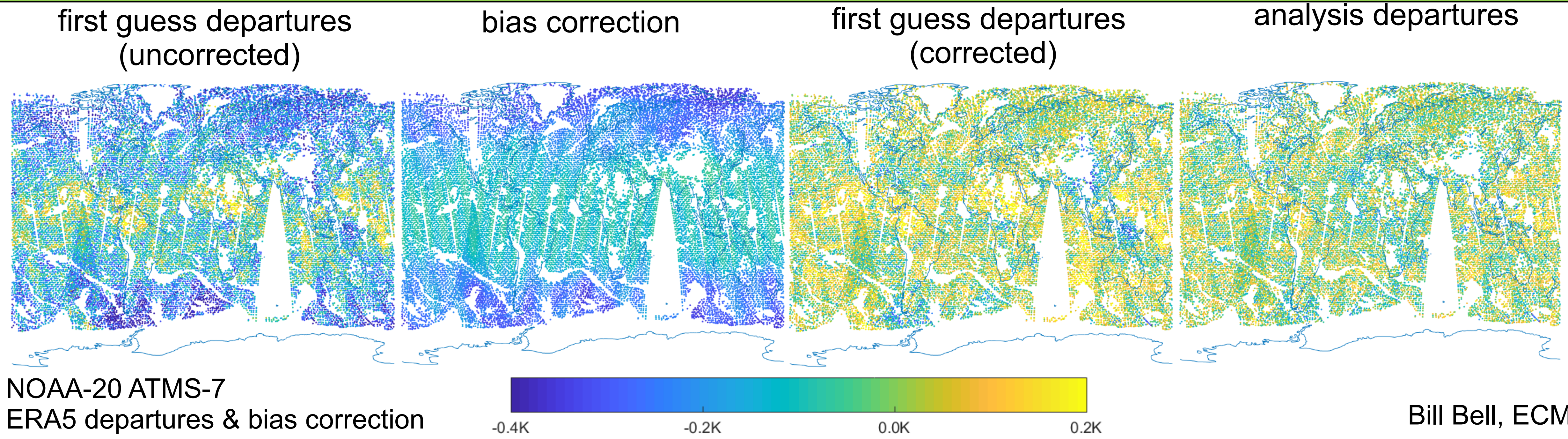
Absolute TB Calibration & NWP Model Biases

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

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

- Bias corrections can be 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

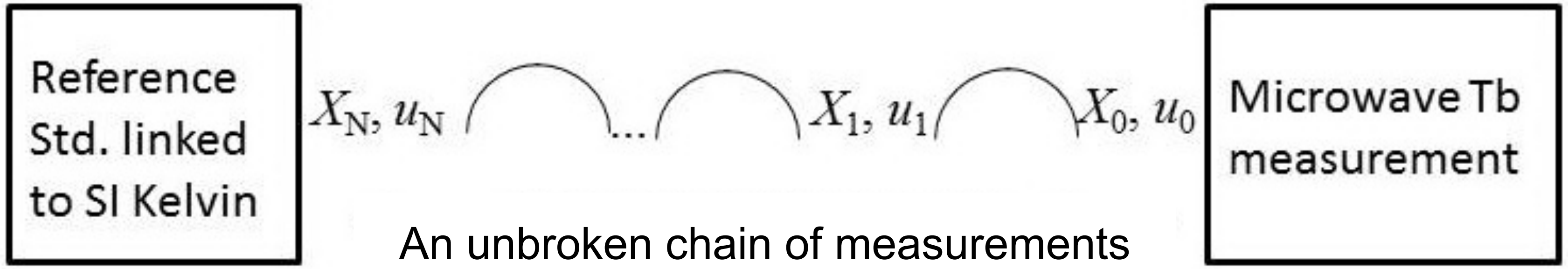
Bill Bell, ECMWF

- 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)

SI Traceable Cal Benefits to FCDRs

- The rigorous uncertainty quantifications as part of traceable TB calibration will assist with generation of Fundamental Climate Data Records (FCDRs) that span multiple generations of MW radiometers
- You'll know the uncertainty contributions more accurately
- Traceable calibration to an external standard helps span multiple sensors and sensor generations, even if temporal gaps occur on-orbit (vicarious Earth targets can also span gaps, but how well do you know their true TB over time?)
- From a EUMETSAT brochure: "Production and continuous improvement of FCDRs are therefore a top priority for EUMETSAT." "…time series from several successive instruments can be…cross-calibrated against data from an external…reference…" "…uncertainties assessed through validation against independent reference data."

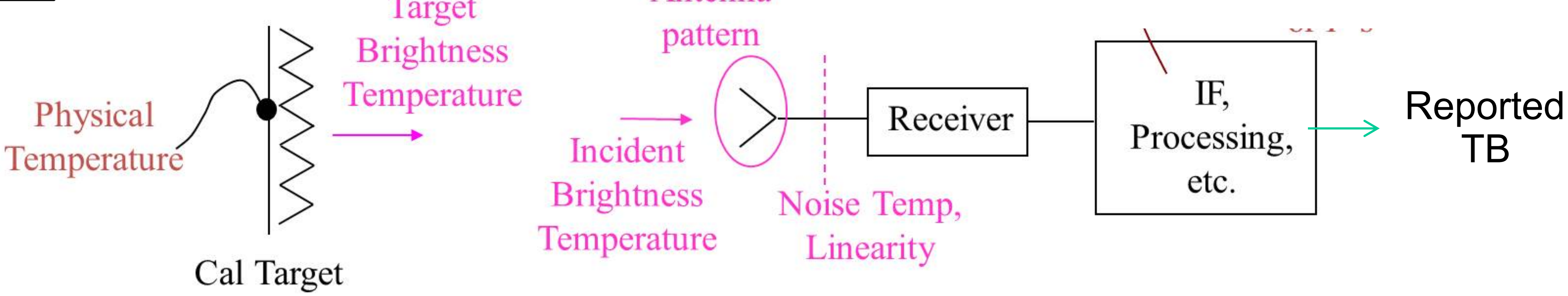
Defining what “SI-traceability” **is**



An unbroken chain of measurements back to an SI standard, yields an SI-traceable TB measurement

Uncertainties are rigorously quantified for each link in the chain

Results in total uncertainty w/respect to the standard being rigorously quantified



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

- GPM X-cal example: constellation radiometer TBs harmonized 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 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 temp, 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

Recent Developments

- NIST blackbody target
- Traceable calibration methodology
- ISO standard

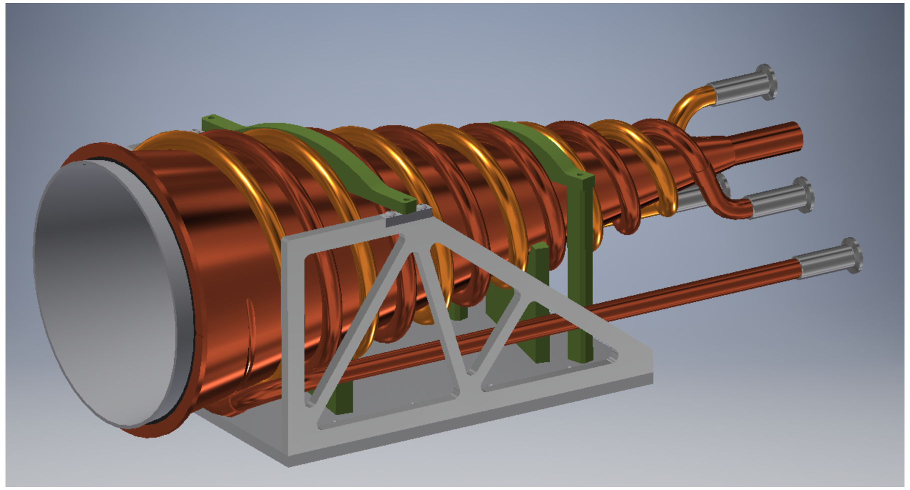
NIST Blackbody Calibration Standard

Broadband passive microwave blackbody

- NIST primary standard; SI traceable to kelvin
- 18-220 GHz design frequency range

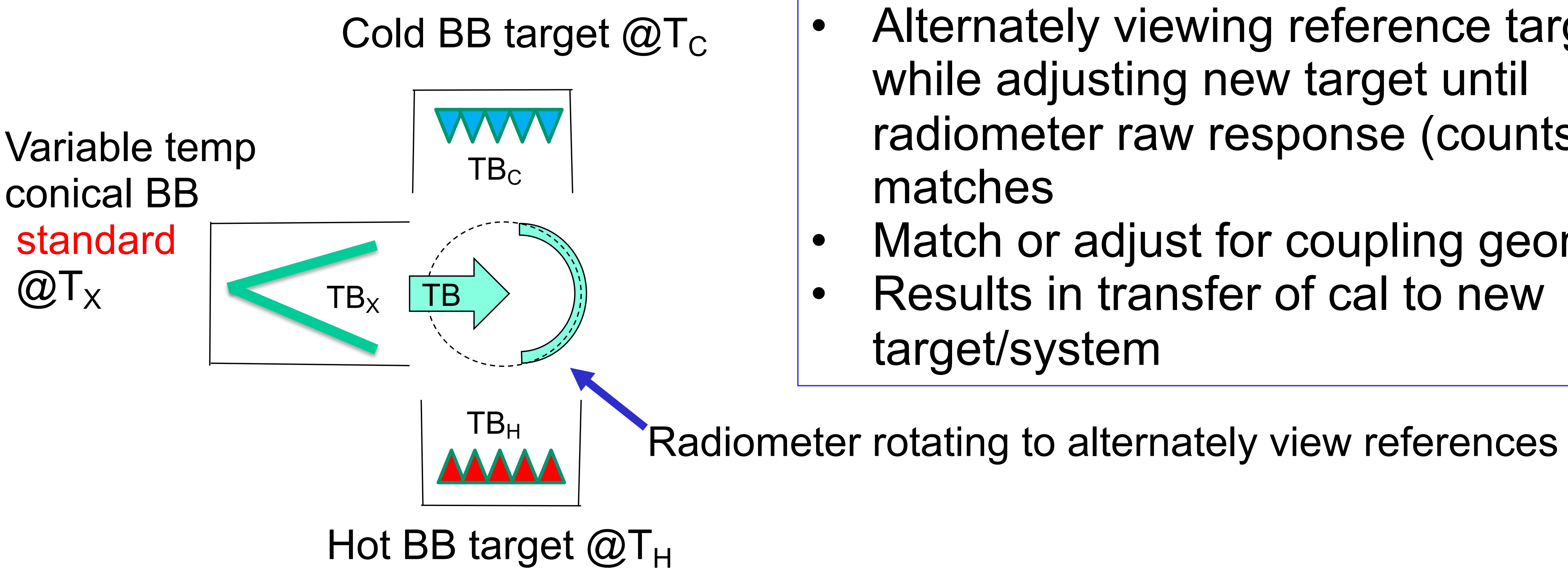
Design requirements:

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



Hollow Cone geometry

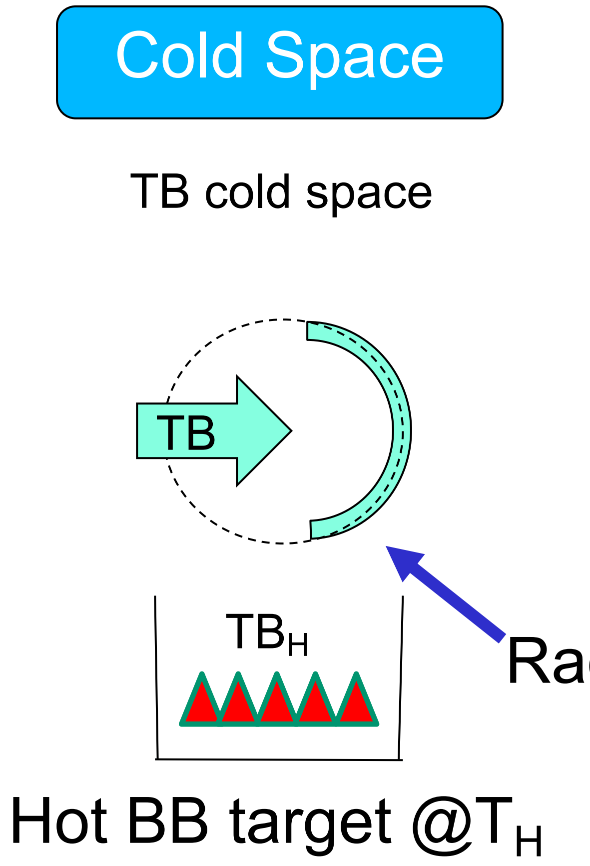
Traceable Calibration Methodology Pre-Launch



Basic methodology:
- Alternately viewing reference target(s) while adjusting new target until radiometer raw response (counts) matches
- Match or adjust for coupling geometry
- Results in transfer of cal to new target/system

Traceable Calibration Methodology Post-Launch

Basic methodology:
- Hot BB target same as pre-launch
- Cold BB target replaced by cold space
- $TB_{\text{cold space}}$ is a primary standard



Radiometer rotating to alternately view references

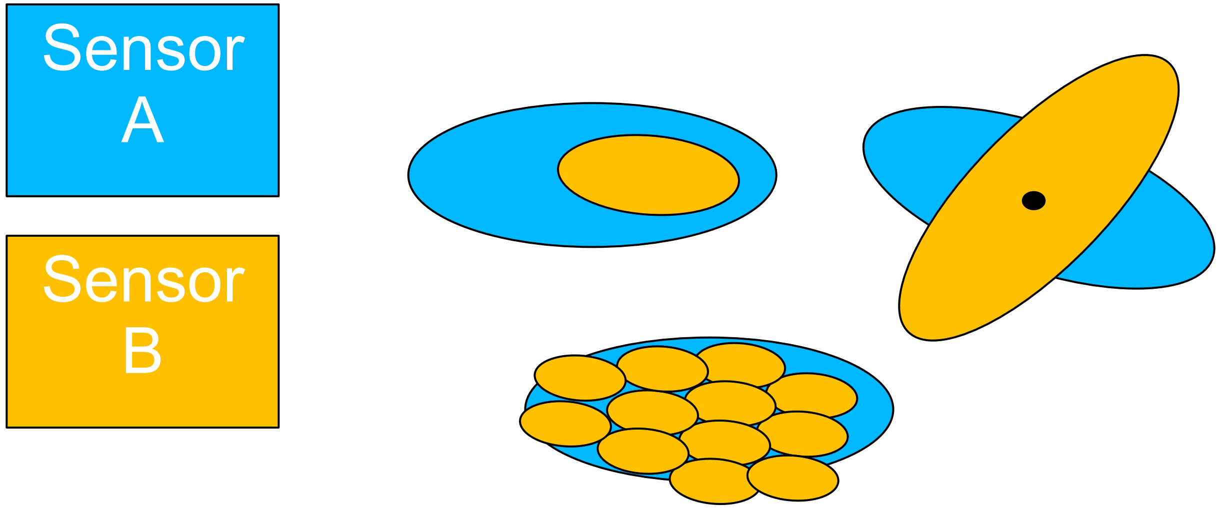
Inter-Calibration: other considerations

General (independent of Inter-cal approach)

- Polarization
- Spectral range (SRF)

If using vicarious inter-cal

- Footprint matching
- Incidence angle
- Azimuth angle



New ISO Standard on Satellite MW Radiometer Calibration

ISO 20930:2018

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

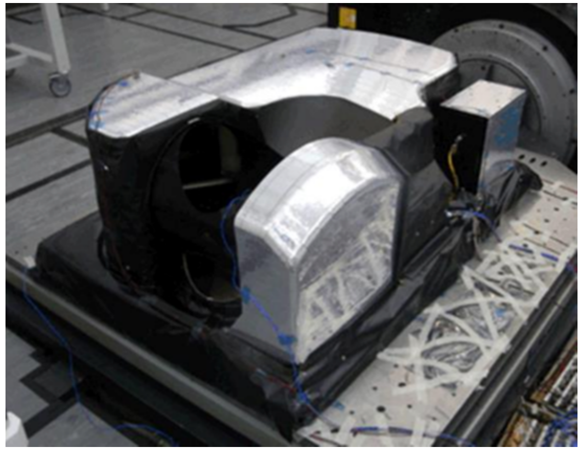
"This document standardizes calibration methods (requirements and verification methods) to minimize errors of observation data among passive microwave sensors. It is expected that this document can improve the accuracy of weather forecasts, ... Moreover, these observations can provide useful information for climate change prediction ..."

Potential Opportunities to Calibrate Future Satellite MW Radiometers

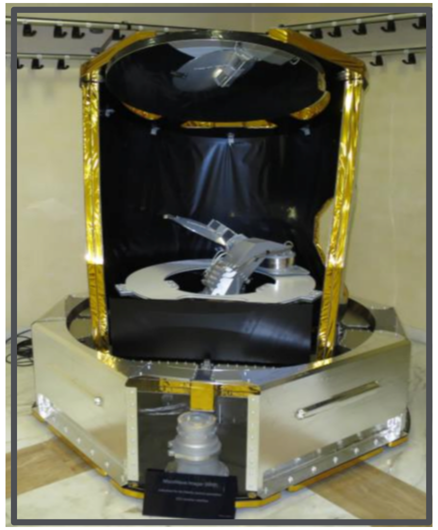
- Metop-SG radiometers (particularly MWI, MWS)
- ATMS beginning on JPSS-3 or 4
- AMSR x ?
- Cubesat radiometers
- Other future sounders & imagers

Radiometers under development at ESA

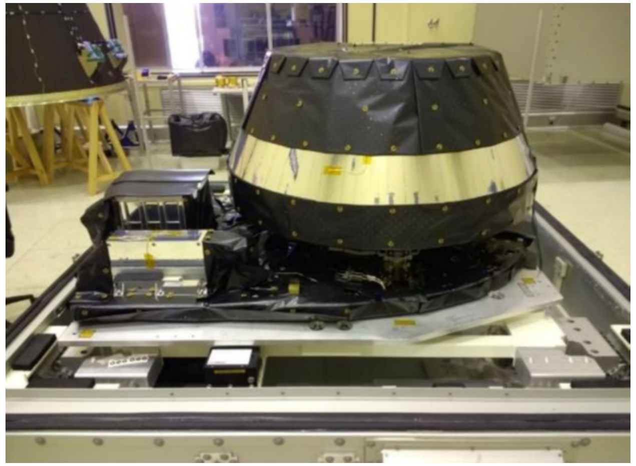
Microwave Sounder (MWS)
24 channels, 23 GHz -230 GHz
155 kg, 190 W
1m x 1.5m x 0.6m



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



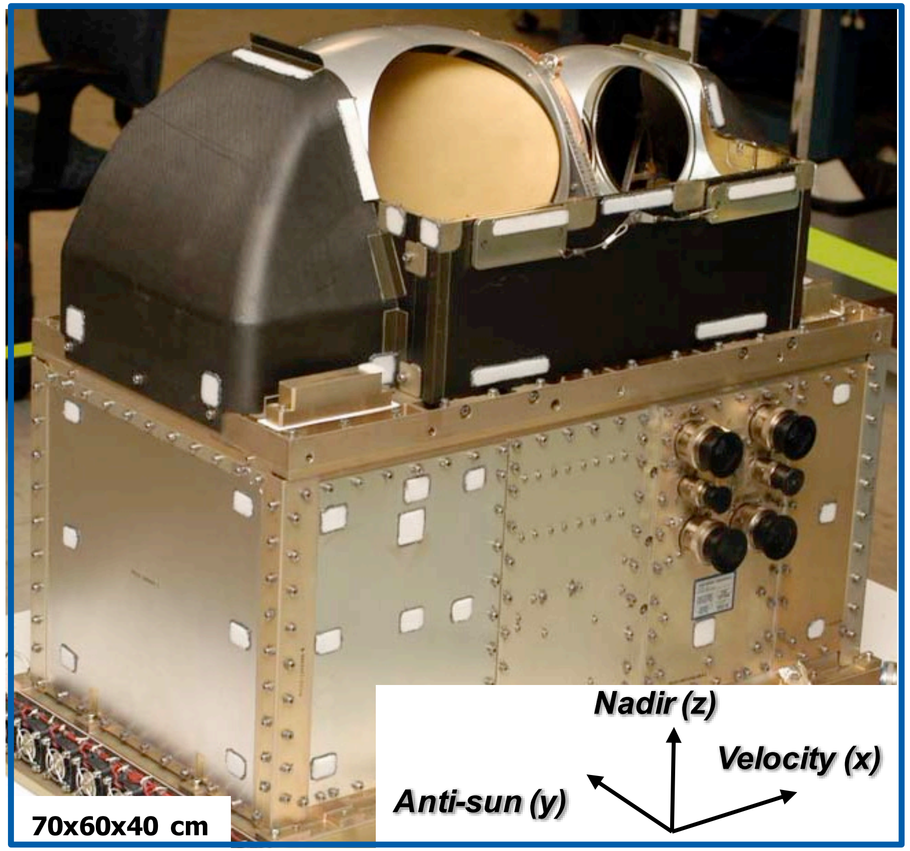
Ice Cloud Imager (ICI)
13 channels (183 to 664 GHz)
175 kg (68 kg rotating @45rpm),130 W
1.3m × 1.6m × 0.8m



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-3
JPSS-4

Status and Future Plans

Status:

- Waveguide blackbody standards already exist; swaps w/antenna so cannot calibrate end-to-end
- 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 while performing *radiative* end-to-end calibration (if aperture size permits)
- Enables desirable pre & post-launch inter-calibration strategies for constellation systems plus long time-series records (e.g., FCDRs) including gaps
- Enables *absolute* TB calibration. permitting more realistic NWP uncertainty allocation (eventually leading to better forecasts) & enhances our ability to generate FCDRs from TB observations
- New standard ISO 20930 for satellite MW radiometer calibration (general, not specific to conical BB target)

Future Plans:

- Additional development work on conical BB target; demonstrate practical calibration transfer
- Possible use with future Metop-SG radiometers and/or ATMS on JPSS-3 or 4 and/or others