Validation of AMSR2 Sea Surface Temperature

Gentemann and Hilburn, In situ validation of GCOM-W1 AMSR2 sea surface temperatures, JGR-Oceans.

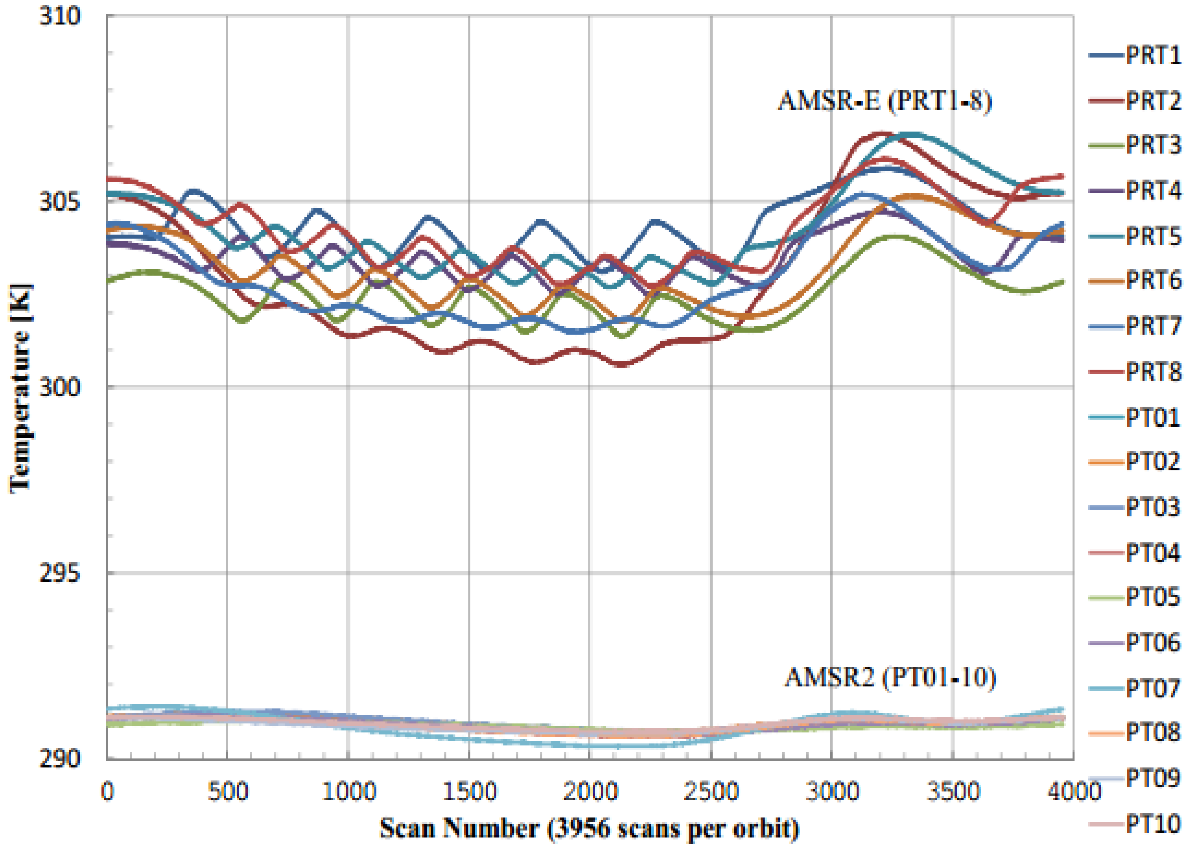
GHRSST, July 2015

Satellite Data

- AMSR2 has several key improvements on AMSRE
  - Hot load has improved thermal stability
  - New 7.3 GHz channel
  - Largest rotating reflector in orbit (2.0 m) gives better spatial resolution (35x62 km) compared with AMSRE (43x75 km)
- But is not without challenges
  - Nonlinearities of several degrees in all channels; only in 6 GHz for AMSRE
  - Intercalibration to AMSRE requires use of slow rotation (2 rpm) AMSRE data
- This study uses data from RSS calibration of AMSR2

AMSR2 Thermal Stability

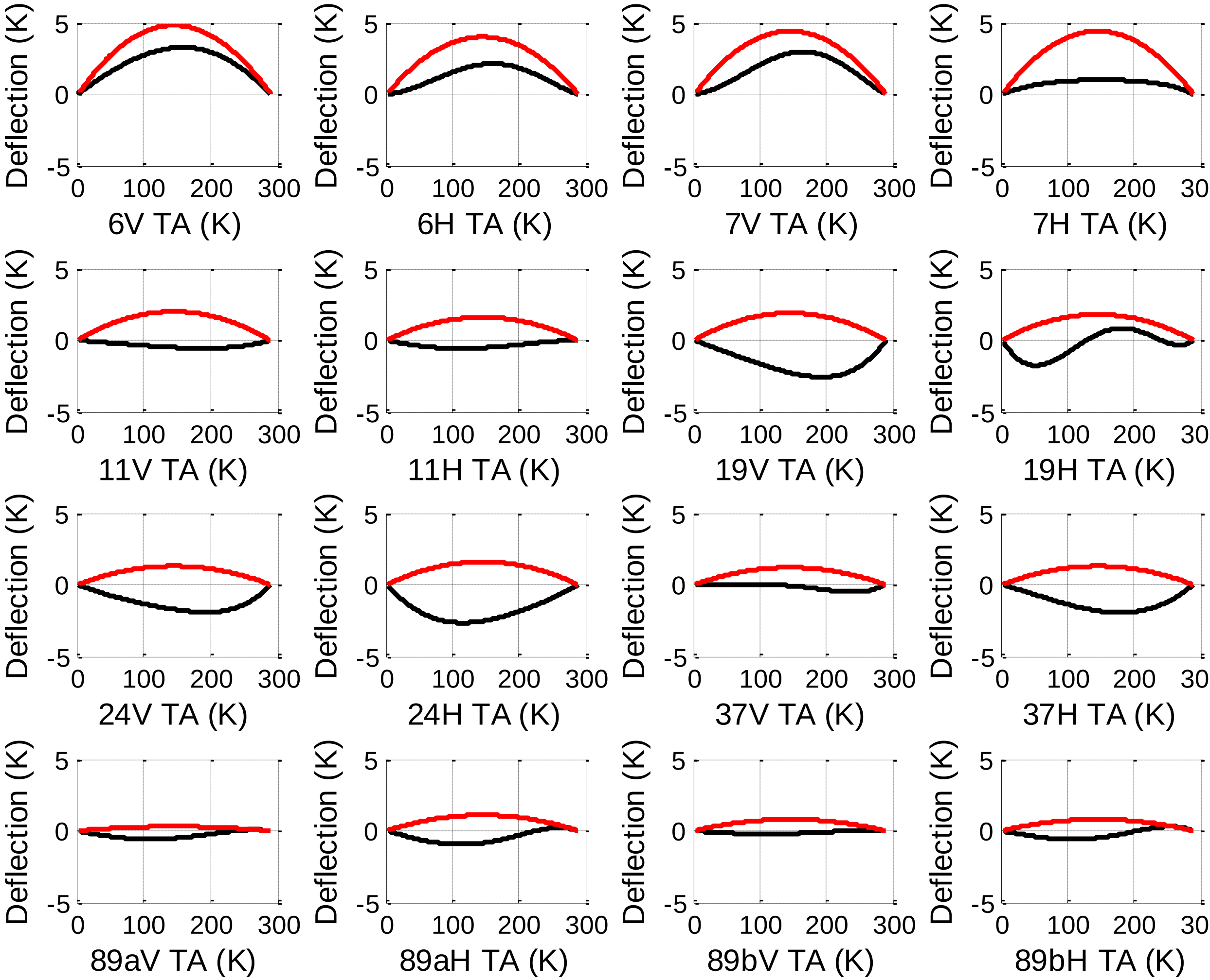
- Thermistors on AMSR-E highly variable. They don't track each other very well and there is high inter-orbit variability.
- Thermistors on AMSR2 track each other well and have low variability



AMSR2 Nonlinearity

Red Curves are JAXA Non-Linear Correction (Marehito Kasahara 21 Feb 2013 X-Cal presentation)
Black Curves are values coming from RSS analysis.

- We have not seen these strong nonlinearities in all channels before. Not present in AMSR-E
- JAXA developed pre-launch
- RSS developed post-launch using RTM model
- 0-5K nonlinearities. JAXA and RSS estimates do NOT match



Intercalibration Methodology

- Calibration to an accurate ocean radiative transfer model (RTM) in rain-free conditions [*Meissner and Wentz, 2012*]
- Requires knowledge of: wind speed, water vapor, and cloud water
  - Obtained from other intercalibrated satellites, namely SSM/I and WindSat
  - SST from Reynolds OI and wind direction from NCEP
- The spillover, cross-polarization, hot load offset, and non-linearity are adjusted to obtain best intercalibration [*Wentz, 2013*]
- Reliability at higher temperatures verified using Amazon comparisons

Advantages of the RTM Intercalibration Methodology

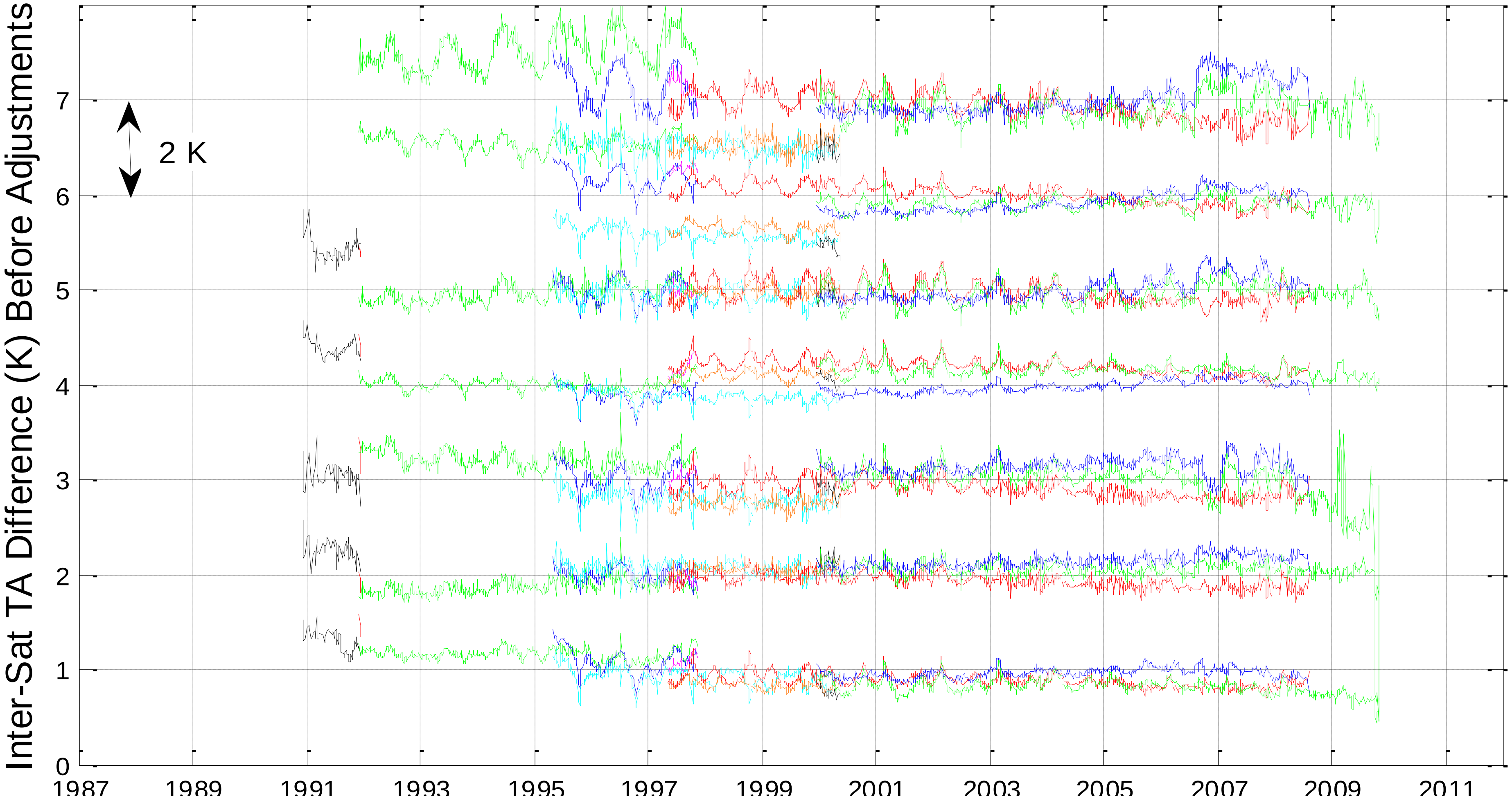
- The RTM in a relative sense over the full range of environmental conditions (excluding rain) is predicting TB to an accuracy near 0.2 K and certainly better than 0.5 K.
- Considering that the prelaunch error in the absolute calibration of the SSM/I due to knowledge error in the antenna spillover and effective target temperatures can easily be 2 K, the ocean RTM is the better calibration reference
- Can easily
  - Handle orbit gaps (overlap no longer required)
  - Adjust for different channel sets and viewing angles (i.e. SSM/I and WindSat)
  - Provides a precise definition of absolute calibration that can be applied to all sensors
  - Closure analysis (W,V, L into RTM to get $TB_{predicted}$, compare this to the $TB_{measured}$)
- Results suggest calibration is applicable over ocean, land, and ice. Separate calibration for land and ice is not necessary.

Nonlinearity

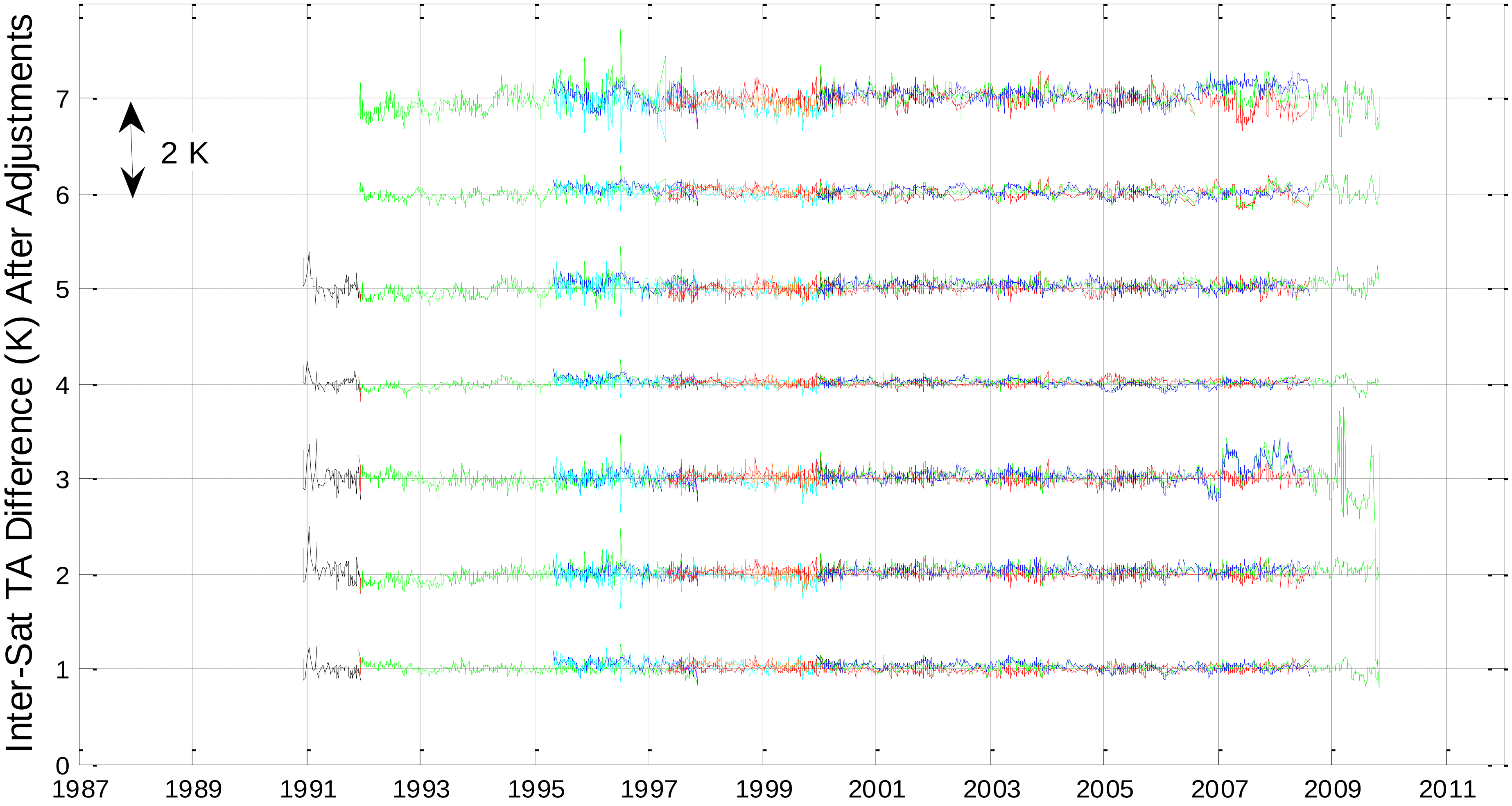
- radiometer nonlinearity manifested on-orbit but not observed pre-launch is possible if the temperature dependence of the nonlinearity in the LNA, IF amplifier, or detector diode have not been properly characterized; or if their temperatures on-orbit are not properly characterized.

“AMSR2 Calibration: Intercomparison of RSS and JAXA Brightness Temperatures”, Hilburn & Gentemann, submitted

Before calibration



After calibration

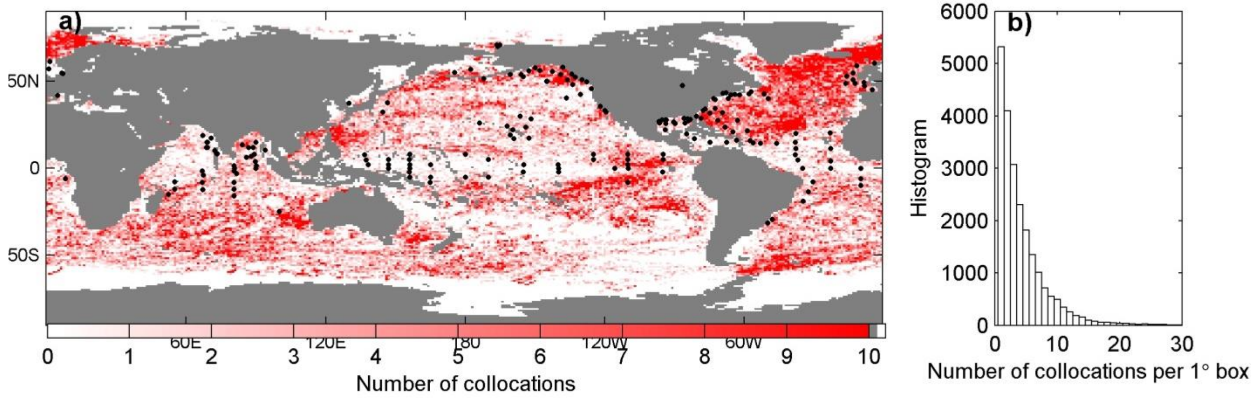


Geophysical Retrieval Methodology

- SST retrieval algorithm based on RTM
  - *Meissner and Wentz, 2012*; *Chelton and Wentz, 2005*; *Wentz and Meissner, 2000*
  - Radiosondes to specify atmospheric temperature and humidity
  - Train by randomly prescribing sea surface temperature, wind speed and direction, and cloud amount and height
- Placed on 0.25-deg cylindrical Earth grid, separating day and night passes; data are quality controlled for contamination by rain, sea ice, sun glint, and radio frequency interference (RFI)
- This presentation specifically uses AMSR2, RSS Version 7.2, which includes:
  - Small water vapor correction [*Gentemann, 2014*]
  - New RFI detection (discussed in this presentation)
  - Seasonal correction for 10V channel
    - Several explanations for this: noise, RFI, non-linearity from out-of-bounds thermistors

In Situ Data

- Moored buoys, drifting buoys, and ship measurements from US Global Ocean Data Assimilation Experiment (USGODAE) server
- Map shows the two-year data coverage
- Histogram shows that most 1 deg boxes have zero observations (white areas on map)
- Uses observations with probability of gross error less than 0.6 K [*Cummings, 2011; Castro, 2012*]
- CMAN have largest STD by far, 1.28 K
- Other ship measurements next highest from 0.72 – 0.87 K
- CMAN and engine room intake have largest biases, 0.17 K
- Consistent with previous assessments of ship SST measurements [*Kaplan et al., 1998; Rayner et al., 2006*]
- Buoys (both moored and drifting) have lowest STD, 0.55 K
- *Gentemann* [*2014*] used AMSRE, MODIS, buoy triple collocation to separate satellite error (0.28 K) from buoy error (0.20 K)
- Errors in ship SST too large; not using



In situ comparison type	Bias	STD	Number
ship engine room intake	0.17	0.86	2513
moored buoy	-0.01	0.57	7817
drifting buoy	**-0.05**	**0.55**	**101533**
ship bucket	0.08	0.78	202
ship hull	0.08	0.70	2284
cman	0.17	1.28	24

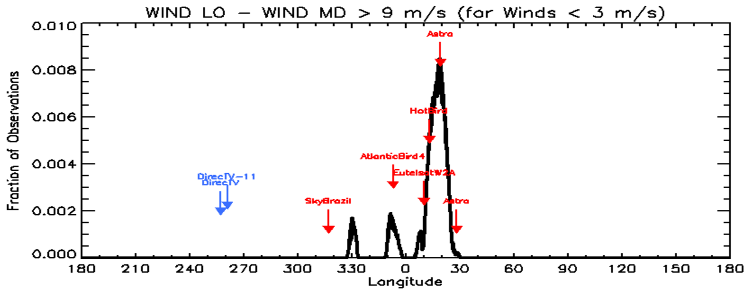
Table: Mean bias (AMSR2 – in situ), standard deviation (STD), and number of collocations for July 25, 2012 – October 9, 2014.

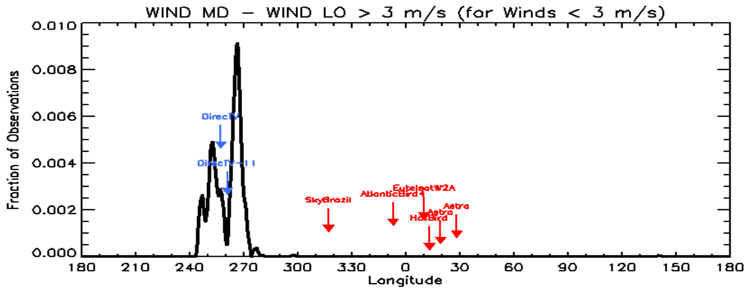
Validation Methodology Challenges

- Space and time sampling
  - Satellite: average over footprint
  - In situ: point measurement
  - Solution: statistics over appropriate space/time averages
- Measurement depth
  - Satellite (microwave): few mm
  - In situ: 0.2-1.5 m, depending on instrumentation
  - Solution: Remove data with conditions favorable to diurnal warming
- RFI contamination
  - Satellite: Difficult problem, ongoing problem
  - In situ: not a problem
  - Solution: RFI detection technique based on retrieval differences

RFI Sources

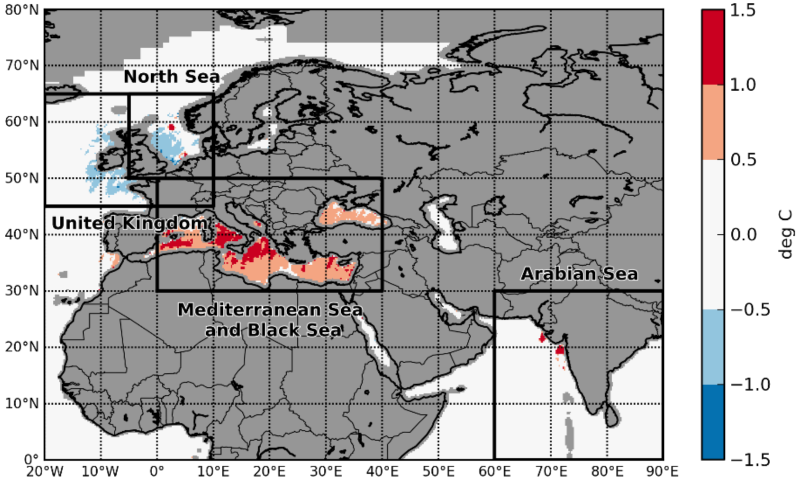
- ITU regulations prohibit operation of transmitters above a specified power level within protected bands
- AMSR2 channels centered in bands, but
  - The complete bandwidth not protected
  - There is out-of-band emission
- Three main sources for AMSR2
  - GEO space-based, ocean-reflected (satellite TV)
  - LEO space-based, ocean-reflected (satellite phones)
  - GEO space-based into the cold mirror
  - Surface-based, direct (oil and gas rigs, cities, military/naval activity)
- GEO space-based RFI occurs in the Southern Hemisphere for ascending passes and Northern Hemisphere for descending passes where the reflection vector is towards the Equator
- GEO space-based ocean-reflected RFI can be identified by tracking the boresight reflection vector back up to geostationary altitude where it originates
  - Must cross at latitude near Equator
  - Histogram of longitudes form peaks
  - Higher winds spread the signal over a larger area on Earth





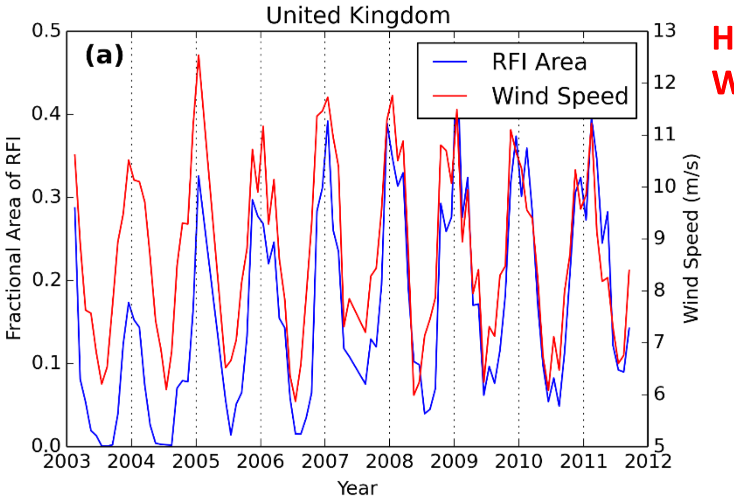
RFI Variability

- RFI is highly variable in space and time
    - For both human and environmental reasons
- Analysis of AMSR-E [*Hilburn et al., 2014*] also found seasonal variability resulting from environmental conditions
- RFI adds to brightness temperature signal, but this can produce either positive or negative SST anomalies depending on the frequency and polarization of the channel
    - Positive SST impact from 6H, 10V, 18H
    - Negative SST impact from 6V, 10H, 18V
- Wind spreading of RFI signal around United Kingdom
- Cloud attenuation of RFI over Mediterranean Sea



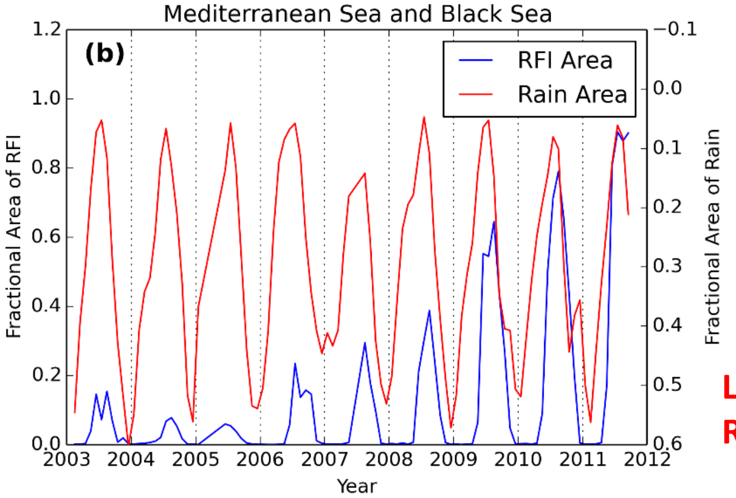
Larger RFI Area

Higher Wind Speed



Smaller RFI Area

Larger Rain Area

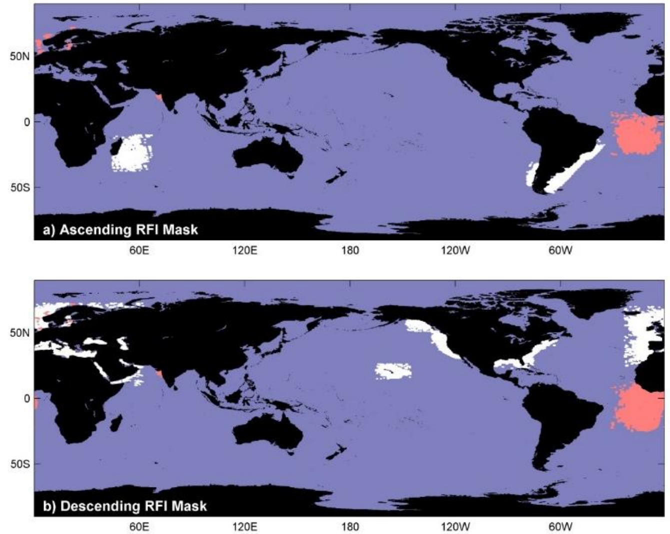


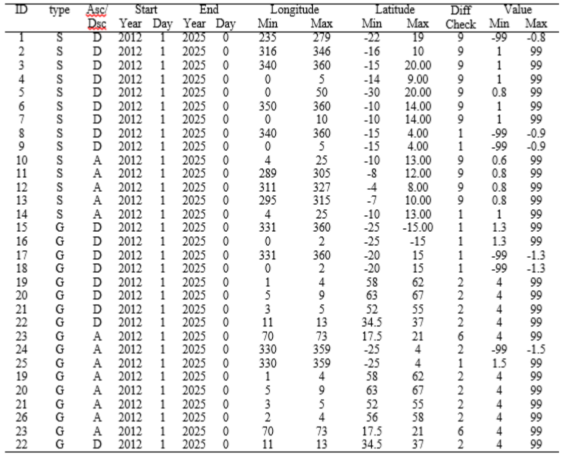
RFI Detection and Removal Methodology

- Simplest: mean and standard deviation of brightness temperatures [*Njoku et al., 2005*]
  - Works well on strong RFI, unable to distinguish weak RFI from natural geophysical variability
- Adding additional information about channel correlations and probability-distribution functions [*Li et al., 2006; Truesdale, 2013*] extends this approach, but detecting weak RFI is still difficult
- Better yet: to separate RFI from natural signals, use RTM to specify expected brightness temperature [*Adams et al., 2010; Adams et al., 2014; Hilburn et al., 2014*]
  - Adams used chi-square goodness-of-fit
- Our approach: differences of SST and wind retrievals made using different channel combinations
  - Retrieval uses RTM, so this information is implicit in technique
  - Disadvantage: retrieval mixes channels, so technique does not directly tell what frequency is the culprit
  - Advantage: spatial patterns in SST and wind have physical meaning, making RFI easier to identify, and making cross-talk with high wind or rain evident

RFI Methodology Details

- Figure shows the RFI mask
    - White regions are space-based
    - Red regions are surface-based
    - This is maximum extent; RFI covers a much smaller area on any given day
- Each RFI type is given an ID number and added to table
- Provides information on type, occurrence in day/night passes, start/end dates, latitude/longitude bounds
- Then use the indicated difference check against the provided min/max values
- Difference checks:
    - 1 = (SST 6) – (SST 10)
    - 2 = (SST 6) – (SST Rey)
    - 6 = (Wind 6) – (Wind 10)
    - 9 = (Wind 10) – (Wind 18)

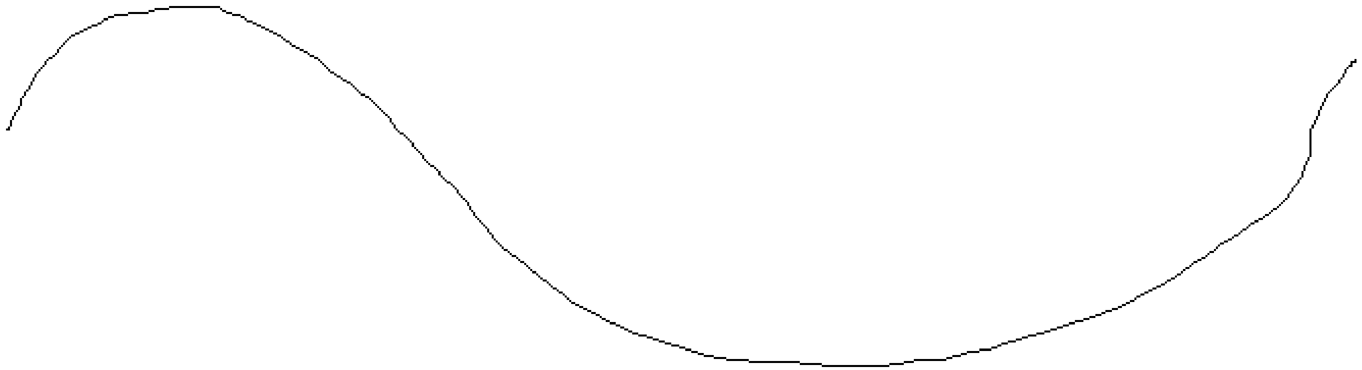




ID	type	Asc/	Start		End		Longitude		Latitude		Diff	Value	
		Dsc	Year	Day	Year	Day	Min	Max	Min	Max	Check	Min	Max
1	S	D	2012	1	2025	0	235	279	-22	19	9	-99	-0.8
2	S	D	2012	1	2025	0	316	346	-16	10	9	1	99
3	S	D	2012	1	2025	0	340	360	-15	20.00	9	1	99
4	S	D	2012	1	2025	0	0	5	-14	9.00	9	1	99
5	S	D	2012	1	2025	0	0	50	-30	20.00	9	0.8	99
6	S	D	2012	1	2025	0	350	360	-10	14.00	9	1	99
7	S	D	2012	1	2025	0	0	10	-10	14.00	9	1	99
8	S	D	2012	1	2025	0	340	360	-15	4.00	1	-99	-0.9
9	S	D	2012	1	2025	0	0	5	-15	4.00	1	-99	-0.9
10	S	A	2012	1	2025	0	4	25	-10	13.00	9	0.6	99
11	S	A	2012	1	2025	0	289	305	-8	12.00	9	0.8	99
12	S	A	2012	1	2025	0	311	327	-4	8.00	9	0.8	99
13	S	A	2012	1	2025	0	295	315	-7	10.00	9	0.8	99
14	S	A	2012	1	2025	0	4	25	-10	13.00	1	1	99
15	G	D	2012	1	2025	0	331	360	-25	-15.00	1	1.3	99
16	G	D	2012	1	2025	0	0	2	-25	-15	1	1.3	99
17	G	D	2012	1	2025	0	331	360	-20	15	1	-99	-1.3
18	G	D	2012	1	2025	0	0	2	-20	15	1	-99	-1.3
19	G	D	2012	1	2025	0	1	4	58	62	2	4	99
20	G	D	2012	1	2025	0	5	9	63	67	2	4	99
21	G	D	2012	1	2025	0	3	5	52	55	2	4	99
22	G	D	2012	1	2025	0	11	13	34.5	37	2	4	99
23	G	A	2012	1	2025	0	70	73	17.5	21	6	4	99
24	G	A	2012	1	2025	0	330	359	-25	4	2	-99	-1.5
25	G	A	2012	1	2025	0	330	359	-25	4	1	1.5	99
19	G	A	2012	1	2025	0	1	4	58	62	2	4	99
20	G	A	2012	1	2025	0	5	9	63	67	2	4	99
21	G	A	2012	1	2025	0	3	5	52	55	2	4	99
26	G	A	2012	1	2025	0	2	4	56	58	2	4	99
23	G	A	2012	1	2025	0	70	73	17.5	21	6	4	99
22	G	D	2012	1	2025	0	11	13	34.5	37	2	4	99

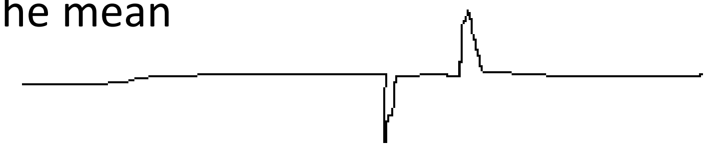
Ascension Island RFI Detection Algorithm

Normal orbit

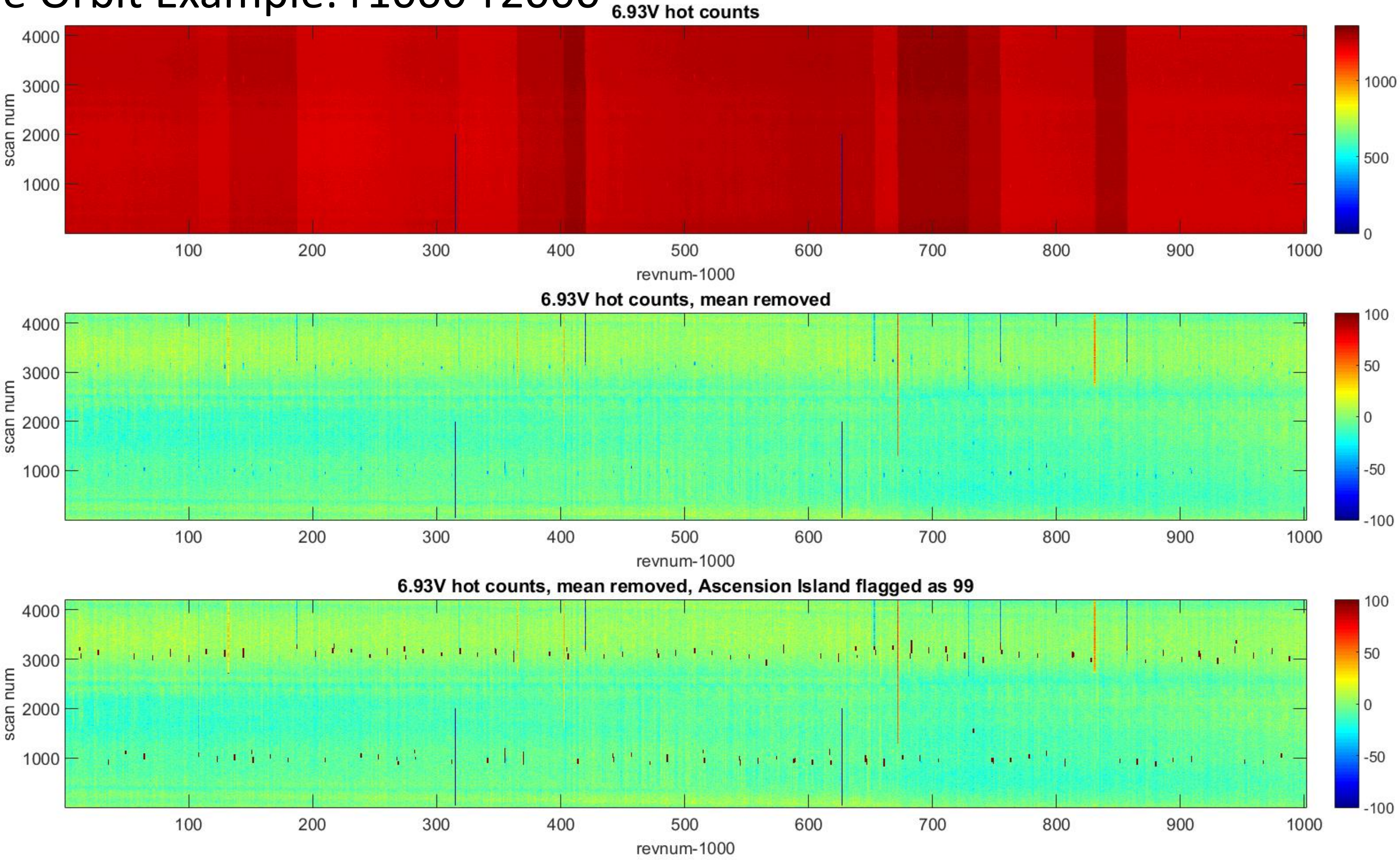


Ascension Island orbit

Offset-difference of the mean



Multiple Orbit Example: r1000-r2000



6.93V hot counts

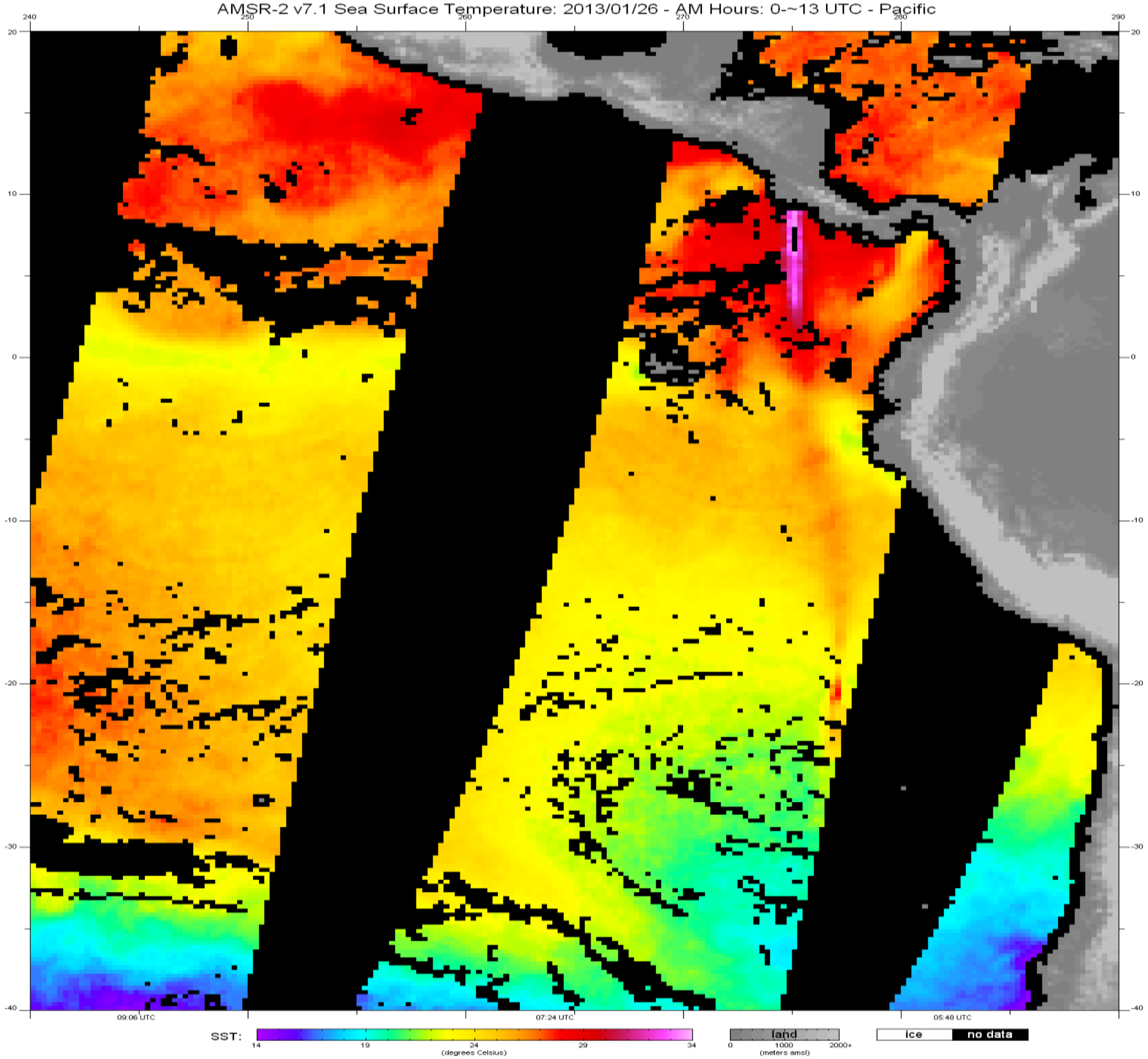
6.93V hot counts, mean removed

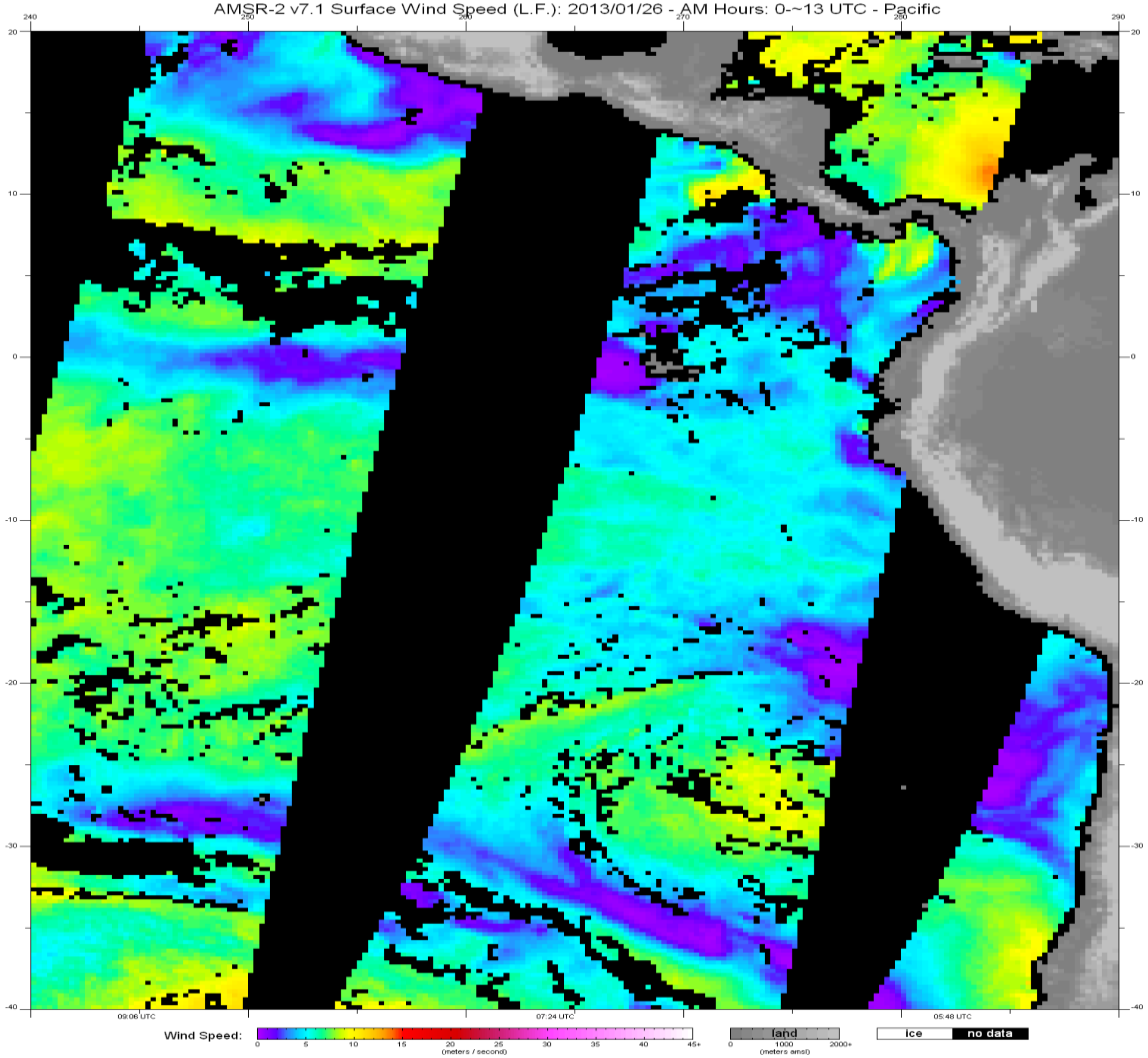
6.93V hot counts, mean removed, Ascension Island flagged as 99

Marty Brewer has repeatedly shown other RFI issues

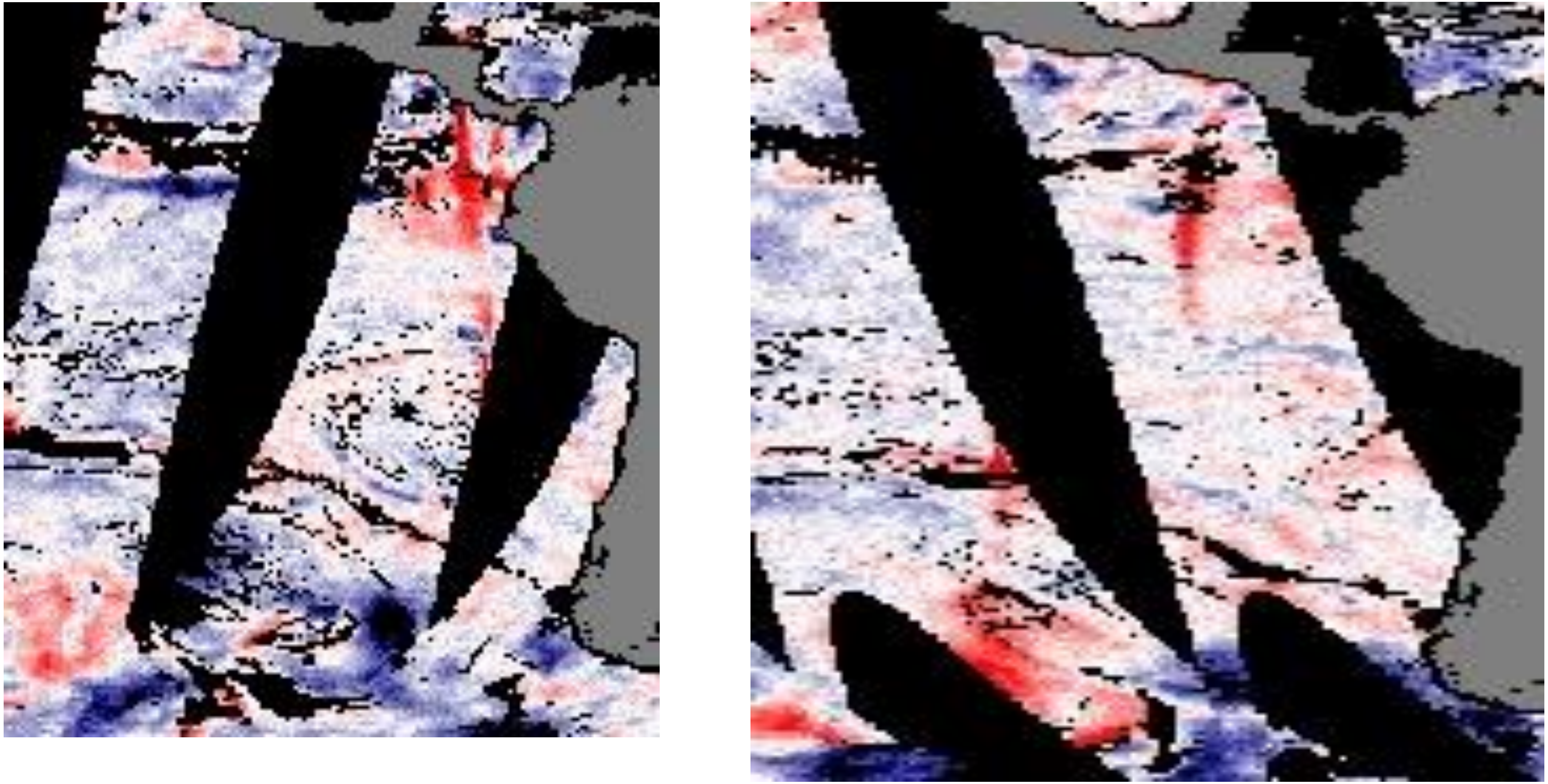
6.9GHz Space-Based Ocean-Reflected RFI

Night


AMSR-2 v7.1 Sea Surface Temperature: 2013/01/26 - AM Hours: 0-~13 UTC - Pacific


AMSR-2 v7.1 Surface Wind Speed (L.F.): 2013/01/26 - AM Hours: 0-~13 UTC - Pacific

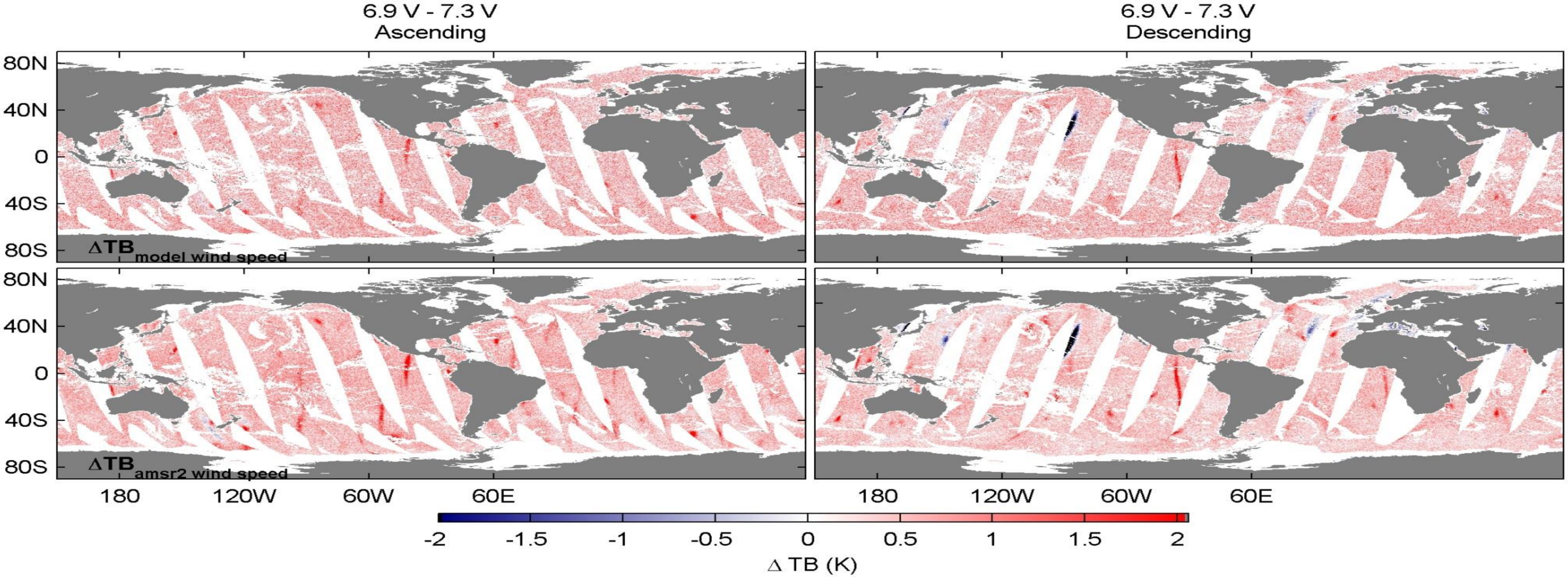
26 May 3012, 6.9 H



MRFI

- In 6.9 VH but NOT the 7.3VH

Double Difference 27 May 2013: $TB_{6.9V} - RTM_{6.9V} - (TB_{7.3V} - RTM_{7.3V})$

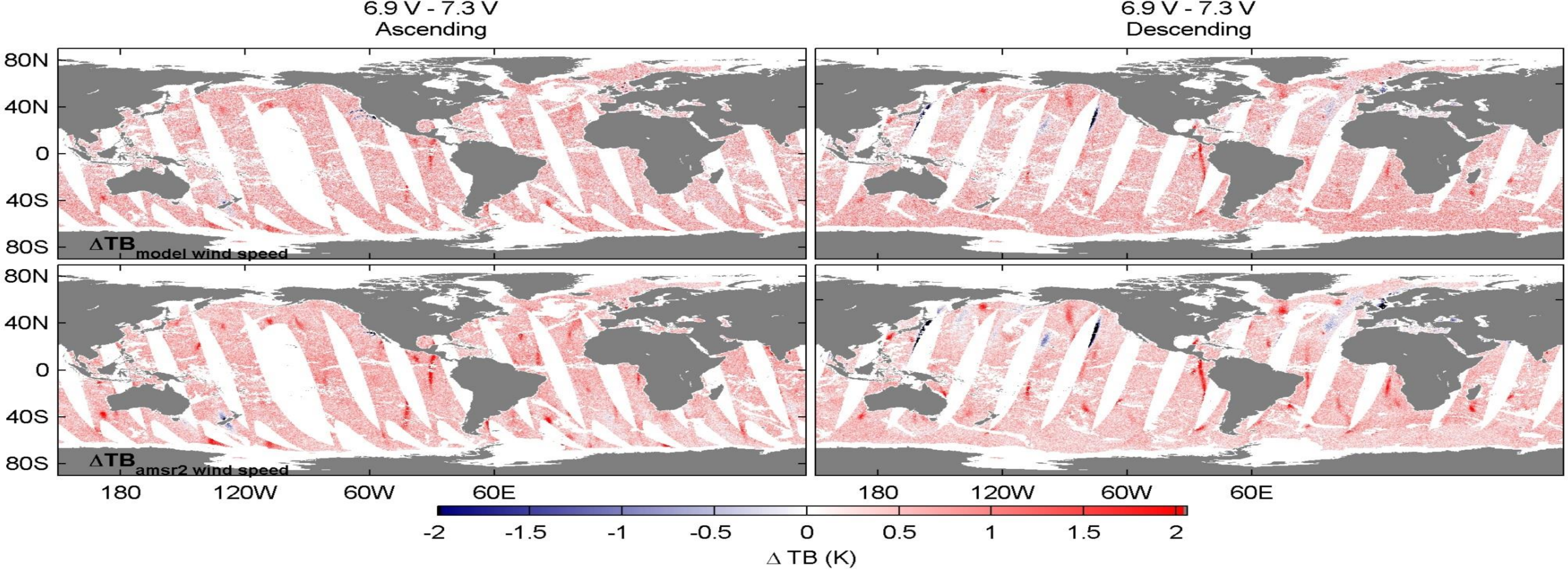


- Warm 6.9 RFI, Cold 7.3 RFI

How to get rid of MRFI

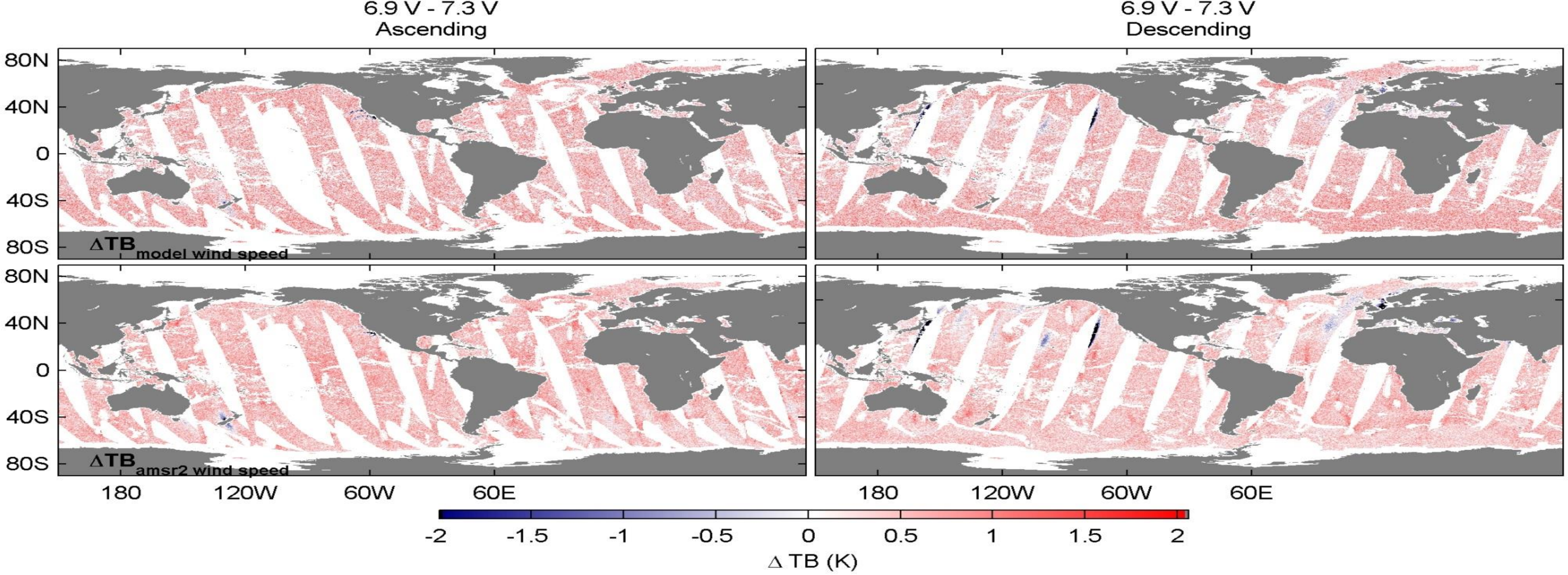
- Look for DD warm (RFI in 6.9)
- 6.9H-7.3H better than V
- Subtract daily mean, deterimine STD
- Find all points > 1K warm
- Look in 3x8 window. If less than 6 other warm measurements, don't mask
- If greater than 6 other warm measurements, then mask any where diff>STD

Double Difference 26 May 2013: $TB_{6.9V} – RTM_{6.9V} – (TB_{7.3V} – RTM_{7.3V})$



- Warm 6.9 RFI, Cold 7.3 RFI
- Note New Zealand 7.3 RFI

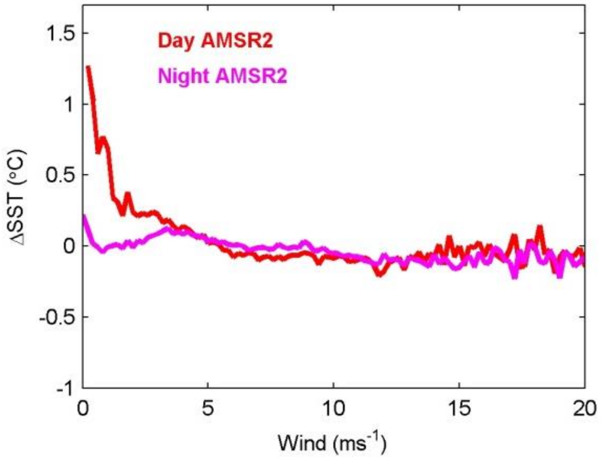
Double Difference 26 May 2013: $TB_{6.9V} – RTM_{6.9V} – (TB_{7.3V} – RTM_{7.3V})$



- Warm 6.9 RFI, Cold 7.3 RFI
- Note New Zealand 7.3 RFI

Diurnal Warming

- *Price et al.* [*1986*] examined R/F Flip, found 0.05 to 0.4 K warming, with most day-to-day variability due to wind stress
- *Soloviev and Lukas* [*1997*] found warming of more than 3 K in top 1 m in western Pacific warm pool
- *Gentemann et al.* [*2003*] examined TMI and AVHRR, found magnitude of 2.8 K during favorable conditions
- *Ward* [*2006*] examined SkinDeEP on R/V Melville in Gulf of California, found warming as high as 4.6 K
- *Gentemann et al.* [*2008*] found events 5-7 K over regions of 1000 km in extra-tropics
- *Matthews et al.* [*2014*] examined CINDY/DYNAMO and found 0.8 K warming in afternoon in Indian Ocean
- Thus, diurnal warming signal is large compared with microwave SST bias/STD, and is also highly variable in time [*Gentemann and Minnett, 2008*]



- Figure shows SST bias as a function of wind speed for day and night
- Figure gives estimate of the difference between diurnal warming at a few mm depth vs 0.2-1.5 m depth
- Best to avoid, rather than trying to model it
- Exclude all collocations between 10 AM and 4 PM local time with winds < 6 m/s

Overall Results

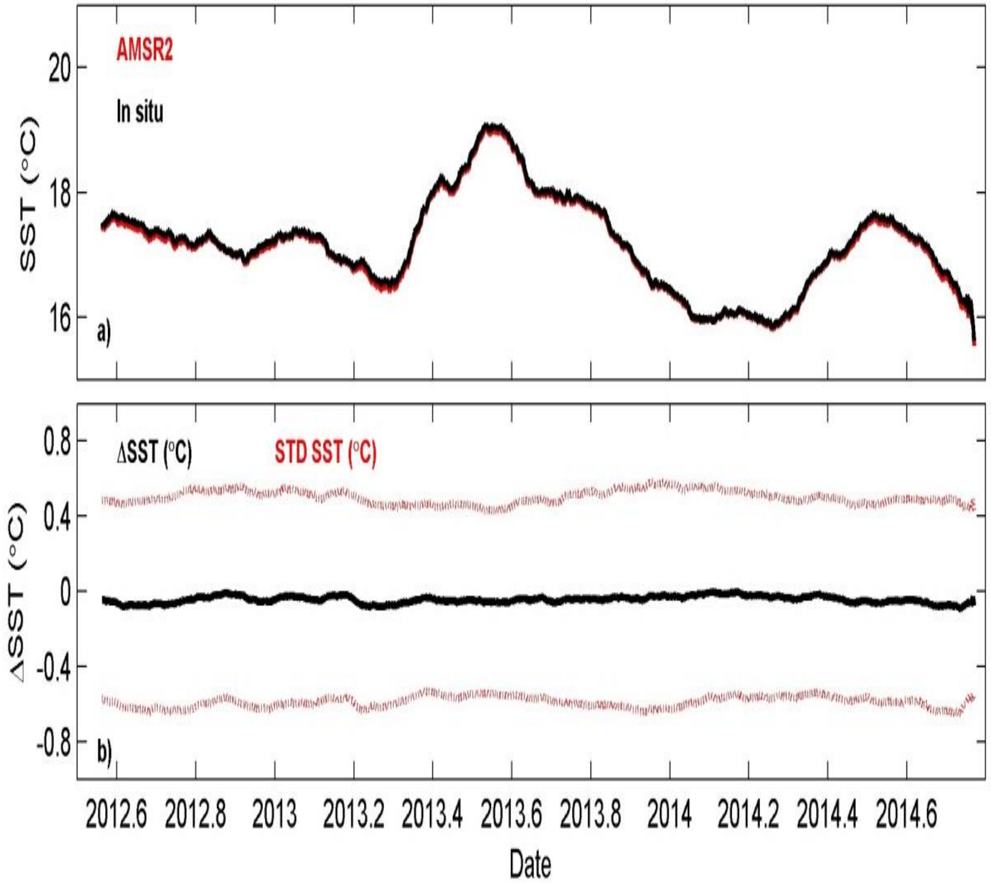
- Overall, AMSR2 SST are slightly cooler (-0.04 K) than the buoys
- SST retrievals provide a particularly stringent requirement on brightness temperature, 0.25 K errors in 6 GHz v-pol would produce a 0.50 K error in SST [*Meissner and Wentz, 2012*]
- Thus, AMSR2 absolute calibration is accurate to 0.02 K, which is sufficiently small to use AMSR2 in climate studies
- The small day/night difference (0.06 K) implies that AMSR2 relative calibration is accurate to within 0.03 K
- Relative calibration errors (e.g., errors vs scan/orbit position) would increase STD, but day and night both have STD of 0.55 K, which are slightly better than TRMM [*Gentemann et al., 2004*]

	Bias	STD	Num
All	-0.04	0.55	109350
Day	-0.09	0.55	40997
Night	-0.02	0.54	68353

Table: Mean bias (AMSR2 – in situ), standard deviation, and number of collocations for July 25, 2012 – October 9, 2014.

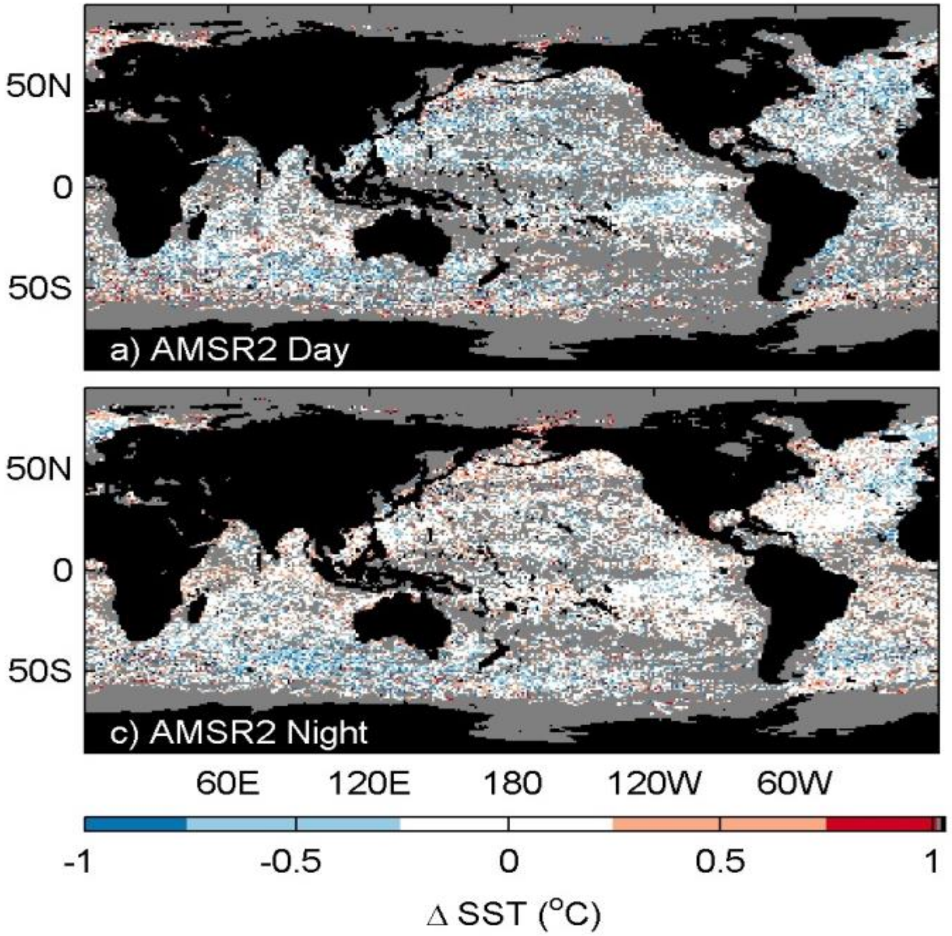
Time Variability

- When relative calibration errors are present, they often manifest themselves as a spurious piece-wise linear trend or as a spurious annual cycle, but our results show no evidence of this
- Top panel shows that AMSR2 and buoy SST agree so well they overlap
- Bottom panel shows bias and STD
- Time variation in bias is on the order of the bias itself, 0.04 K
- This implies AMSR2 calibration is stable in time on the order of 0.02 K
  - Demonstrates that nonlinearities are stable and calibration developed during initial period has not changed
- STD does exhibit some time variability
- With two complete annual cycles, see that STD is smaller in boreal summer and larger in boreal winter
- Is this evidence of minor calibration error or SST retrieval errors?



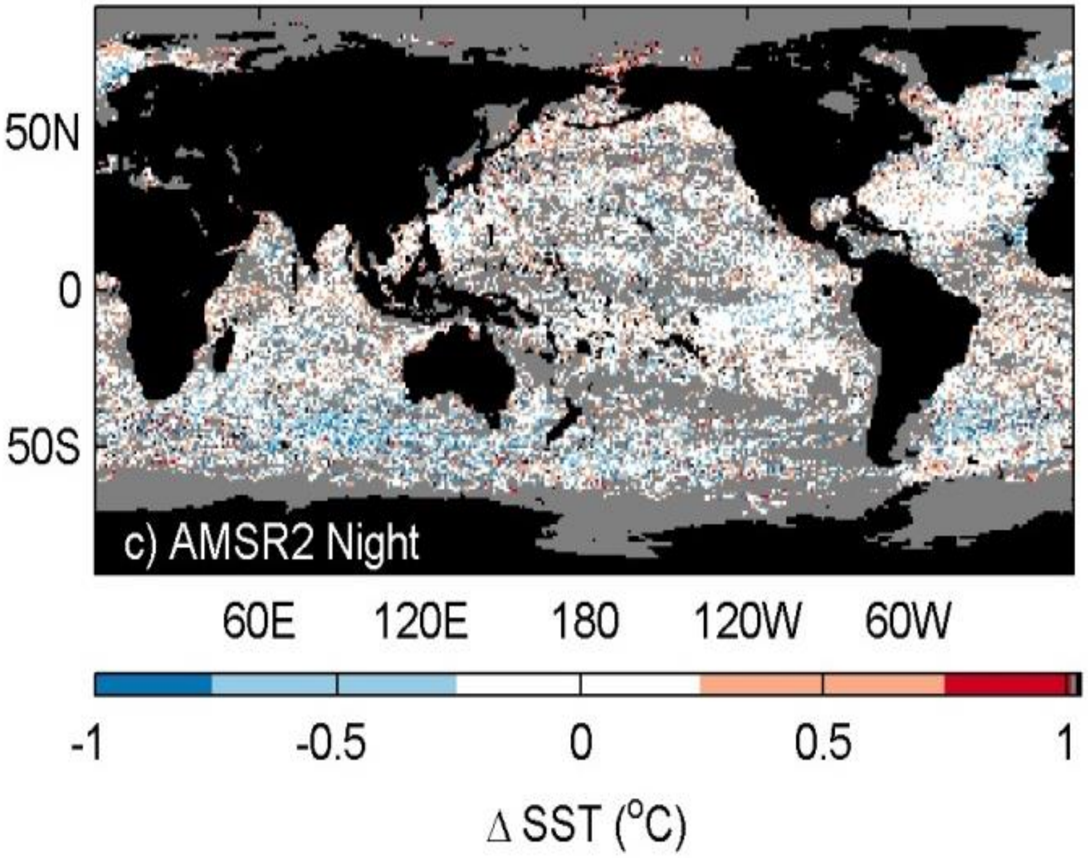
Spatial Variability: Day vs Night

- Daytime differences are slightly cooler, as already seen
- In most locations, the daytime map resembles the nighttime map, with slight shift cooler
  - Would imply that difference is a minor relative calibration error
  - Not true in Labrador Sea and Davis Strait, where nighttime biases are warm and large (0.5 K)… problem with satellite or drifters?
  - Also not true in far southern extent of Southern Ocean, daytime biases are warmer and strikingly zonally symmetric
    - Zonally symmetry could imply calibration error depending on orbit position
    - Warmer daytime consistent with diurnal warming, but not consistent with high winds in region that mix-out stratification effects



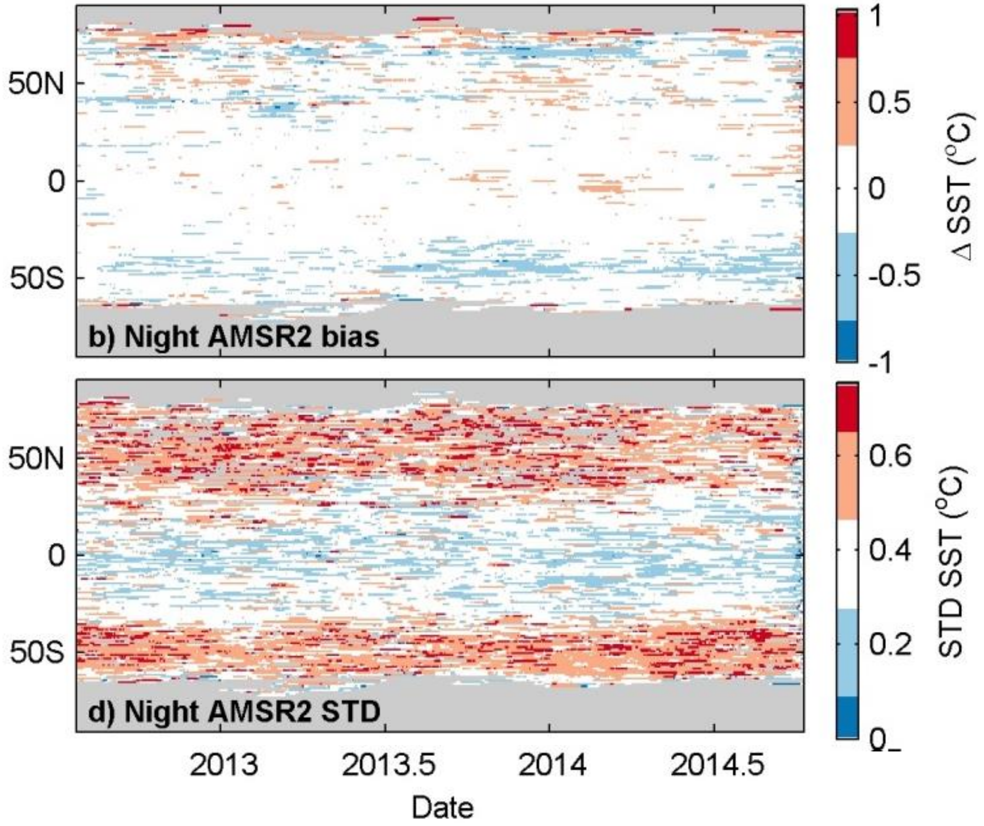
Spatial Variability Patterns

- Warm biases
  - Kuroshio-Oyeshio and northward through Bering Strait and into Chukchi Sea
  - California coast
- Cool biases
  - Peru coast westward to Marquesas
  - Arabian Sea relative to Bay of Bengal
  - Northeastern Atlantic
  - Southern Ocean (northern part)
- Comparison with TRMM and AMSRE
  - Also found warm biases off California and cool biases off Peru [*Gentemann et al., 2004; Gentemann, 2014*]
  - AMSR2 did not find large warm biases in Gulf of Mexico present in earlier version of TRMM [*Gentemann et al., 2004*]
  - AMSRE also found warm biases in Kuroshio and cool biases in N. Atlantic and S. Ocean
  - Similarity in SST difference patterns among different satellites suggests these are SST retrieval or in situ data



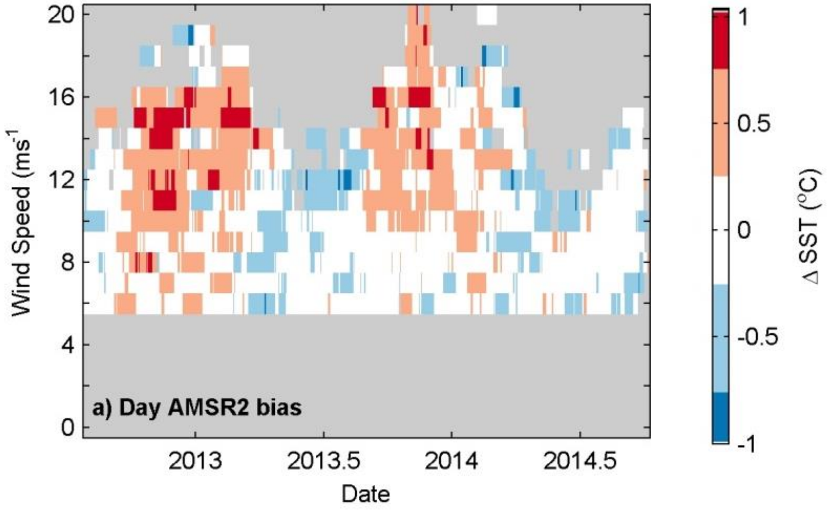
Seasonal Variability

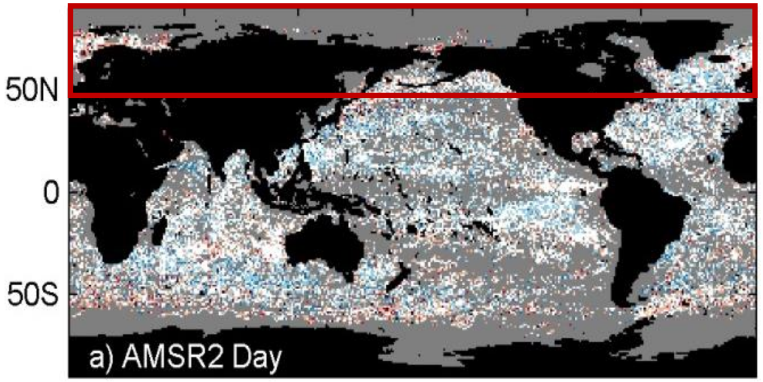
- What is time variability of the warm biases in North Pacific and cool biases in North Atlantic?
- Time-latitude plot shows the warm differences in boreal winter and cool differences in summer
- The largest SST error occurs where SST is coolest [*Gentemann et al., 2010*]
- In Northern Hemisphere, there is very little data in the Pacific, results are primarily from the Northern Atlantic and Arctic Ocean north of Europe
- Since warm bias in NH is in winter, not artifact of un-removed diurnal warming
- In Southern Hemisphere, cool bias is nearly constant throughout the year



Seasonal Biases Depend on Wind Speed

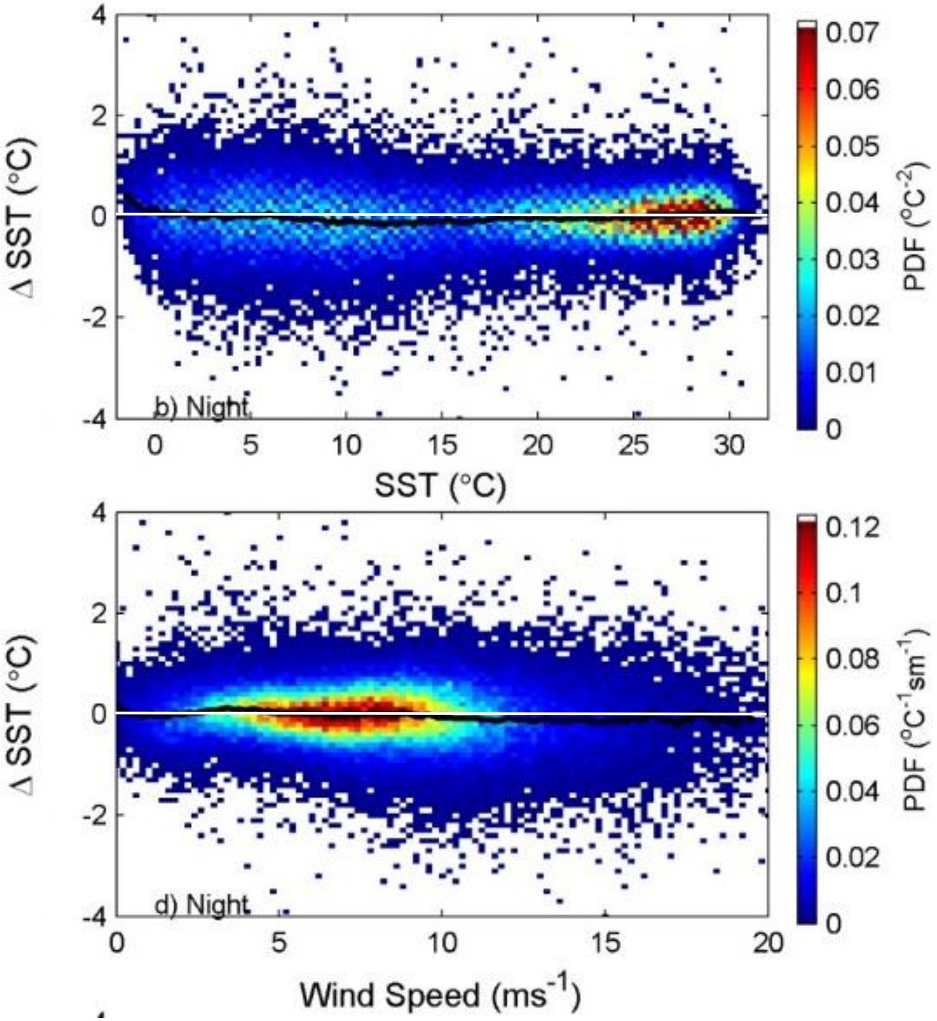
- Figure shows the SST bias vs time and wind speed for the sub-region shown on map
- Daytime has few observations below 6 m/s because of diurnal warming exclusion criteria
- The N. Hem. winter warm biases occur in high winds (> 10 m/s)
- *Meissner and Wentz* [*2013*] demonstrated that RT modeling of ocean is most uncertain at high winds and cold water
- Also, at high winds, errors from incorrect wind direction knowledge are largest
- Keep in mind that 86% of winds are below 12 m/s, so the large areas of red shading in these figures are small fraction of all data





Bias vs SST, Wind

- Bias in SST is flat with respect to SST, except for warm bias in coldest SSTs
- Bias in wind is flat with respect to wind speed
- Uncertainty increases for SST below 15 deg C
- Uncertainty increases for winds above 8 m/s
- The seasonal biases are not evident on these plots because the biases come from the combination of cool SST and high wind speed
- Biases as a function of water vapor and cloud water are flat



Summary

- AMSR2 estimates of SST were compared with buoys for a two year period
- Excluded potential diurnal warming and RFI
- Overall mean bias is -0.04 K
- Overall standard deviation is 0.55 K
- Results show that errors are stable in time
- There is a seasonally-occurring warm bias in cold water and high winds; appears to be a retrieval error, rather than a calibration error

Conclusions

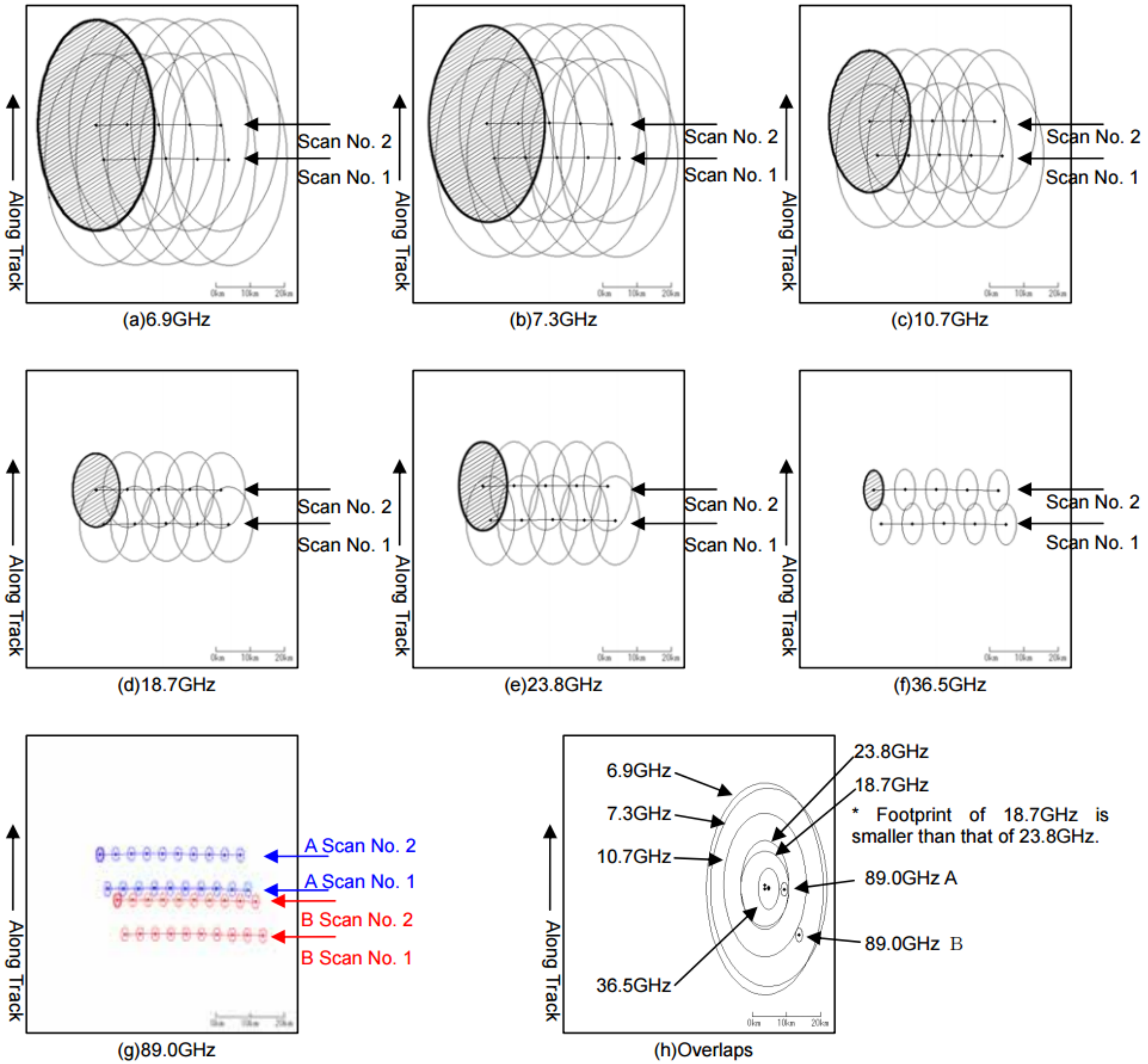
- Results imply an absolute calibration accuracy of 0.02 K
- AMSR2 STD is 0.55 K (this is over the whole globe)
  - TMI is 0.57 K
  - AMSR-E is 0.48 K
  - There are now a much higher number of drifting buoys at high latitudes where MW SSTs have a higher error then when AMSR-E was operating. The AMSR2 STD is 0.49 K when collocations are restricted to +- 40 latitude. Comparable to the AMSR-E result.
- There are some new RFI sources (intra-satellite) that we are not masking out, but it is unlikely this would significantly contribute to the error.
- Overall: AMSR2 SST are of comparable quality to AMSR-E SST and contribute to the continuation of the climate MW SST record

Processing steps that affect spatial resolution

- Resampling
- Calibration scan line averaging

Oversampling and Pointing

- http://suzaku.eorc.jaxa.jp/GCOM_W/data/doc/amsr2_data_user_guide.pdf



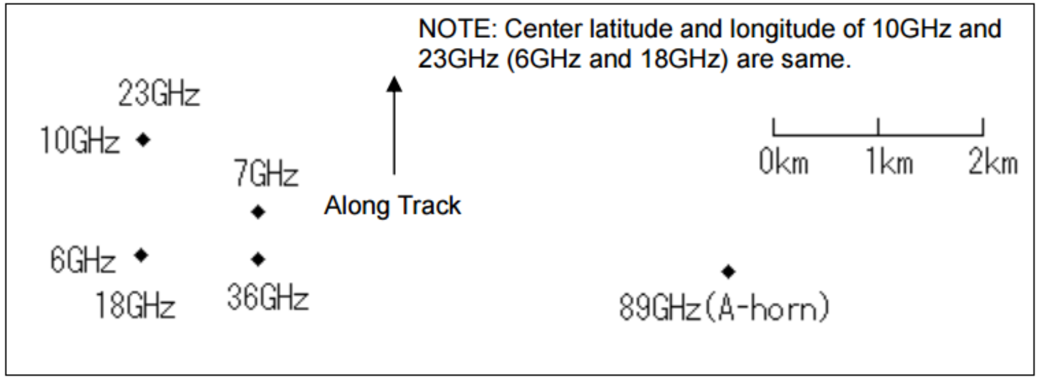
(a)6.9GHz (b)7.3GHz (c)10.7GHz

(d)18.7GHz (e)23.8GHz (f)36.5GHz

(g)89.0GHz (h)Overlaps

* Footprint of 18.7GHz is smaller than that of 23.8GHz.

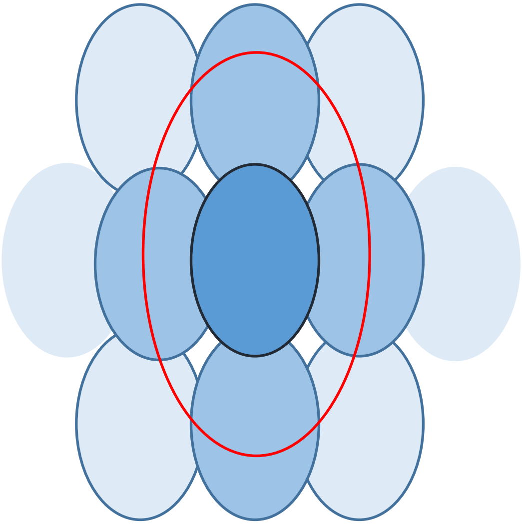
Figure 9. Schematic Image of footprint



NOTE: Center latitude and longitude of 10GHz and 23GHz (6GHz and 18GHz) are same.

Figure 10. Example of center latitude and longitude of same observation point

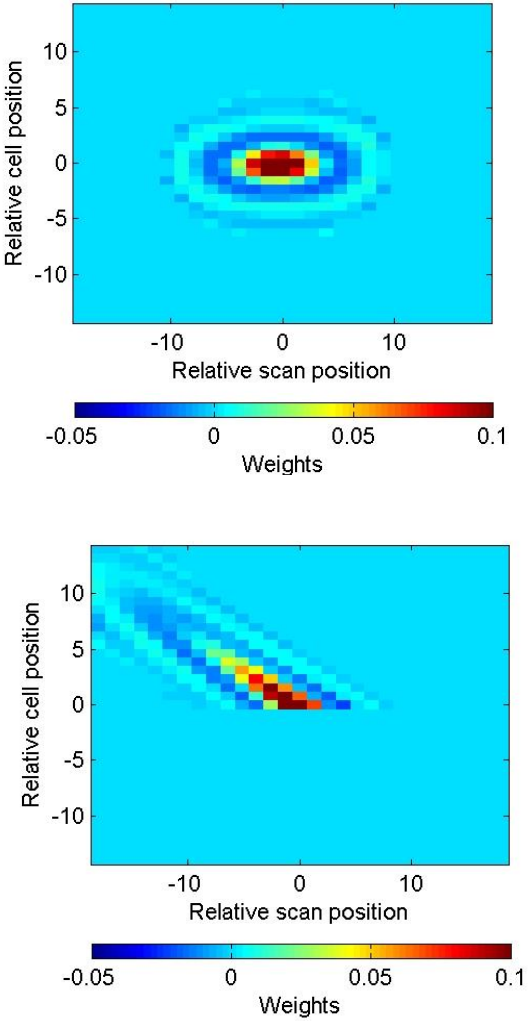
NEDT for each channel/footprint size
Effect of averaging is important



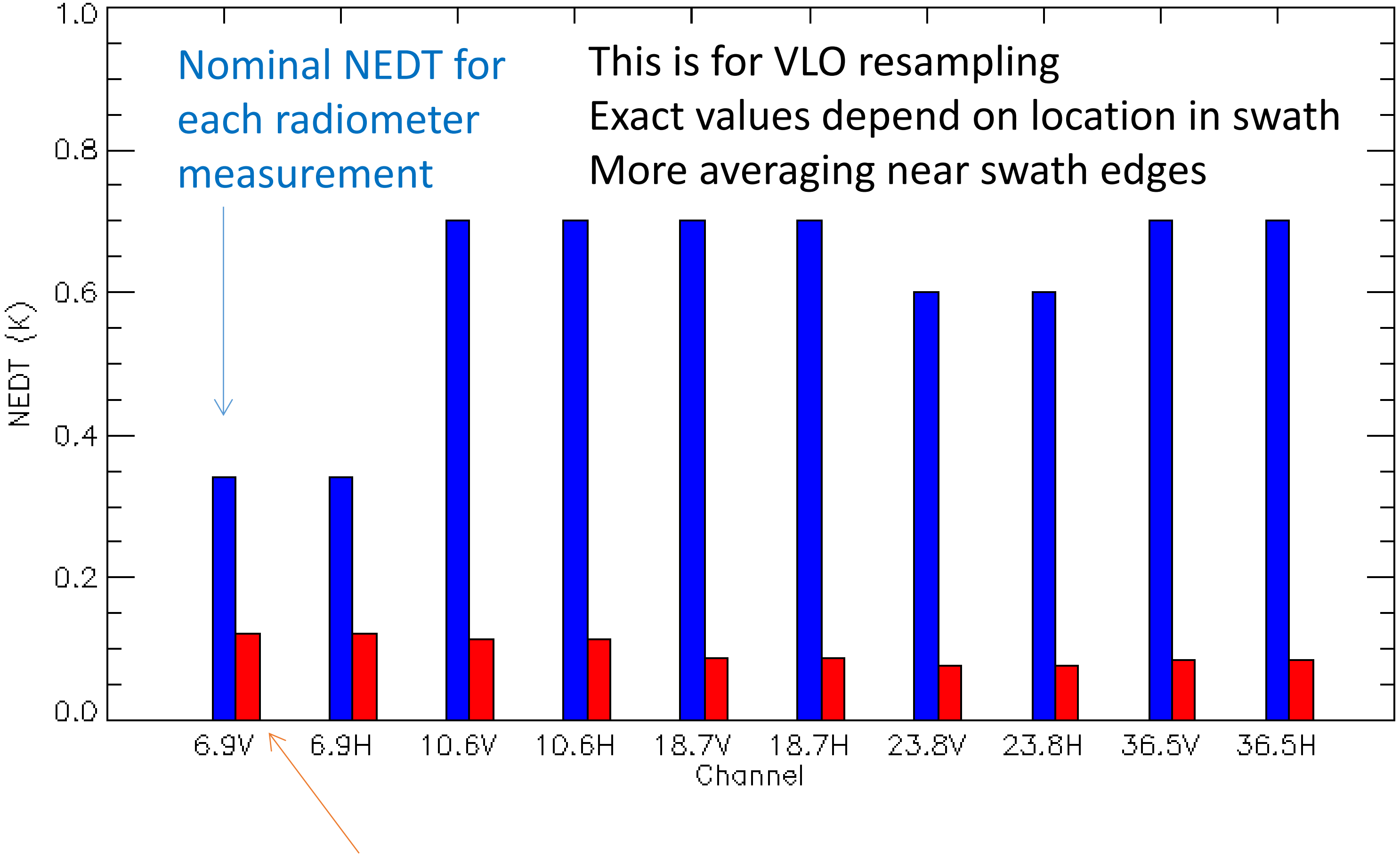
Lower resolution footprints are made up of many high resolution footprints.

Even 6.9 GHz footprints have some resampling/averaging

Random radiometer noise is substantially reduced by averaging



NEDT for each channel
Effect of averaging is important



Nominal NEDT for each radiometer measurement

This is for VLO resampling
Exact values depend on location in swath
More averaging near swath edges

NEDT after resampling is taken into effect

Calibration scan line averaging

- AFTER calculating SST (for SST only!)
- +- 2 scans, no across scan (cell) averaging, simple smoothing performed
- To remove slight striping, only seen in SST which is very sensitive to small calibration errors