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Climate-quality Calibration for LEO-microwave Radiometry

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11 September 2019

SI-Traceable Space-based Climate Observing System

CEOS & GSICS Workshop

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Outline

- Spaceborne Microwave Radiometry and Climate Monitoring
- Spaceborne Climate-quality Reference Radiometer
- Long-term Stability (SI traceable)
- Optimal Orbit
- Improved Climate Science
- Conclusion

Spaceborne Microwave Radiometry and Climate Monitoring

- **Temperature is the fundamental climate variable most directly affected by the accumulation of greenhouse gases in the atmosphere**
- **Tropospheric oxygen is a stable tracer for climate monitoring**
- **Microwave radiometry directly measures the thermal emission of the diatomic oxygen, which is related to its physical temperature**
- **Microwave thermal emission from molecular oxygen in the middle troposphere is relatively insensitive to water vapor, the earth's surface, and cloud (e.g., cirrus) variation**
- **Passive microwave radiometers have been taking tropospheric measurements near oxygen lines consistently since 1979**

Spencer *et al.* "Global atmospheric temperature monitoring with satellite passive microwave measurements: methods and results 1979-84," J. Climate, 1990, 3, 1111-1128

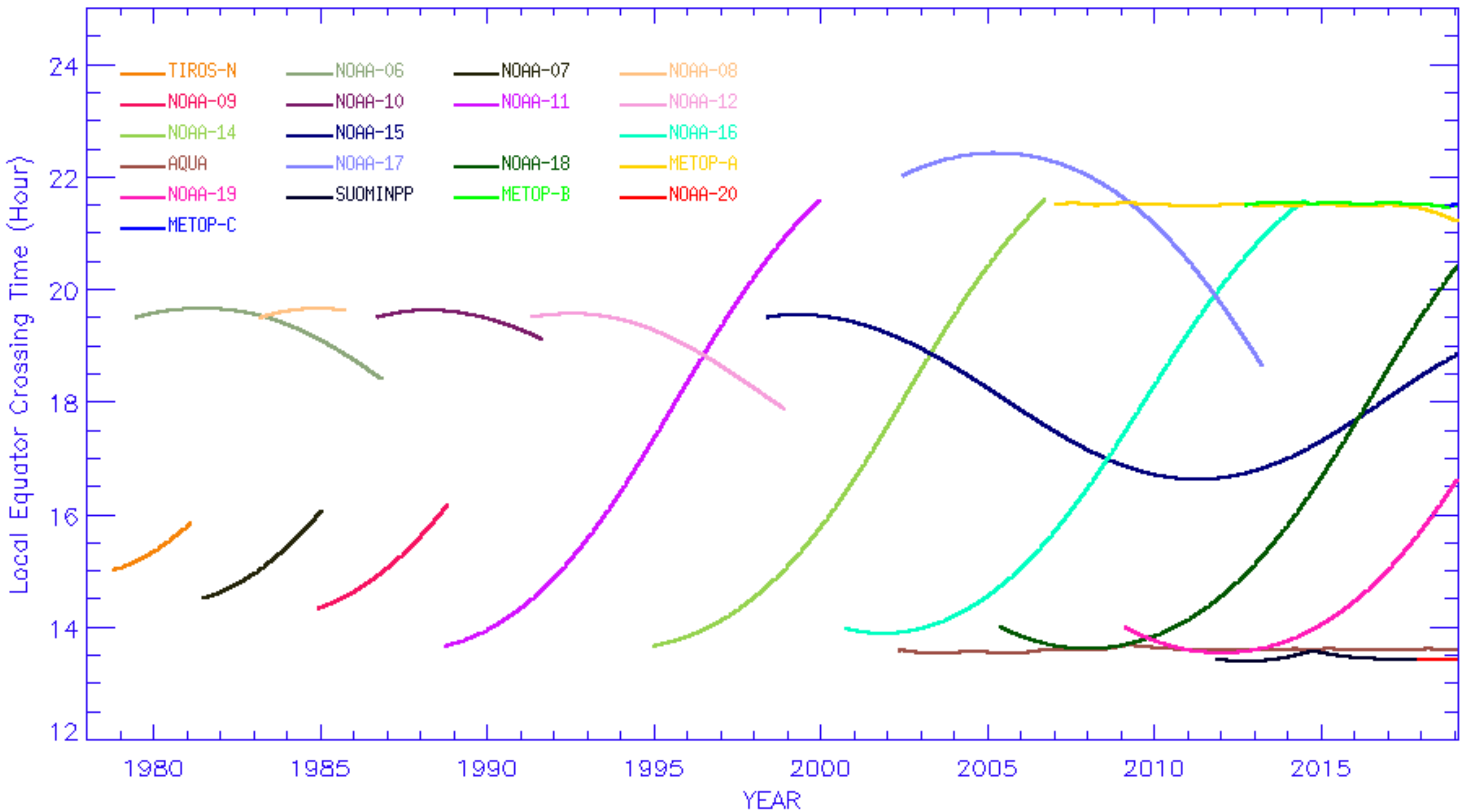
Problem

- Projection of future changes in climate due to the accumulation of anthropogenic gases in the atmosphere is one of the main goals of NASA's Earth Science program
- Ensuring a continuous record of temperature is critical both to characterize our changing climate and to evaluate climate models
- Microwave sounders provide upper air temperature measurements, but have exhibited problems in the past:
  - Calibration drifts
  - Instrument nonlinearities
  - Inconsistent measurement times (i.e., diurnal variation)

Issues with Climate-quality Microwave Measurements

Calibration problem with NOAA MSU/AMSU	Solution	S-NPP and NOAA ATMS	MetOp AMSU
Seasonal and orbital thermal variation	Enhanced spacecraft thermal interface	Yes	Better
Channel frequency drift	Phase-locked local oscillators	Yes	No
Orbit decay changes observation angles	Satellite orbit stabilization	Yes	Yes
Orbit drift introduces diurnal variation	Satellite orbit stabilization	Yes	Yes
Reflector spillover	Eliminate reflector	No	No
Gain change impacts calibration through nonlinearity	Better than two-point calibration	No	No
Possible changes in target temperature sensors or emissivity in space environment?	Onboard GPS-RO cross-calibration	No	Yes, but not collocated

Spaceborne Microwave Sounding Missions (MSU, AMSU, or ATMS)



NOAA NESDIS STAR

Climate-quality Solution

Our goal is to improve the accuracy of adjustments for non-climatic artifacts in the satellite temperature record by developing a mission that:

- **Future measurements: Continues the accurate temperature record**
  - **Requires channels that duplicate the small number operational sounder channels that are used for climate trends**
  - **Need to have excellent linearity and stability, accurate calibration, and very low antenna-sidelobe contamination**
- **Past measurements: Improves correction factors in heritage sounders**
  - **Requires channels that duplicate the small number of heritage operational sounder channels that are used for climate trends**
  - **Has an orbit that measures the diurnal-cycle climatology that will provide the information needed to address the largest component of trend uncertainty in the 36-year temperature record**

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Features Desired for a Microwave Reference Instrument

- A phase-locked local oscillator to prevent frequency drift.
- A low-sidelobe horn antenna without a reflector, to eliminate spillover of energy at the edge of the reflector.
- Extra emphasis during design and integration on linearity.
- An internal noise diode to provide correction of residual non-linearity (i.e., four-point calibration)
- Dual-polarization measurements to allow exact cross-calibration with rotating-polarization instruments like ATMS.
- Dicke-switching or some other means to reduce sensitivity to short-term gain fluctuations within the calibration cycle (i.e., 1/f noise)
- The scan should include the earth limbs for cross-calibration of limb radiometric measurements to GPS radio-occultation.
- The orbit should facilitate cross-calibration with instruments on several weather satellites (e.g. 90°-inclination orbit).
- Stabilized orbit altitude.

Instrument characteristics for the 50-60 GHz band

Specification	Value	Comments
(Noise-equivalent ΔT) $\cdot\tau^{1/2}$	≤ 0.05 K $s^{1/2}$	
Absolute accuracy of calibration	±0.1 K	for antenna temperature
Long-term stability of calibration	±0.01 K $yr^{1/2}$	with GPS-RO cross-calibration
Lifetime frequency stability	±1 MHz	with phase-locked LO
Antenna 3-dB FWHM beamwidth	5°	from Blackwell et al. (2014)
Antenna stray factor (1-η)	≤1 %	>15° from center
Antenna off-earth stray factor	≤0.03 %	for nadir view
Non-linearity max. deviation (before correction)	≤0.1 K	for $3 \leq T_A \leq 300$ K

The first four are k=1 uncertainties; the others are upper limits. These should be achievable with currently available technology.

Potential Channel Set for Climate Record

Ch.	Center Frequency (GHz)	Bandwidth (MHz)	Notes
1	50.300	180	MSU-1, AMSU-3, & ATMS-3
2	52.800	380	AMSU-4 & ATMS-5
3	53.452	220	Averaging Ch. 3 & 4, simulates AMSU-5 and ATMS-6
4	53.740	220	MSU-2 (Mid-troposphere)
5	54.400	220	Weighted difference of Ch. 4 & 5 yields lower troposphere; ~AMSU-6 & ATMS-7
6	54.960	220	MSU-3, ~AMSU-7, & ATMS-8 (troposphere)
7	55.500	330	AMSU-8 & ATMS-9
8	57.290	330	AMSU-9 & ATMS-10 (lower stratosphere)
9	57.950	220	MSU-4 (lower stratosphere)

Frequency Allocations for ATMS V-band Channels

- **50.2-50.4 GHz (ATMS ch. 3) is reserved for passive use only.**
- **51.4-52.6 GHz (containing ATMS ch. 4) is allocated to fixed and mobile services.**
- **52.60-54.25 GHz (containing ATMS ch. 5, 6) is reserved for passive use only.**
- **54.25-55.78 GHz (containing ATMS ch. 7, 8, 9) is shared with geostationary inter-satellite communication.**
- **57.0-58.2 GHz (containing ATMS ch. 10-15) is shared with geostationary inter-satellite, fixed, and mobile services. Because of the high opacity (>100 dB) of the atmosphere in this band, earth-based transmitters are not expected to interfere.**

It is possible that occasional interference would be encountered from inter-satellite transmissions, or from the sun or moon, when the antenna is in one of the space-cal or limb-viewing positions, so prediction or detection measures would be necessary.

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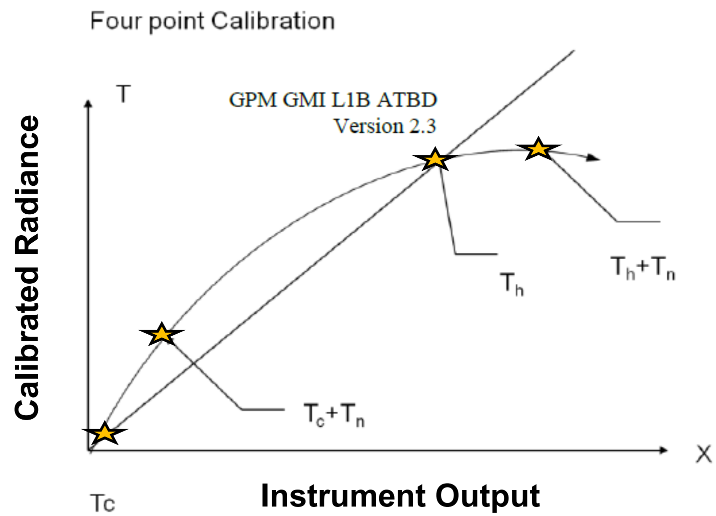
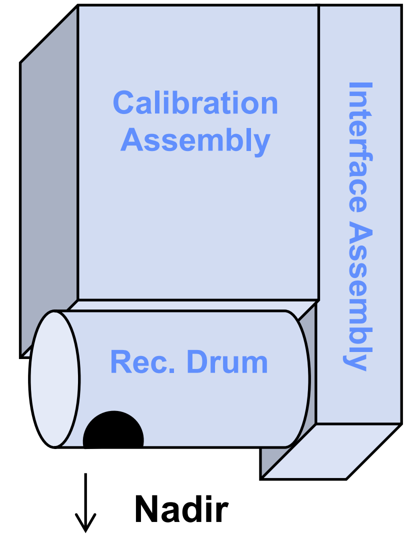
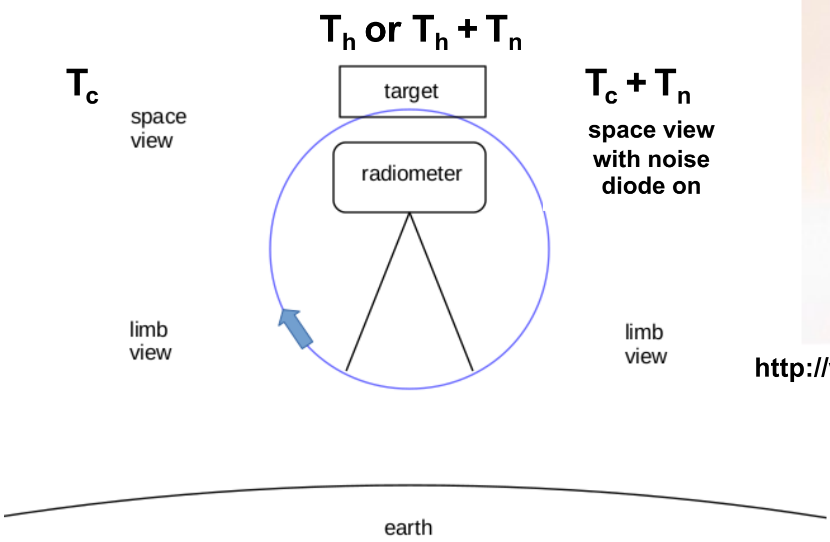
Calibration

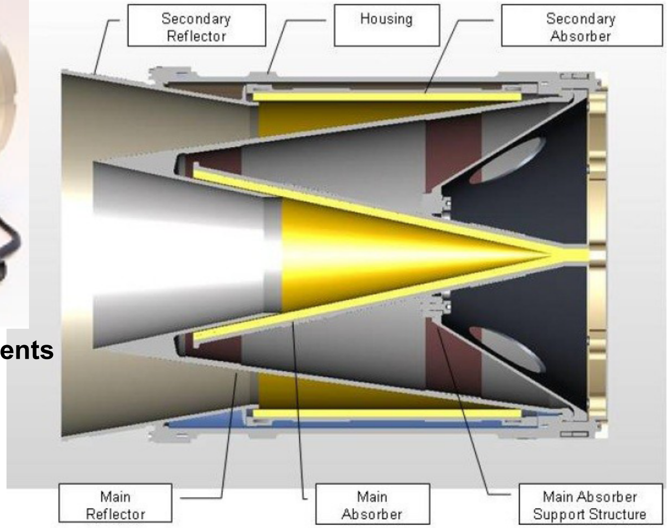


Isometric cartoon





http://www.terahertz.co.uk/tk-instruments



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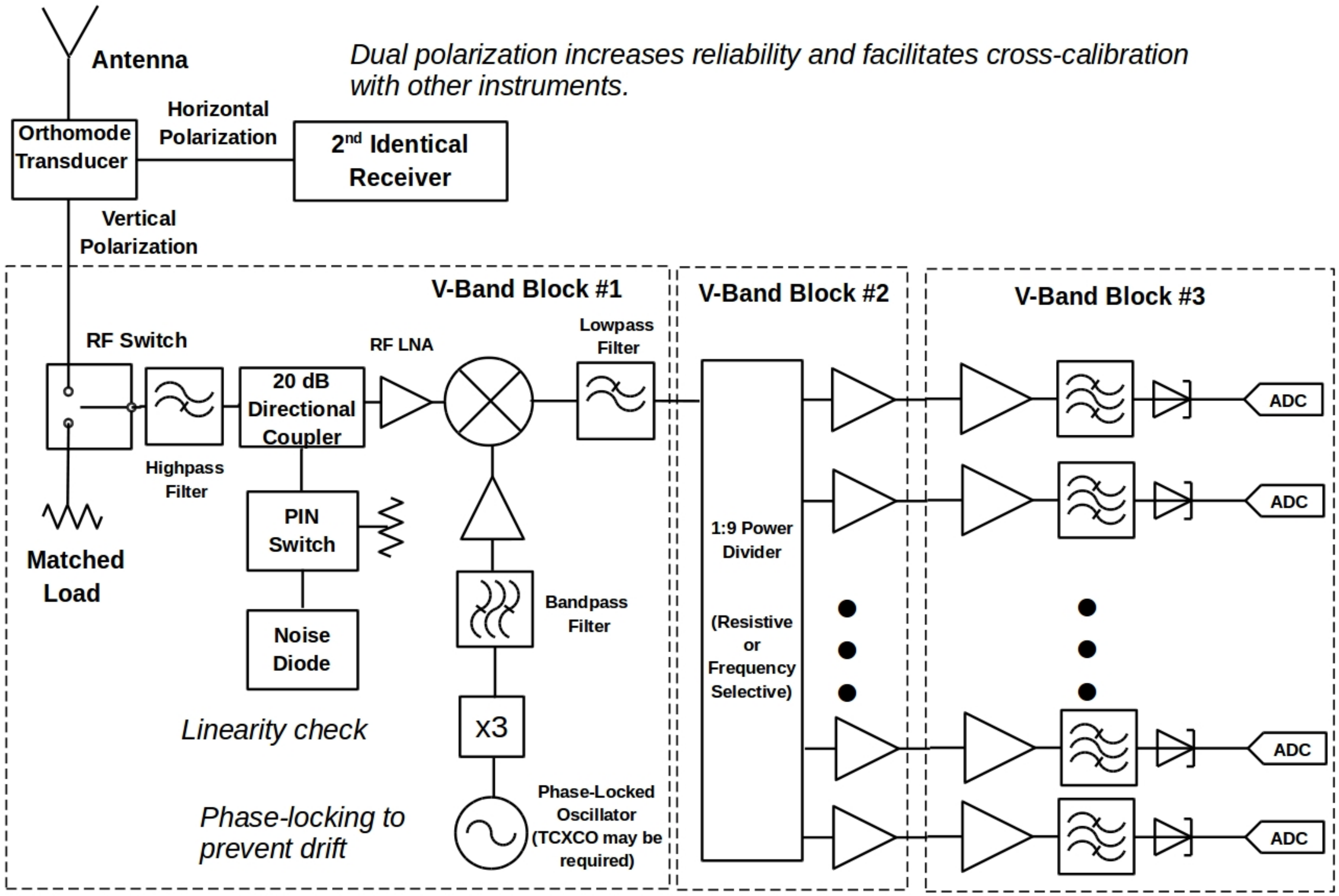
Potential Receiver Architecture



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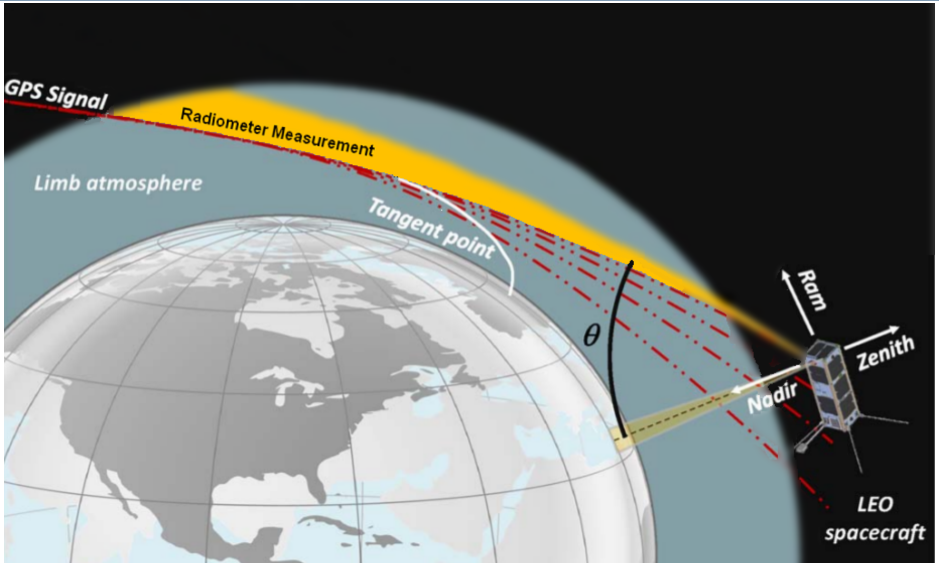
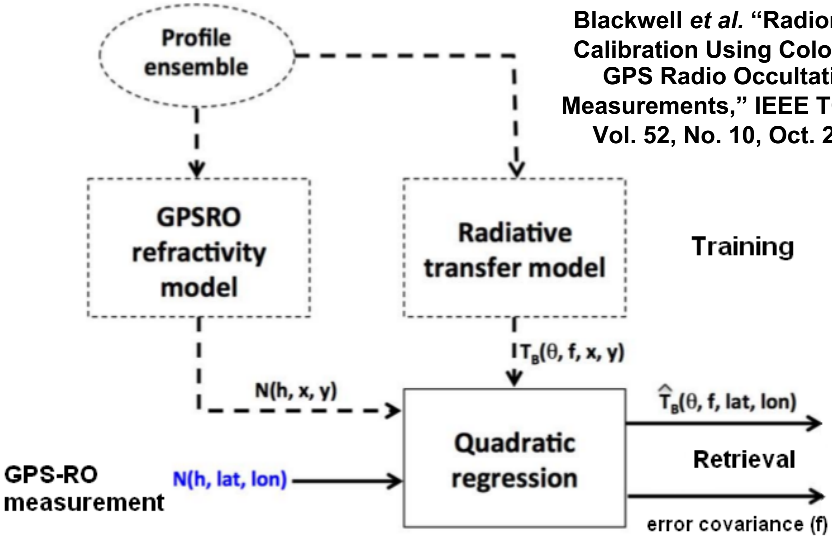
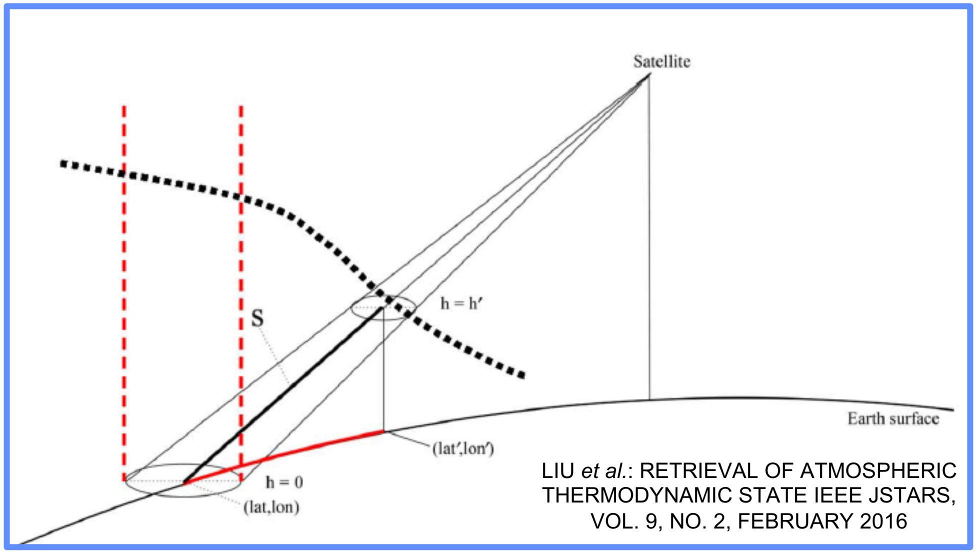
Long-term Stability: Frequent GPS-RO Matchups

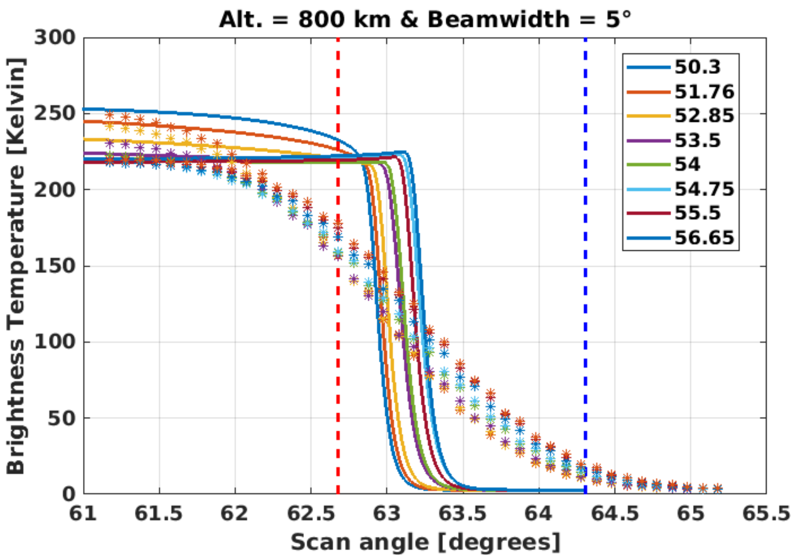




Blackwell *et al.* "Radiometer Calibration Using Colocated GPS Radio Occultation Measurements," IEEE TGARS, Vol. 52, No. 10, Oct. 2014



LIU *et al.*: RETRIEVAL OF ATMOSPHERIC THERMODYNAMIC STATE IEEE JSTARS, VOL. 9, NO. 2, FEBRUARY 2016

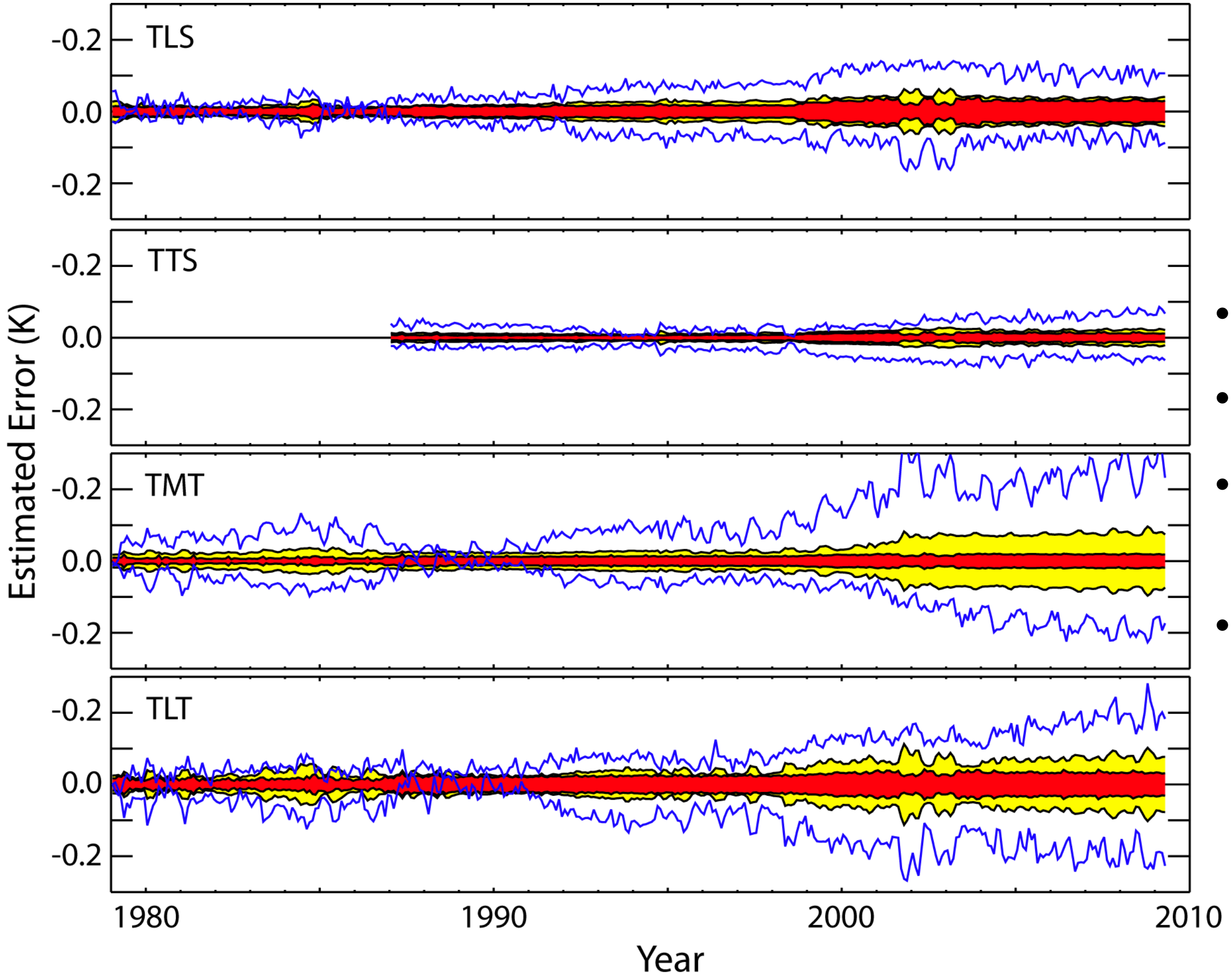


MetOp GRAS provides >500 occultations per day

Trade-offs in Choosing An Orbit

- **Need fast precession to measure an entire diurnal cycle in a month.**
- **Need a high (near polar) inclination angle to get near-global coverage.**
- **Want a high altitude so the satellites lasts longer. (Small satellites decay more quickly because of lower mass to area ratio.)**
- **Need to overlap missions to allow cross-calibration**

Diurnal Cycle Characterization Improvement



- Lower troposphere (TLT)
- Middle troposphere (TMT)
- Troposphere-stratosphere (TTS)
- Lower stratosphere (TLS)

Mears, C. A., F. J. Wentz, P. Thorne, and D. Bernie (2011), Assessing uncertainty in estimates of atmospheric temperature changes from MSU and AMSU using a Monte-Carlo estimation technique, J. Geophys. Res., 116, D08112, doi:10.1029/2010JD014954.

Conclusion

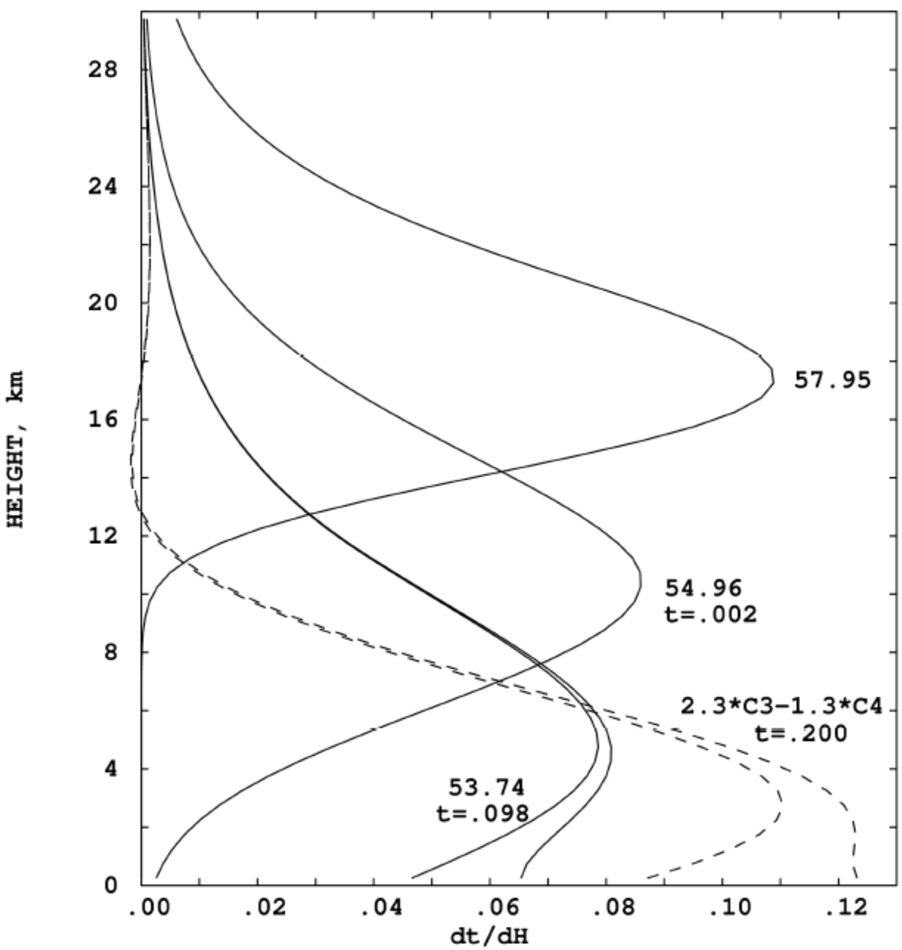
The design of a reference microwave instrument for GSICS should prioritize:

- **A linear radiometric response**
- **Very low sidelobe levels**
- **Comparison with an independent reference (such as GPS-RO) to verify long-term stability of the calibration**
- **Stable orbit**
- **Similar, but different orbit inclination from sun-synchronous missions**

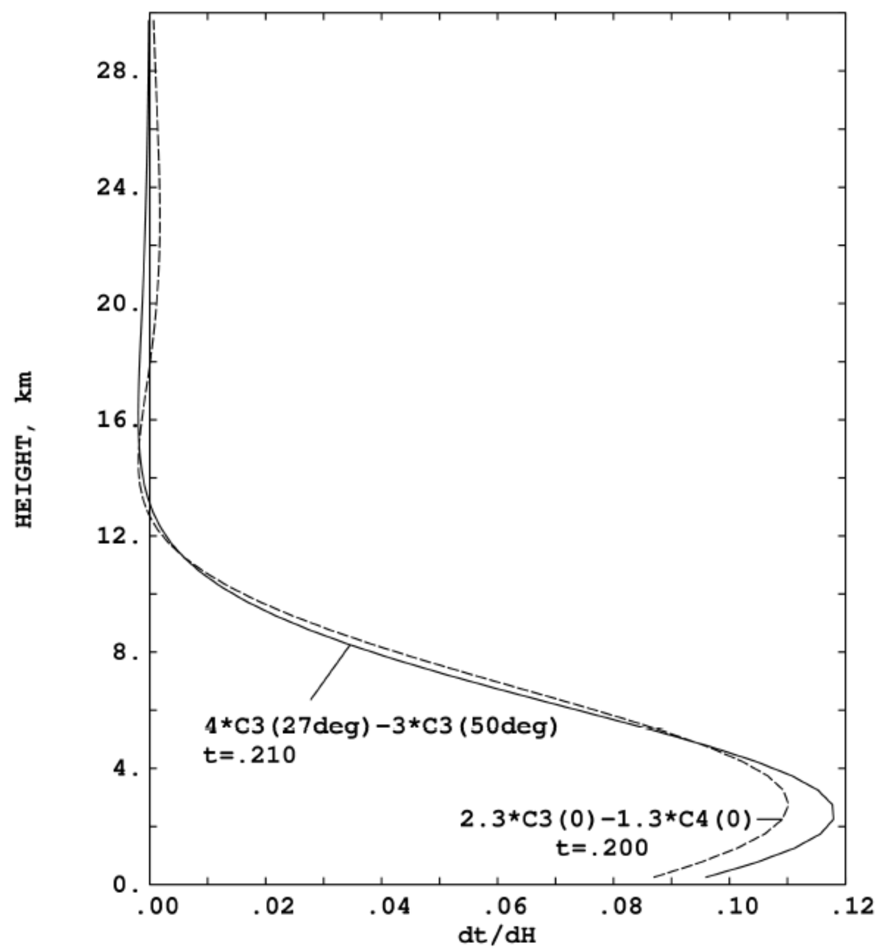
Backup

MSU-Like Weighting Functions

MSU-like weighting functions (nadir view, 1976 U.S. Std. Atmos.)



Comparison of frequency-differencing to angle-differencing



Dual curves are for surface reflectivity = 0 and 0.5; t = transmittance.

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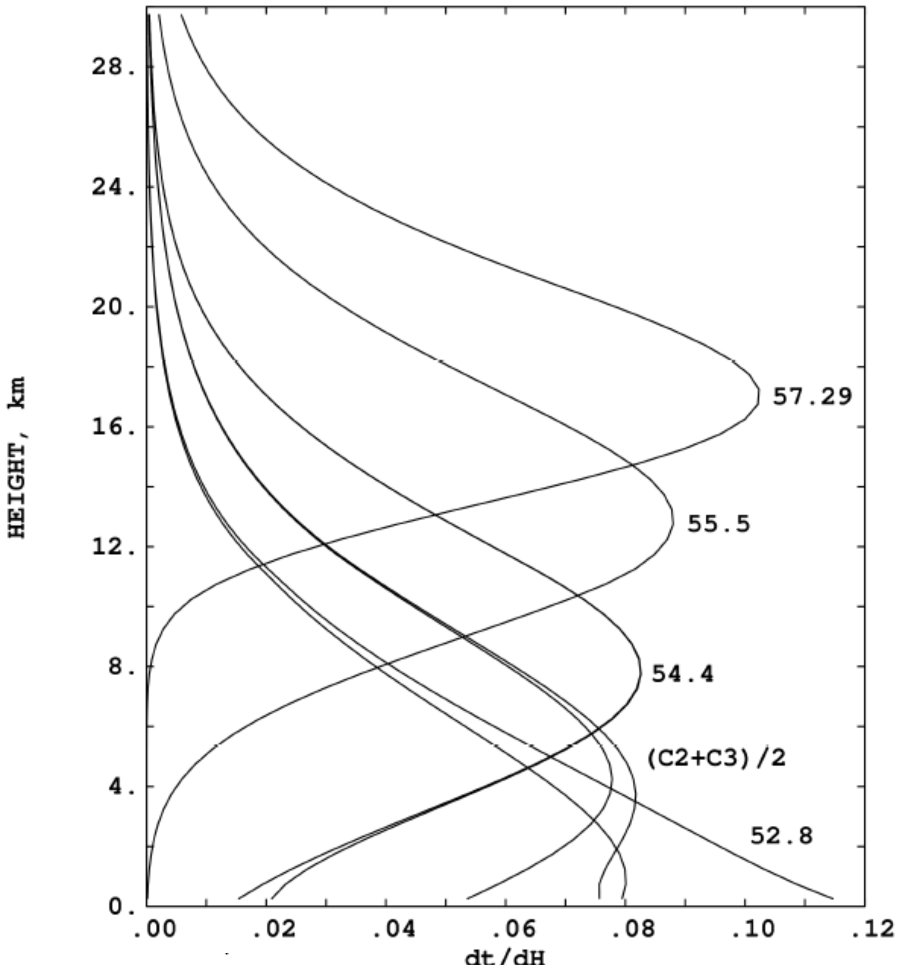
AMSU-Like Weighting Functions

AMSU or ATMS-like weighting functions (nadir view, 1976 U.S. Std. Atmos.)



Dual curves are for surface reflectivity = 0 and 0.5; t = transmittance.

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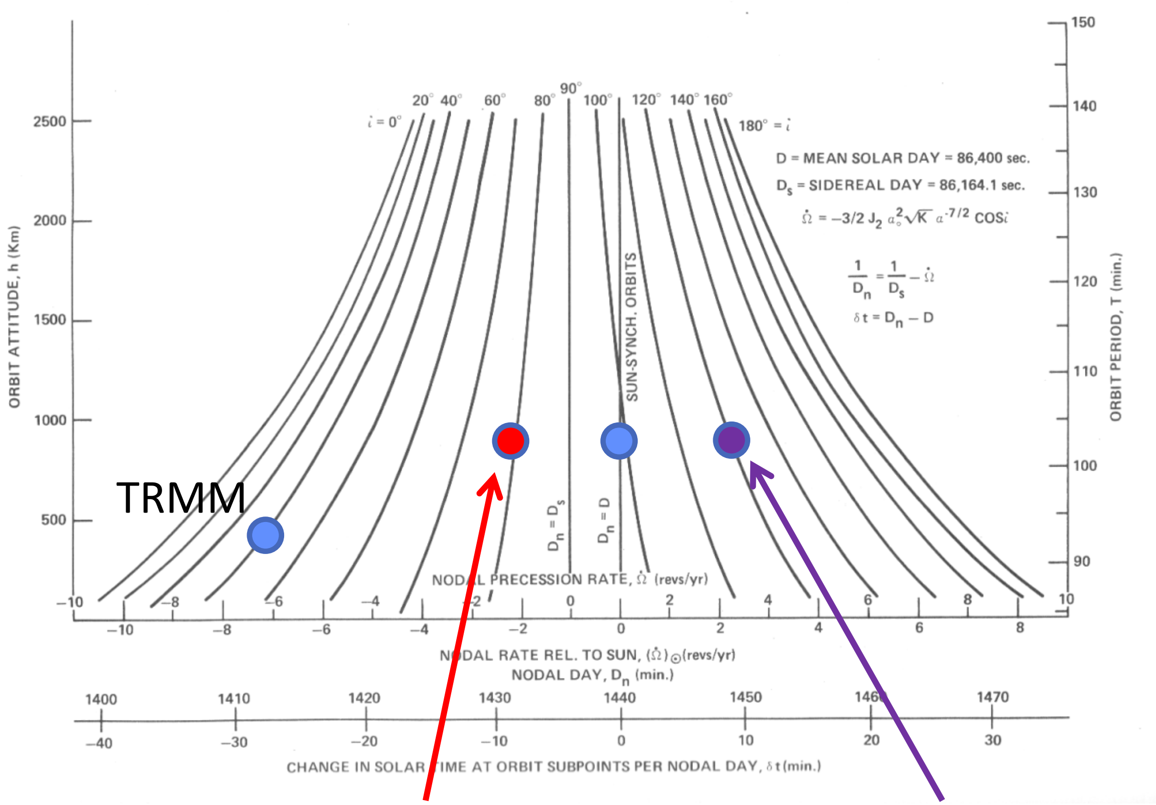
Choosing An Orbit



Only ~10 degrees from polar

~30 degrees from polar

Trade-offs:

- Want fairly fast precession so that one can measure an entire diurnal cycle in a month.
- Want a high (near polar) inclination angle to get near-global coverage.
- Want a high altitude so the satellites lasts longer. (Small satellites decay more quickly because of lower mass to area ratio.)

Carl Mears (REMSS)

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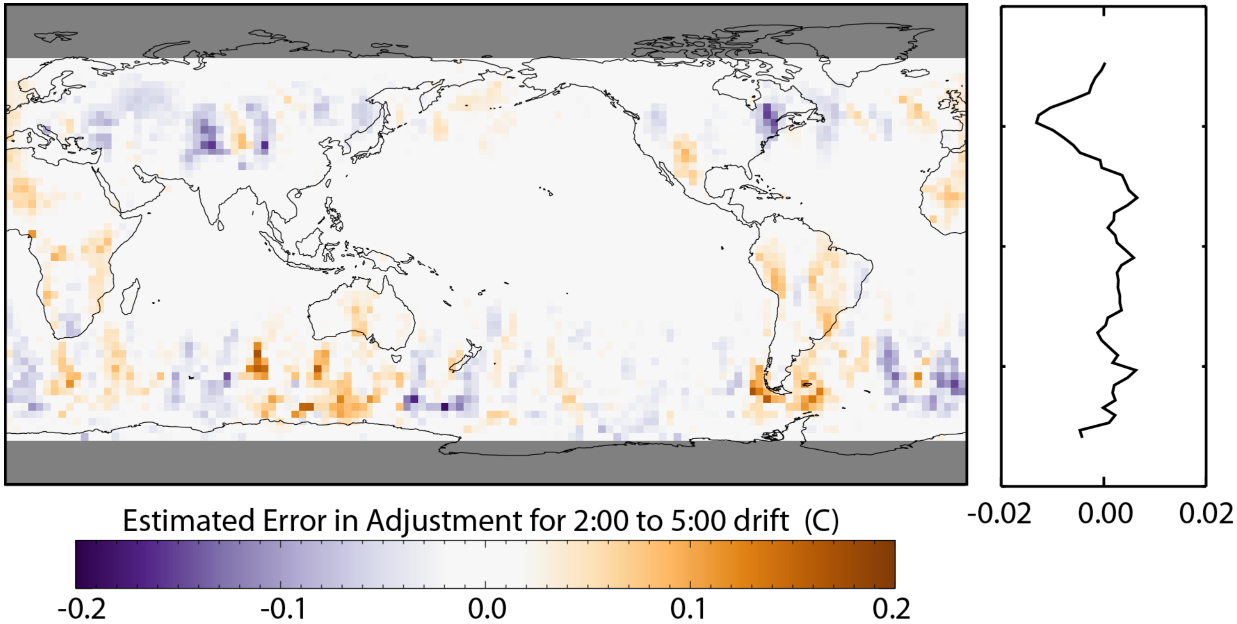
Simulated diurnal adjustment error after 1 month of measurements in Northern Hemisphere Summer.



~ 10 times better than we can currently do over land after evaluating 15 years of AMSU data.
Over sea, the diurnal cycle is very small in most locations, so improvement is not as obvious, but could still be important

Carl Mears (REMSS)