Investigating Shortcomings of Radiative Transfer Models at Microwave Frequencies

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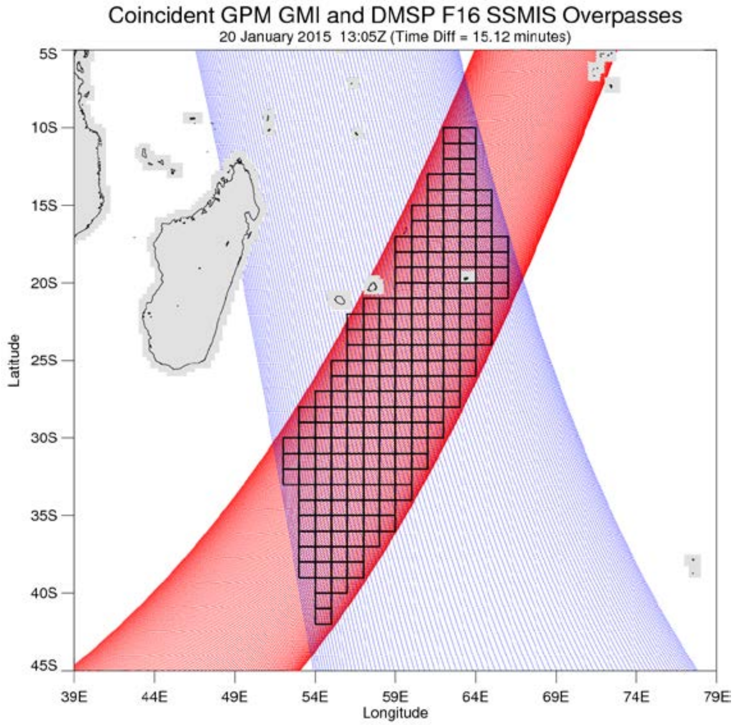
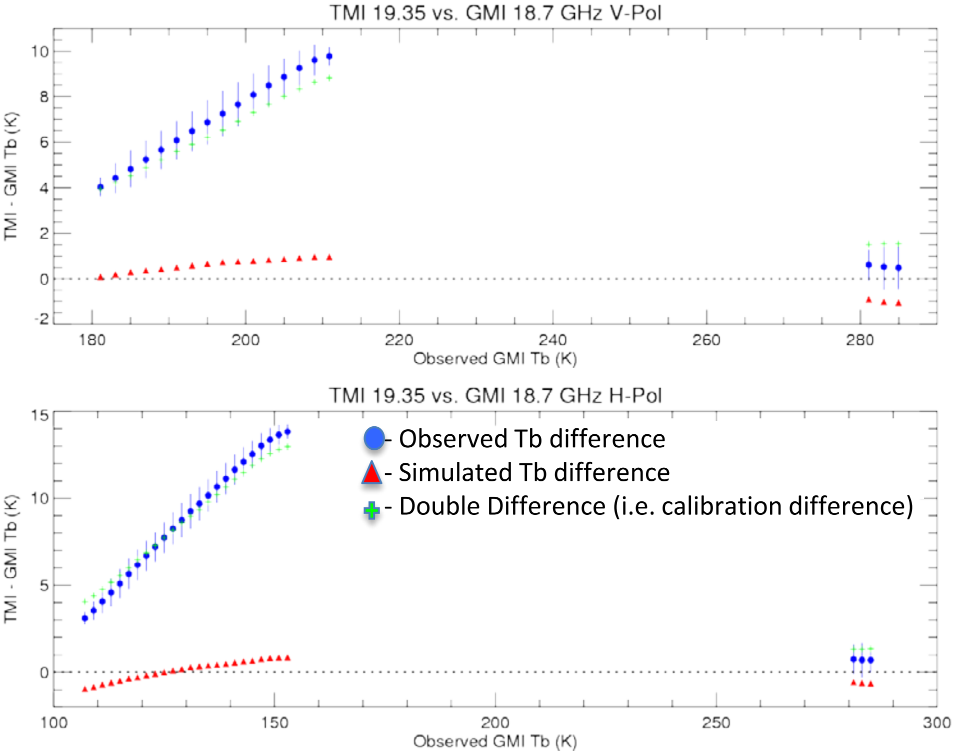
Intercalibration vs. GPM GMI

Double Difference Approach





Double Difference Technique

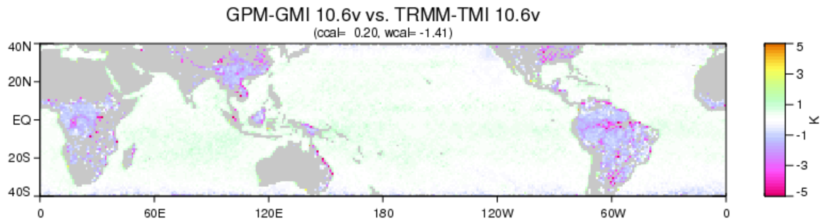
- Identify and collect near-coincident observations between target sensor (e.g. TMI) and reference sensor (i.e. GPM GMI).
- Grid Tb into 1x1 degree boxes and screen for precipitation, land etc.
- Get geophysical parameters from global model analysis or use retrieval algorithm run on GMI for clear-sky scenes.
- Compute simulated Tb for target and reference sensors to account for differences in channel frequencies, bandwidths, view angles etc.
- Compute double difference as follows.
    - Tb_obs(DIF) = Tb_obs(REF) – Tb_obs(TGT)
    - Tb_sim(DIF) = Tb_sim(REF) – Tb_sim(TGT)
    - Ddiff = Tb_obs(DIF) – Tb_sim(DIF)

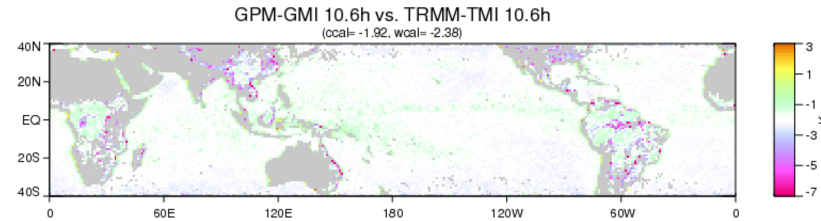
Intercalibration comparisons for the 19.35 GHz channels on TRMM TMI versus the equivalent channels on GPM GMI. The observed differences, simulated differences, and double differences (i.e. calibration differences), are shown as a function of Tb for the reference sensor (GMI). Cold temperature Tbs correspond to ocean scenes while warmer Tb values correspond to unpolarized vegetated scenes.

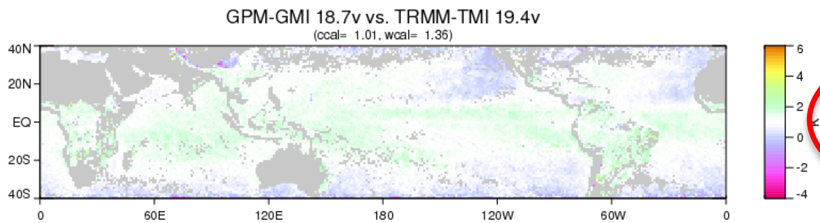
For similar channels between sensors most, but not all, of the errors in the simulated Tb due to the RTM and geophysical parameters are subtracted out. The example shown above, however, indicates the importance of accurately simulating the Tb differences in the case of significant frequency differences near the 22 GHz water vapor line.

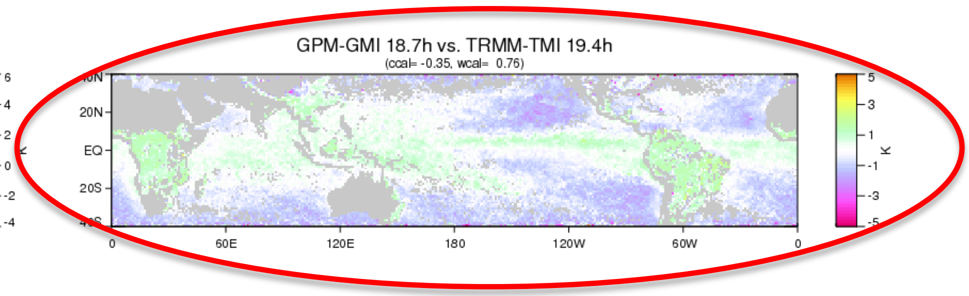
Regional Double Differences by Channel

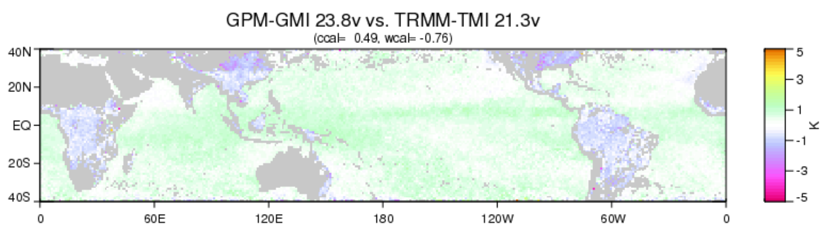
GPM GMI vs. TRMM TMI



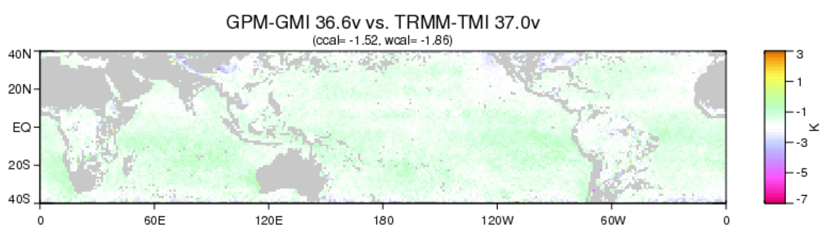


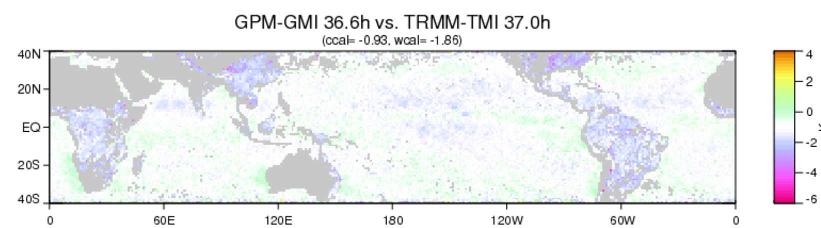


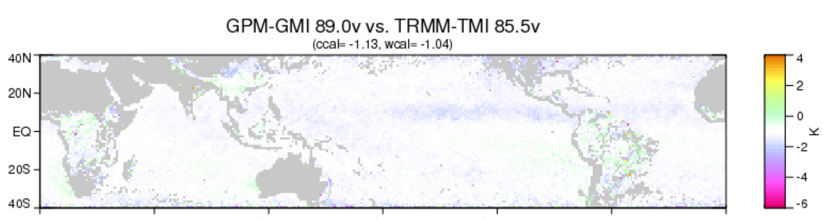


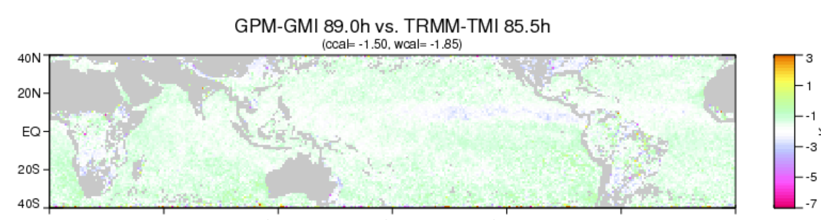


Large regional variability in double differences for certain channel combinations.









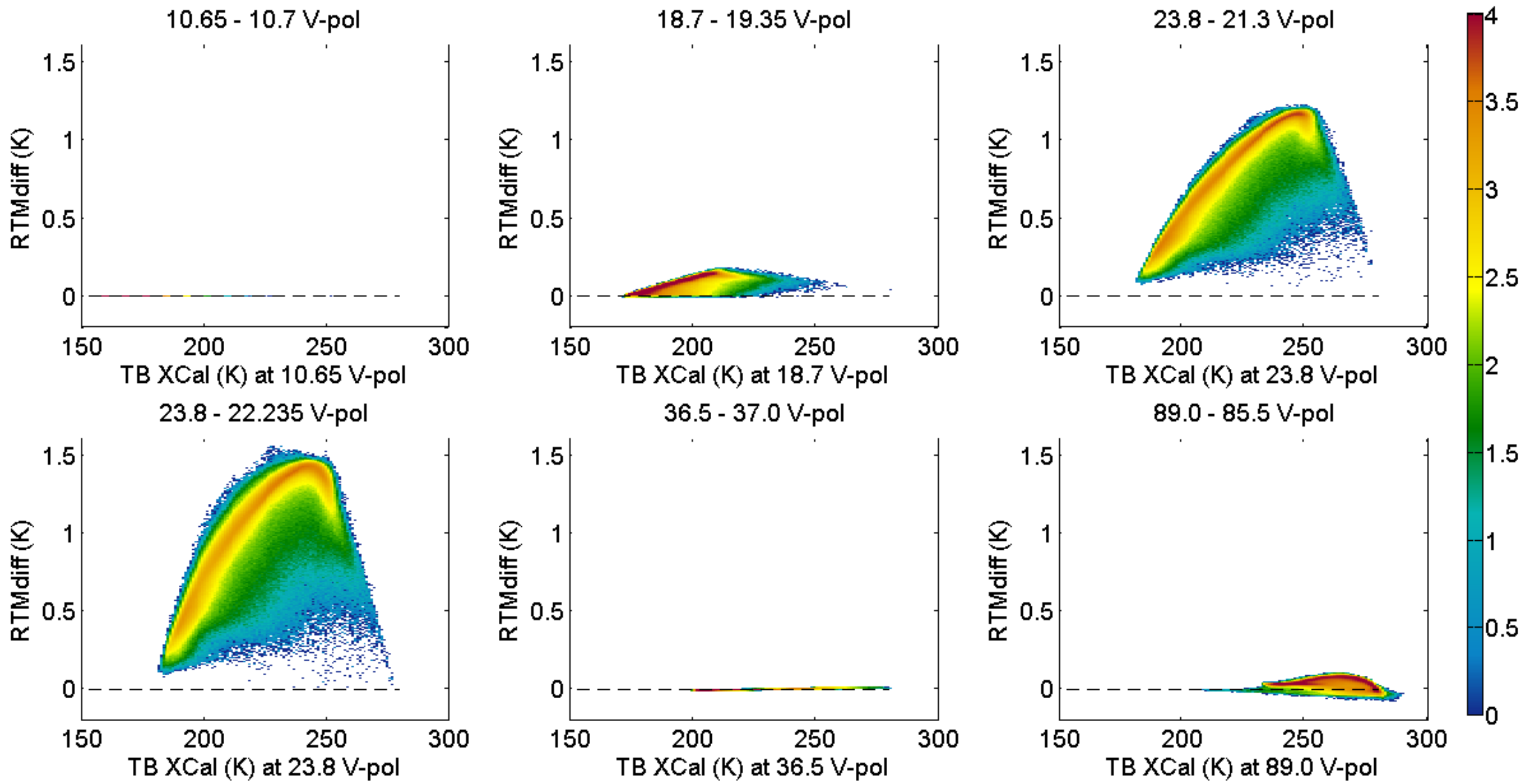
Potential Error Sources leading to Regional Biases in Simulated Tb

- Instrument
  - Scene temperature dependent calibration differences (e.g. GMI vs. AMSR2): Account for with 2-point intercalibration using cold (ocean) and warm (vegetated land) scenes.
  - Nonlinearity: Note that there is a significant correction applied to AMSR2 Ta. GMI has four point calibration (standard warm, cold-sky, and 2 noise diodes).
- Geophysical parameters
  - Ocean surface: wind speed and direction, skin SST, salinity
  - Atmosphere: Temperature and water vapor profiles, cloud water
  - Compare results using retrieved (e.g. GMI 1DVar) and model analyses (e.g. ECMWF interim renanalysis). Both show similar regional differences in most cases.
- **Radiative transfer models**
  - Atmospheric absorption models
    - XCAL currently uses Rosenkranz model
    - Comparisons made with MonoRTM considered state of the art
  - Ocean surface emissivity models
    - XCAL currently uses Remote Sensing Systems (RSS) model
    - Comparisons made with FASTEM6 from CRTM

Atmospheric Absorption Models

V-Pol Channels, Rosenkranz (XCAL) vs. MonoRTM

$$RTMdiff = \left(TB_X^{f_1} - TB_M^{f_1}\right) - \left(TB_X^{f_2} - TB_M^{f_2}\right)$$

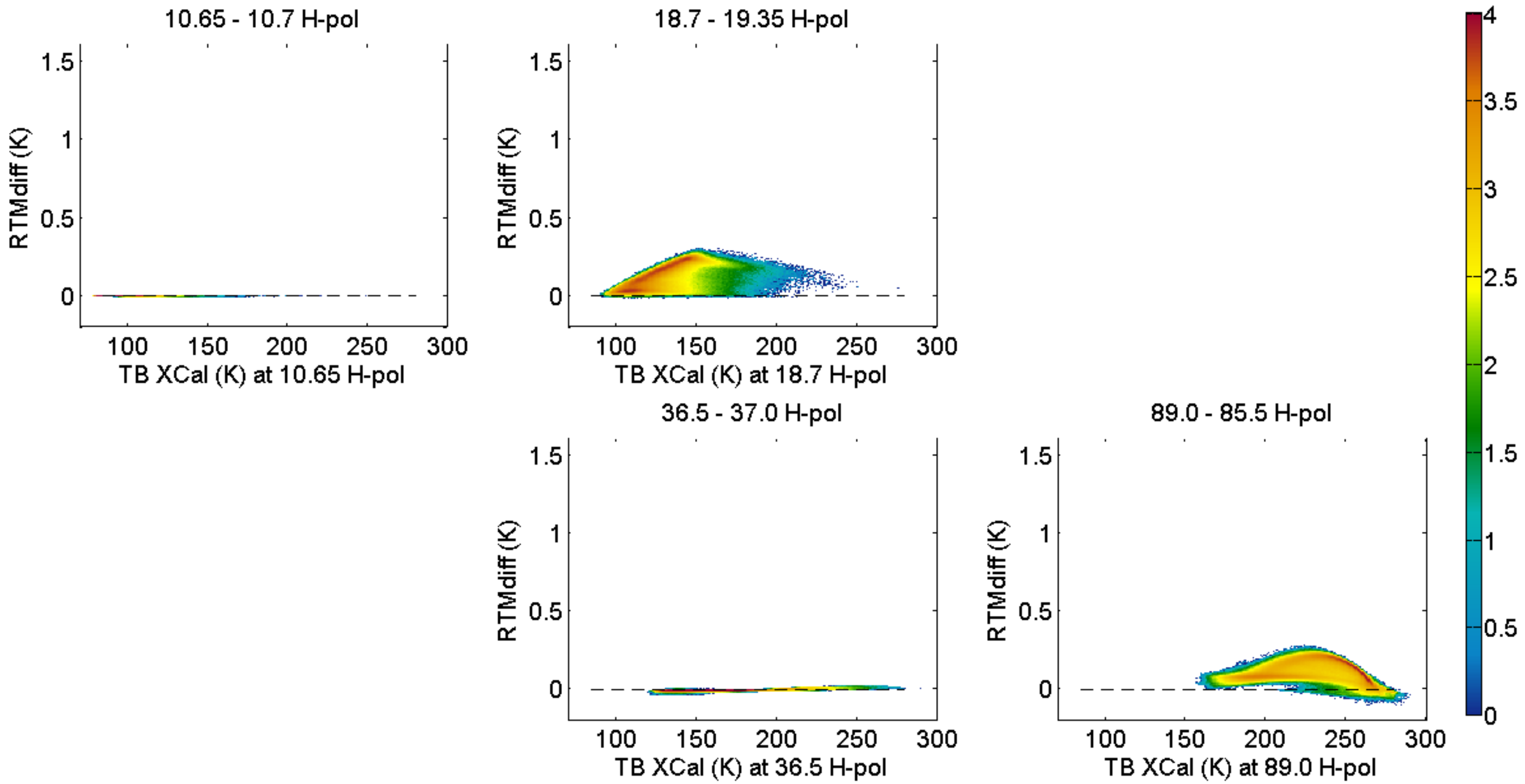


Courtesy Rachael Kroodsma at NASA Precipitation Processing System

Atmospheric Absorption Models

H-Pol Channels, Rosenkranz (XCAL) vs. MonoRTM

$$RTMdiff = \left(TB_X^{f_1} - TB_M^{f_1}\right) - \left(TB_X^{f_2} - TB_M^{f_2}\right)$$



Courtesy Rachael Kroodsma at NASA Precipitation Processing System

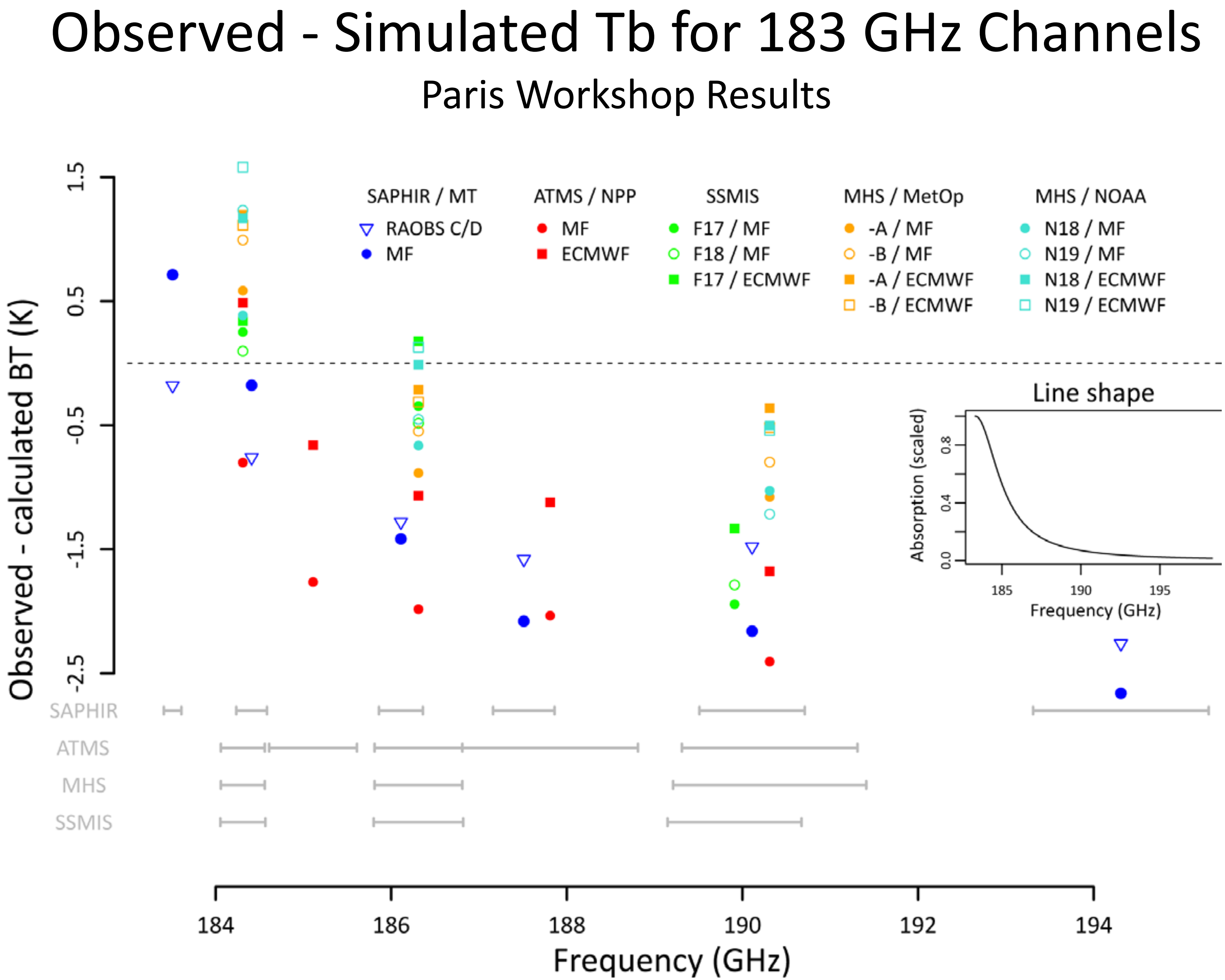
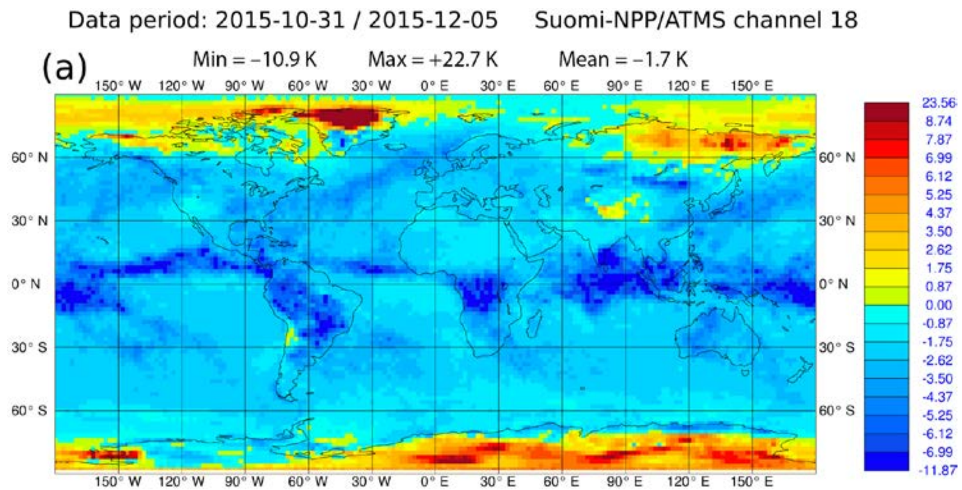


Figure 1. Mean observed minus calculated BT. All the calculated BTs are from RTTOVv11 run on RAOBs measurements (triangles) or Météo France NWP profiles (MF, circles) or European Centre for Medium-range Weather Forecasts NWP profiles (ECMWF, squares). Each color refers to a specific sensor, as in the legend. The horizontal gray bars indicate the width of the band passes. For simplicity, only one side of the absorption line is represented. The RAOB measurements were collected during the CINDY/DYNAMO/AMIE field campaign, winter 2011–2012. The inset is a scaled representation of the 183.31 GHz line, assuming a Van Vleck–Weisskopf shape.

Observed – Simulated Tb

Suomi-NPP ATMS

183±7 GHz



183±1 GHz

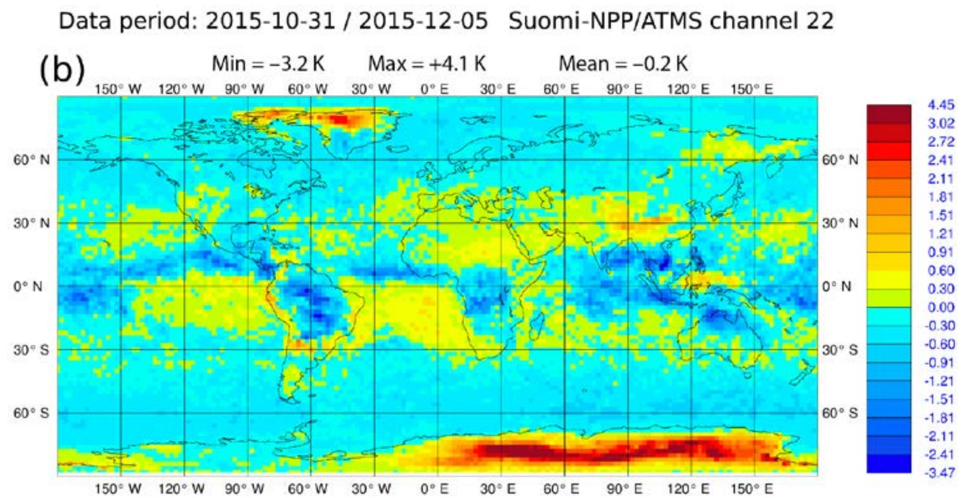


Figure 2. First-guess departures (observed BTs – those calculated from the forecast background) for Suomi-NPP/ATMS (a) channel 18 (1837 GHz) and (b) channel 22 (1831 GHz) and the current ECMWF NWP system. The maps show the mean, with the global minima, maxima and means in the legend.

A review of sources of systematic errors and uncertainties in observations and simulations at 183 GHz*

1. Errors and uncertainties in measurements with the RS92 radiosonde instruments, being the most commonly used during both field campaigns and operationally, could only explain biases in the center of the line associated with upper tropospheric moisture. A combined use of RAOBs, of PW derived from ground-based GNSS and of water vapor profiles from lidar systems should help to better attribute and understand the observed biases.

2. Intercomparison studies between microwave RTMs of varying complexity (line-by-line and fast models) show good consistency.

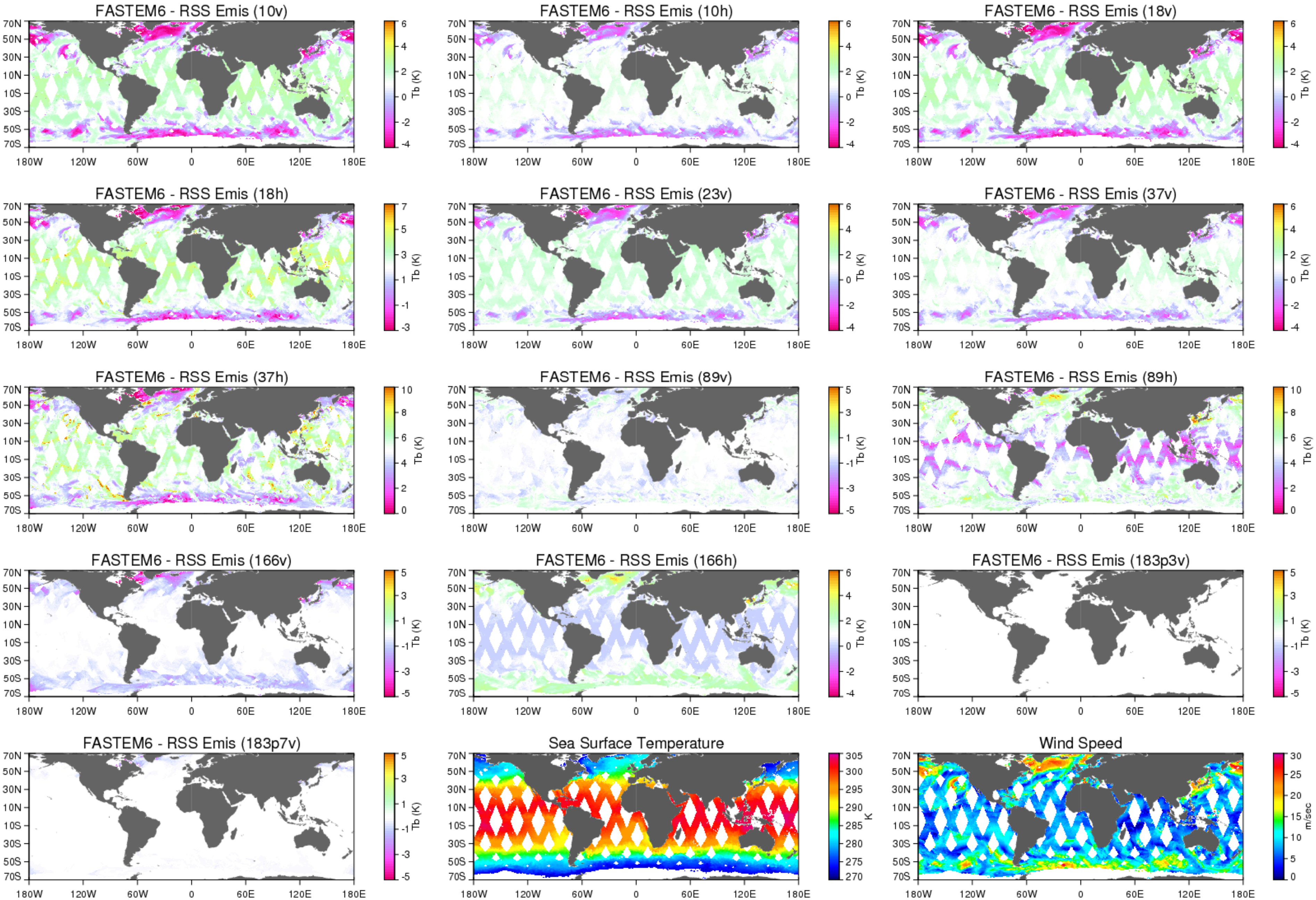
3. Different spectroscopic inputs, necessary to describe molecular absorption, are used in the various RTMs. While the uncertainties related to the dry air absorption (dry continuum and resonance absorption) could not account for the observed biases, the water vapor continuum (foreign and self) currently is the focus of most of the discussions within the expert community. Inconsistencies between laboratory and radiometric measurements have been highlighted and are not yet understood. Moreover, the H_2O dimer absorption, recently detected in the MW spectral domain, remains to be included in RTMs.

4. The analysis of water vapor fields produced by NWP data assimilation systems points towards deficiencies in the cloud detection methods required to screen out the clouds and precipitation that are not usually included in RTMs. The resulting omission of some cloudy scenes tends to lower the 183 GHz BT by scattering and/or absorption with respect to clear air situations. Tests on filtering techniques suggest that residual clouds contribute partly to the observed bias.

5. Beside the observed discrepancy between the measured and the calculated 183 GHz BTs, comparisons of measurements from space-borne sensors at 183 GHz using dedicated techniques show a very good level of agreement, within 1K for all channels and all sensors. However, the lack of publicly available SRFs and antenna patterns for most sensors makes it difficult to close the error budget due to the instrument calibration.

*Brogniez, H., English, S., Mahfouf, J.-F., Behrendt, A., Berg, W., Boukabara, S., Buehler, S. A., Chambon, P., Gambacorta, A., Geer, A., Ingram, W., Kursinski, E. R., Matricardi, M., Odintsova, T. A., Payne, V. H., Thorne, P. W., Tretyakov, M. Yu., and Wang, J.: **A review of sources of systematic errors and uncertainties in observations and simulations at 183 GHz**, Atmos. Meas. Tech., 9, 2207-2221, doi:10.5194/amt-9-2207-2016, 2016.

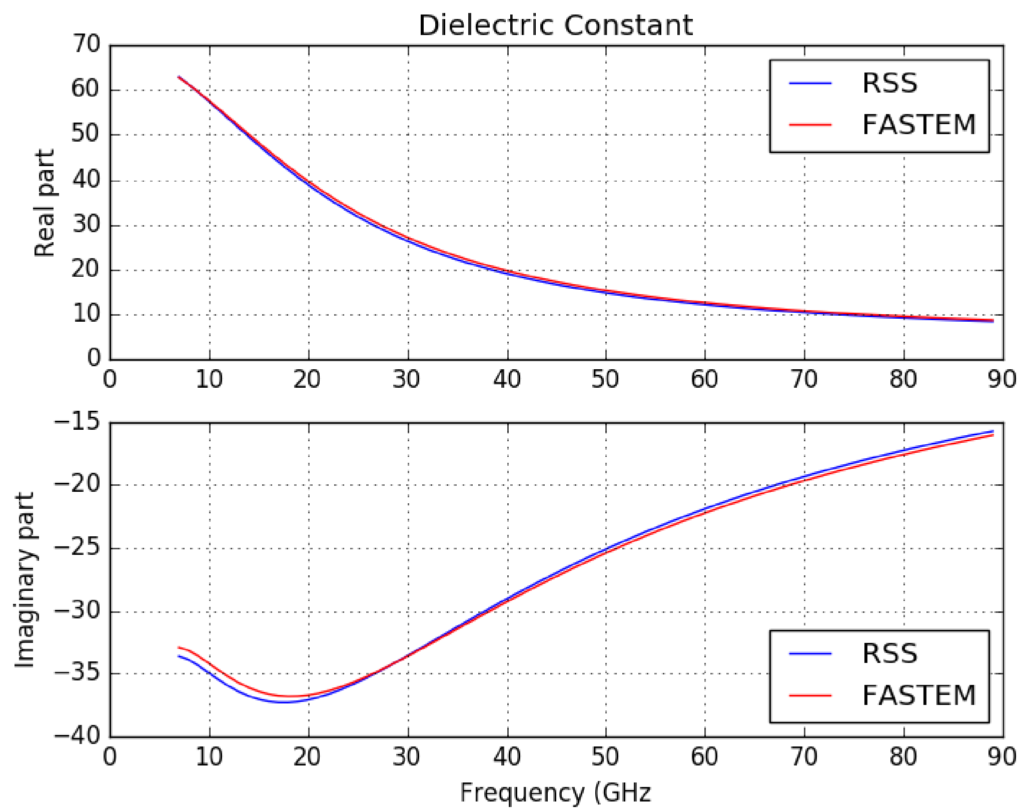
Difference in Simulated Tb Using FASTEM6 vs. RSS Emissivity



RSS vs. FASTEM6 Emissivity Model Differences

Dielectric Constant

- Differences in the dielectric constant are small:
  - For the real part, the maximum difference occurs at 25 GHz, with a difference of 0.83, FASTEM > RSS
  - For the imaginary part, the maximum difference occurs at 10 GHz, with a difference of 0.76, FASTEM > RSS
  - Above 29 GHz, the imaginary part of FASTEM < RSS, with maximum difference of -0.33
- This produces differences in the Fresnel emissivity:
  - For V-pol, the FASTEM-RSS difference decreases from 0.44 K at 7 GHz to -1.0 K at 89 GHz
  - For H-pol, the FASTEM-RSS difference decreases from 0.25 K at 7 GHz to -0.89 K at 89 GHz

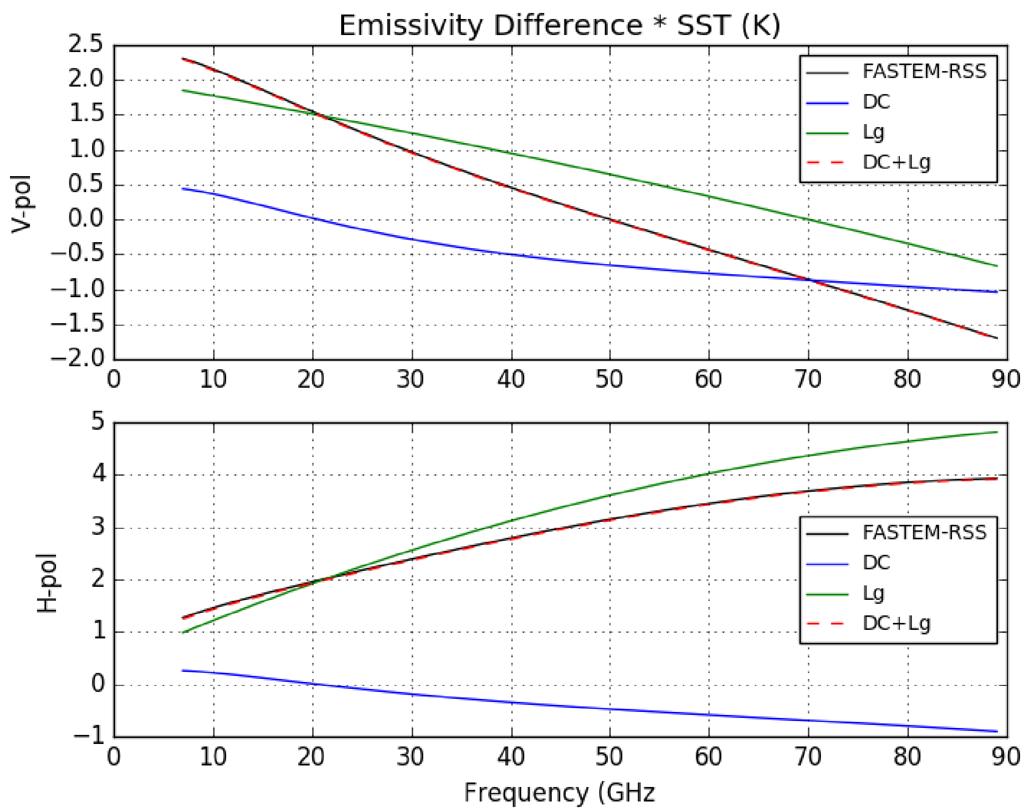


Earth incidence angle = 53 deg
Sea surface temperature = 28 deg C
Sea surface salinity = 35 ppt
Wind speed = 0 m/s

RSS vs. FASTEM6 Emissivity Model Differences

Large-Scale Wave Spectrum

- The full emissivity has much larger differences:
  - For V-pol, the FASTEM-RSS difference decreases from 2.3 K at 7 GHz to -1.6 K at 89 GHz
  - For H-pol, the FASTEM-RSS difference increases from 1.2 K at 7 GHz to 3.9 K at 89 GHz
- For RSS, when there is zero wind, the emissivity equals the Fresnel value
  - Perfectly flat specular surface
- For FASTEM, at zero wind, there are “small-scale” and “large-scale” corrections applied
  - A long wave spectrum is present even with zero wind
  - Small-scale is multiplicative and independent of polarization
  - Large-scale is additive and depends on polarization
- The figure shows that the large-scale component is responsible for most of the differences
- One might expect the best agreement at zero wind speed, but this is where the largest differences are observed

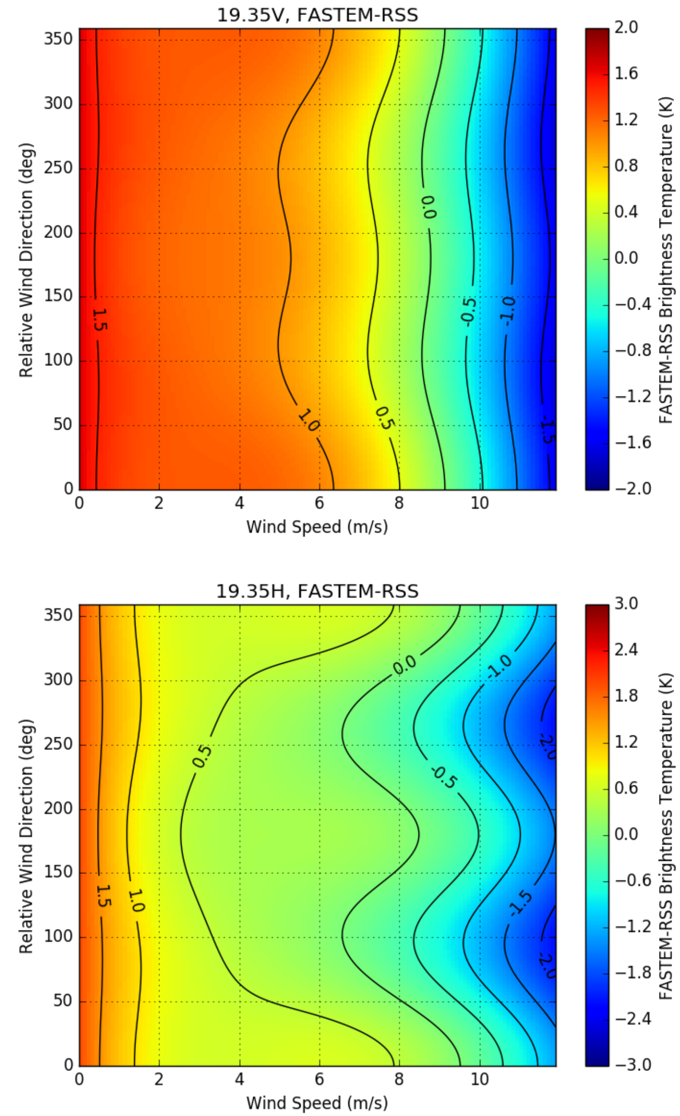


Earth incidence angle = 53 deg
Sea surface temperature = 28 deg C
Sea surface salinity = 35 ppt
Wind speed = 0 m/s

RSS vs. FASTEM6 Emissivity Model Differences

Differences vs. Wind Speed and Direction

- The difference in large-scale wave spectrum leads to large differences between these models for low winds
- FASTEM is warmer at low winds
- RSS is warmer at high winds
- Models are in best agreement for 7-10 m/s, depending on frequency and incidence angle
- 19V has zero diff ~ 9 m/s
- 19H has zero diff ~ 8 m/s
- Figures specific to:
  - SST = 302 K
  - EIA = 53 deg



RSS vs. FASTEM6 Emissivity Model Differences

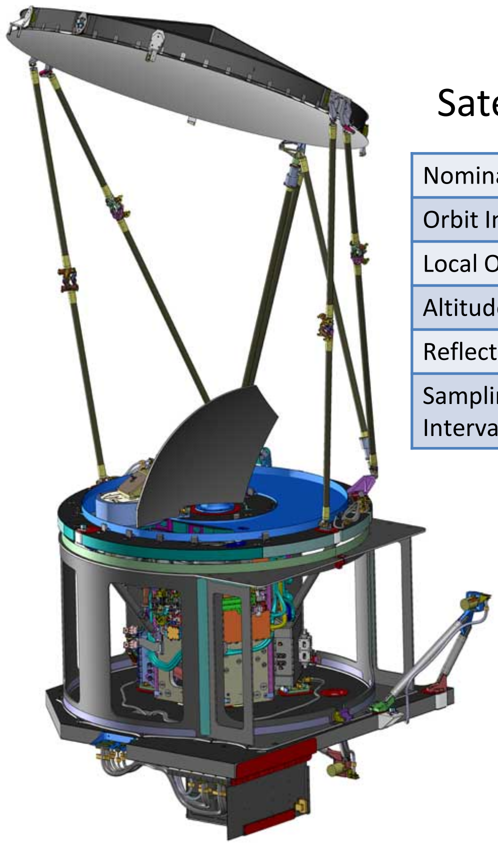
Summary

- Despite the major advances over the last 30+ years of the satellite era, ocean surface emissivity models remain a leading source of error in microwave Tb simulations
  - Dielectric constant: differences < 1 K
  - Large-scale wave spectrum: differences as large as 5 K at zero wind speed
  - Differences are smallest near the average wind speed over the ocean
- These models augment surface reflectivity to account for non-specular reflection
  - Failure to properly do this produced spurious differences as large as 4 K
  - Current version of CRTM does not easily allow user to specify reflectivity for microwave/ocean case

- How do we identify errors and/or deficiencies in the radiative transfer models?
- Instead of using in-situ observations to validate satellite calibration, we propose using these observations along with GPM GMI to investigate RTM errors.
- On-orbit calibration maneuvers were used to identify and correct for GMI calibration errors independent of RTMs. Result is that GMI appears to be extremely well calibrated and stable.

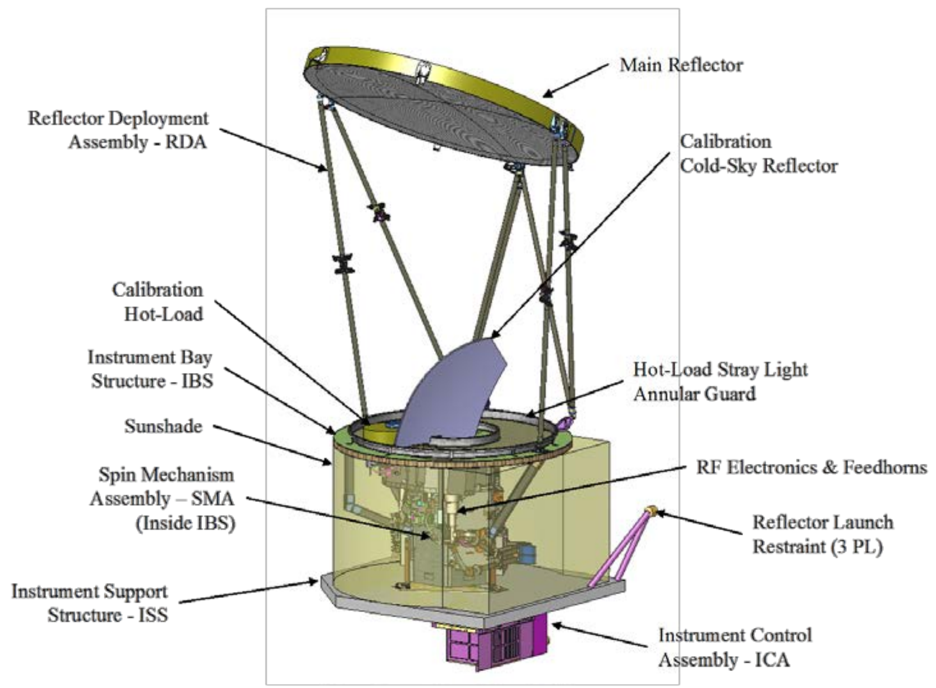
GPM GMI Channel Specifications

GMI Specs	10.65v/h		18.7v/h		23.8v		36.64v/h		89.0v/h		165.5v/h		183+3v	183+7v
DT x CT Res in km	32.1x19.4		18.1x10.9		16.0x9.7		15.6x9.4		7.2x4.4		6.3x4.4		5.8x3.8	5.8x3.8
Beamwidth (deg)	1.72		0.98		0.85		0.81		0.38		0.37		0.37	0.37
NEDT (K)	0.96		0.84		1.05		0.65		0.57		1.5		1.5	1.5
Beam Efficiency (%)	91.1		91.2		93.0		97.8		96.8		96.5		95.2	95.2
Uncorr Nonlinearity (K)	0.2	0.2	0.1	0.1	0.1	0.1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Band Width (MHz)	100		200		400		1000		6000		4000		3500	4500
Feedhorns	1		1		1		1		1		1		1	1
Integration Time (ms)	3.6		3.6		3.6		3.6		3.6		3.6		3.6	3.6

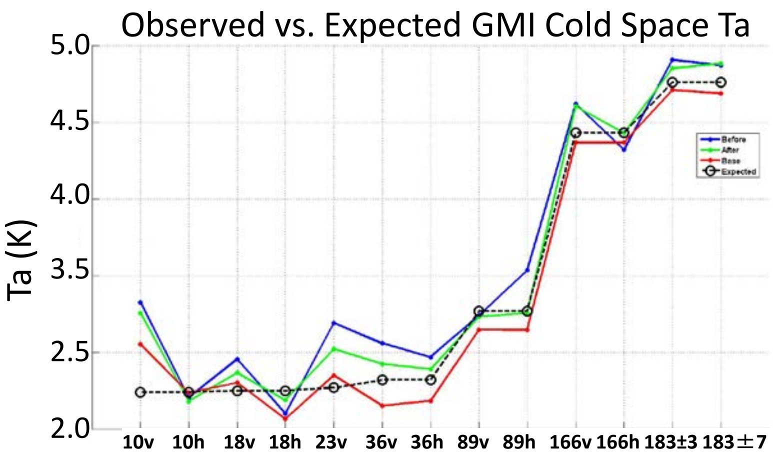


Satellite/Instrument Characteristics

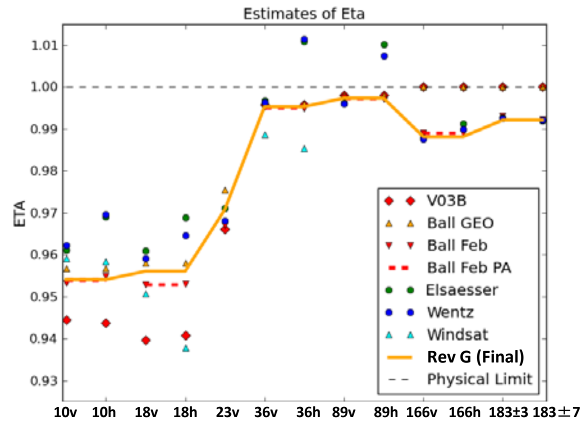
Nominal EIA	52.8/49.2
Orbit Inclination	65.0 deg
Local Obs. Time	Variable (Precessing)
Altitude	407 km
Reflector Size	1.22 m
Sampling Interval	13.5 km



GMI Calibration Summary



Observed vs. expected antenna temperatures by channel based on analysis of data from deep space calibration manuever (Courtesy Spencer Farrar, Univ. Central Florida).



Various estimates for spillover correction (eta) for each GMI channel. Final values are indicated by solid yellow line (Courtesy Tom Wilheit).

Channel	Pre-Launch (η_F)	On-Orbit (η_G)	ΔTb (ocean)
10v	0.94435	0.95404	1.7
10h	0.94369	0.95404	1.0
18v	0.93968	0.95603	3.3
18h	0.94082	0.95603	2.0
23v	0.96601	0.97075	1.1
36v	0.99590	0.99535	-0.1
36h	0.99590	0.99535	-0.1
89v	0.99810	0.99734	-0.2
89h	0.99810	0.99734	-0.2
166v	1.00000	0.98814	-3.2
166h	1.00000	0.98814	-3.2
183±3v	1.00000	0.99212	-2.1
183±7v	1.00000	0.99212	-2.1

- On-orbit calibration maneuvers used to check for calibration anomalies and to develop corrections.
- Calibration Checks
  - ➢ Emissive Reflector (No evidence found)
  - ➢ Polarization Check (Differences < 0.3K at nadir)
- Calibration Corrections
  - ➢ Magnetic anomalies
    - Along-track due to spacecraft flying through Earth's magnetic field
    - Cross-track due to magnetic latches for GMI cover
    - Correction developed/applied. Residual anomalies are very small.
  - ➢ Spillover Corrections
    - Forward part of antenna pattern measured by Ball at near field range pre-launch, but spillover region could not be measured so they used two different models, which gave different answers.
    - Initial spillover corrections (Eta) for 166 and 183 channels were 1.0 (unphysical)
    - Data from 2 inertial hold maneuvers were analyzed by David Draper at Ball Aerospace, The resulting Eta values (see above table/figure) are based on physical observations rather than models (as used initially). These values are also not tuned to match any radiative transfer model.

Summary

- Significant changes were made to the spillover corrections (see above). Given limitations of pre-launch measurements this is a likely cause of significant calibration differences between sensors, particularly for lower frequency channels.
- Calibration corrections are based on data from on-orbit calibration maneuvers and are not dependent on radiative transfer models
- Independent comparisons with by both Ball/RSS and XCAL indicate that the GMI calibration is very consistent with clear-sky ocean simulated Tb.
- A conservative estimate for the absolute calibration errors of the GMI window channels are < 1K
- Comparisons of the GMI 166 and 183 GHz channels with the MHS and SAPHIR cross-track sounders indicate differences of < 0.5K

Total GMI On-orbit Calibration RMS Error

- The Total RMS calibration error is a combination of all errors from previous slides.
- Overall, the GMI RMS calibration error for on-orbit operations is 0.25K RMS bias and 0.14K RMS time-varying component
  - Please note, that these are considered as 1-sigma numbers, i.e. 68% probability of a particular channel falling within this error range.
  - An individual channel's error may be higher or lower.
- Comparison with Independently Calibrated Radiometers Suggests Absolute Accuracy Better than 1K RMS Across All Channels

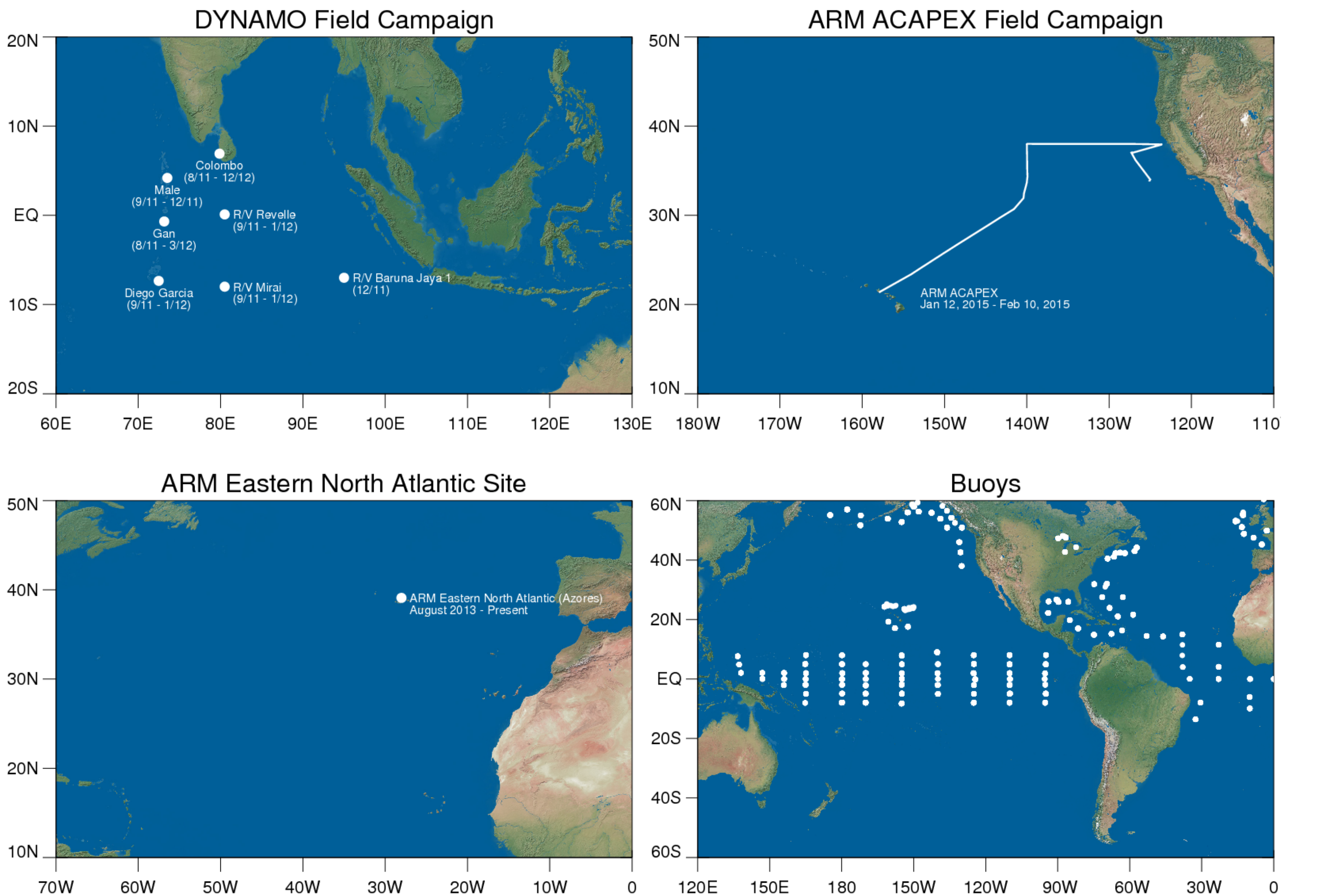
Channel	Magnetic Correction		TA Calibration		Antenna-Induced Bias		**Total TA ERROR (ocean)**		Spillover		Cross-pol		**Total TB ERROR (ocean)**	
	Total Bias	Total Time-varying error	Total Bias	Total Time-varying error	Total Bias	Total Time-varying error	**Total Bias**	**Total Time-varying error**	Total Bias	Total Time-varying error	Total Bias	Total Time-varying error	**Total Bias**	**Total Time-varying error**
10V	0.09	0.09	0.12	0.07	0.00	0.03	**0.15**	**0.12**	0.29	0.02	0.07	0.00	**0.34**	**0.12**
10H	0.05	0.11	0.18	0.06	0.00	0.04	**0.18**	**0.13**	0.17	0.02	0.07	0.00	**0.26**	**0.13**
18V	0.05	0.05	0.09	0.08	0.00	0.02	**0.10**	**0.10**	0.26	0.02	0.05	0.00	**0.28**	**0.10**
18H	0.04	0.07	0.09	0.06	0.00	0.03	**0.09**	**0.09**	0.17	0.03	0.05	0.01	**0.20**	**0.09**
23V	0.06	0.08	0.09	0.09	0.00	0.01	**0.11**	**0.12**	0.23	0.03	0.02	0.03	**0.25**	**0.13**
36V	0.01	0.11	0.08	0.11	0.00	0.00	**0.08**	**0.16**	0.21	0.01	0.01	0.00	**0.23**	**0.16**
36H	0.02	0.07	0.07	0.08	0.00	0.00	**0.07**	**0.11**	0.15	0.02	0.01	0.00	**0.17**	**0.11**
89V	0.00	0.03	0.07	0.14	0.00	0.00	**0.07**	**0.14**	0.22	0.01	0.01	0.00	**0.23**	**0.14**
89H	0.02	0.09	0.08	0.12	0.00	0.01	**0.08**	**0.15**	0.20	0.02	0.01	0.00	**0.21**	**0.15**
166V	0.04	0.05	0.05	0.14	0.00	0.01	**0.06**	**0.15**	0.28	0.01	0.02	0.02	**0.29**	**0.16**
166H	0.04	0.09	0.05	0.14	0.00	0.01	**0.06**	**0.17**	0.28	0.02	0.02	0.02	**0.29**	**0.17**
183VA	0.02	0.06	0.04	0.14	0.00	0.01	**0.04**	**0.15**	0.24	0.01	0.01	0.07	**0.24**	**0.16**
183VB	0.02	0.09	0.03	0.14	0.00	0.01	**0.04**	**0.17**	0.24	0.01	0.01	0.07	**0.25**	**0.18**
RMS	0.04	0.08	0.09	0.11	0.00	0.02	**0.10**	**0.14**	0.23	0.02	0.03	0.03	**0.25**	**0.14**

TA BIAS

TB BIAS

*Results provided courtesy David Draper, Ball Aerospace & Technologies Corp. Boulder, Colorado USA

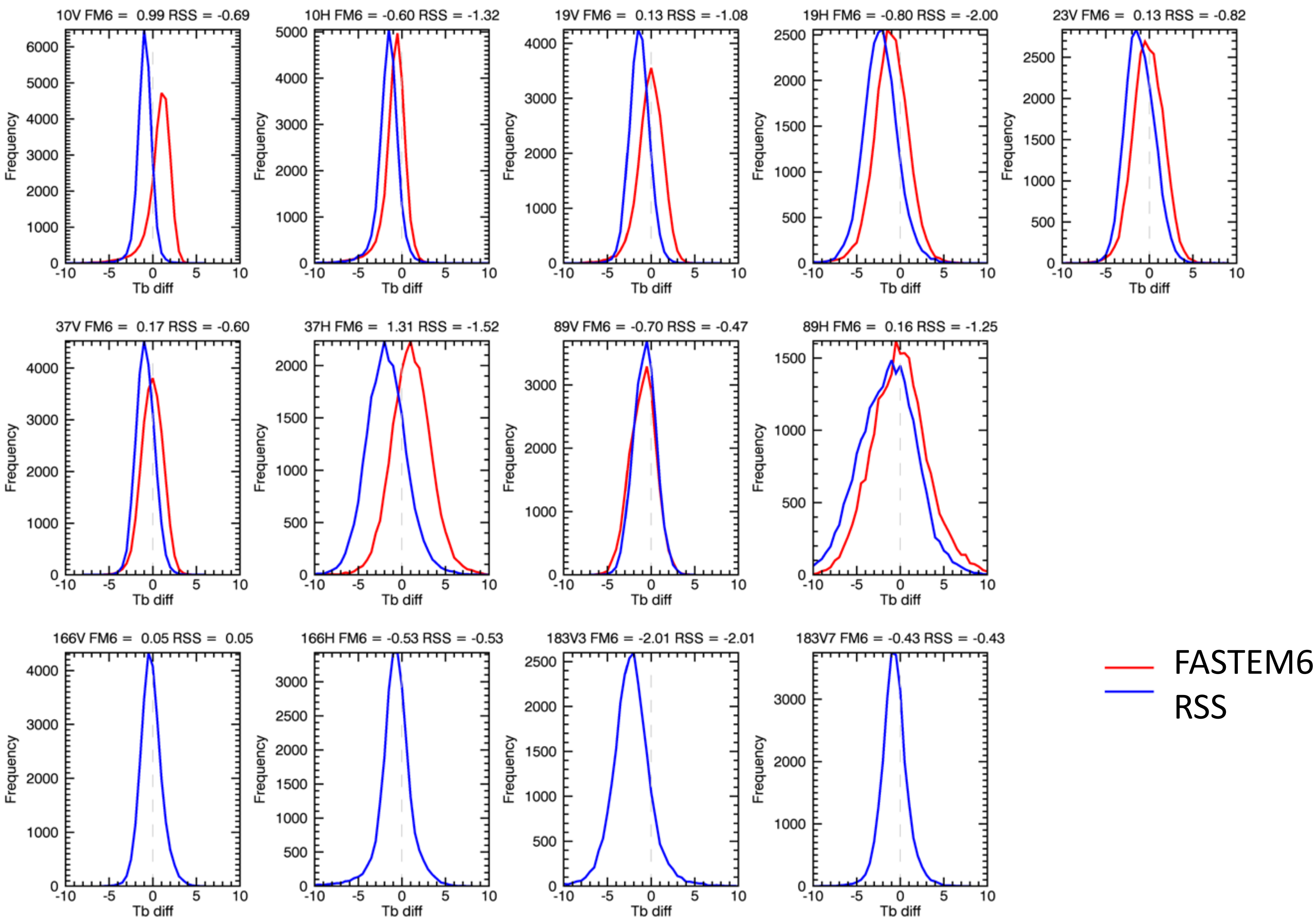
Investigating RTM Errors Using In-situ Observations



These are some of the initial datasets we are using to investigate regional biases in simulated Tb. Buoy dataset provides good statistics, but no atmospheric profile information. DYNAMO ship datasets include surface flux and radiosonde observation, but are pre-GPM (i.e. TRMM TMI).

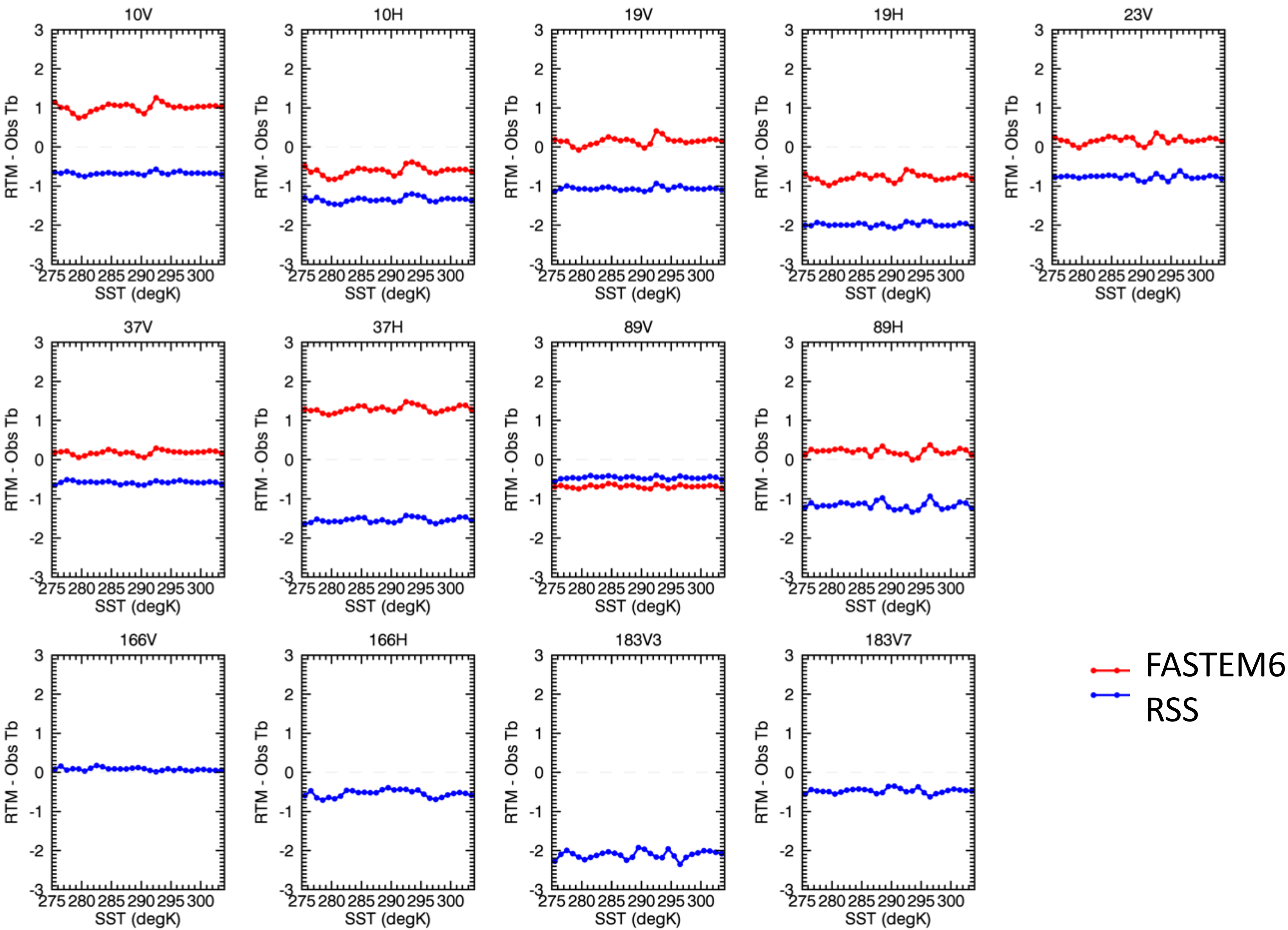
Observed – Simulated Tb

Preliminary Results (Based on Ocean Buoy Dataset)



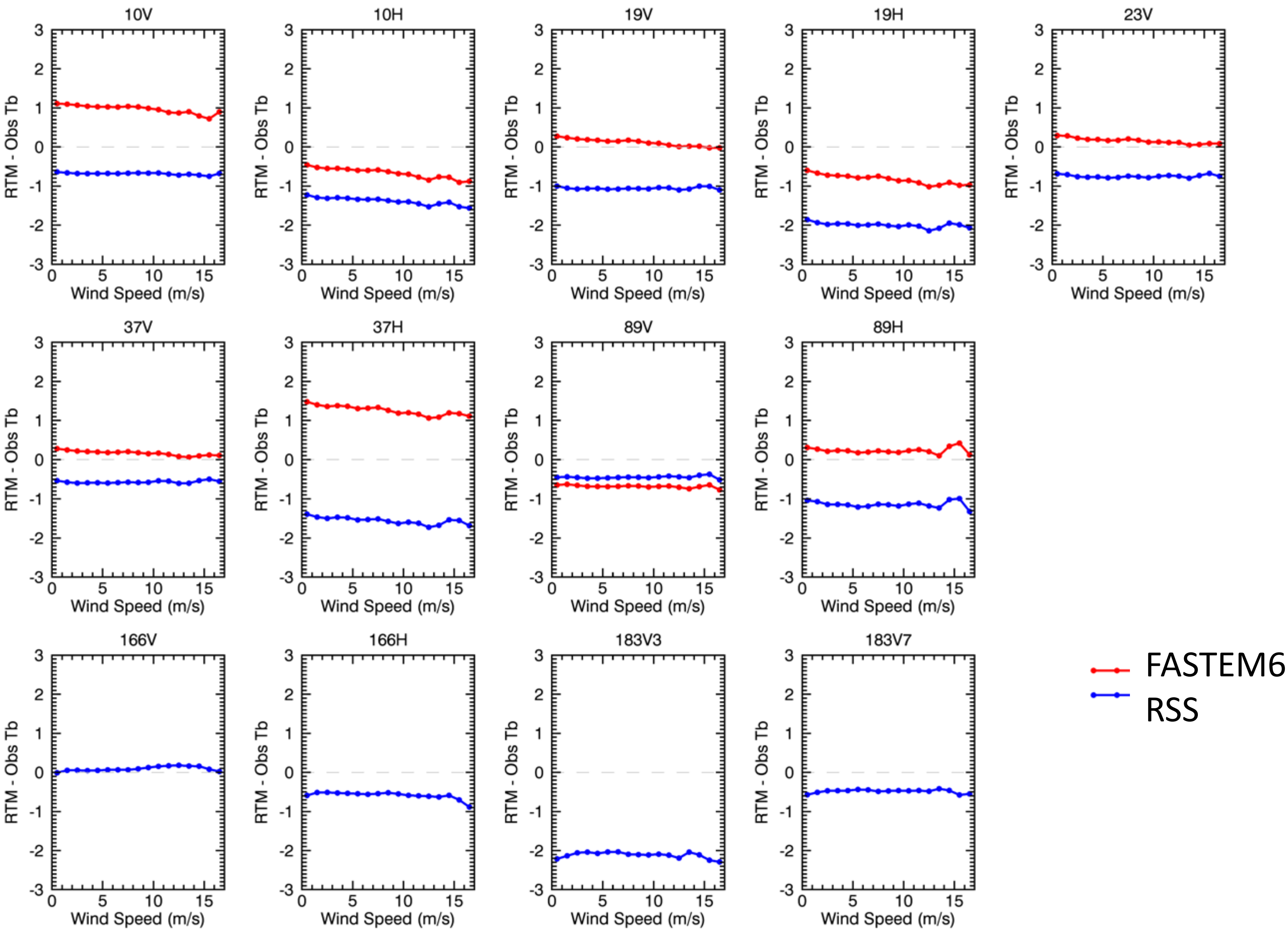
Simulated – Observed Tb

vs. SST (Based on Ocean Buoy Dataset)



Simulated – Observed Tb

vs. Surface Wind Speed (Based on Ocean Buoy Dataset)



Relevant Issues to both XCAL and GSICS

- Importance of a Calibration Reference.
  - Both GMI and MHS appear to be very well calibrated.
  - On-orbit GMI calibration corrections not dependent on RTMs.
  - Detailed on-orbit GMI error analysis extremely valuable.
- We need to understand the strengths and weaknesses of various RTMs. This is important for calibration, retrievals and data assimilation.
- We need better estimates of RTM uncertainties and variations with SST, wind speed, TPW etc.
- Identifying and sharing high quality validation datasets (radiosondes, ocean buoys, surface flux measurements etc.)
  - GRUAN radiosonde obs.?