Lecture 1

Principle of Microwave Radiometry

Dr. Fuzhong Weng
Center for Satellite Applications and Research
National Environmental Satellites, Data and Information Service
National Oceanic and Atmospheric Administration

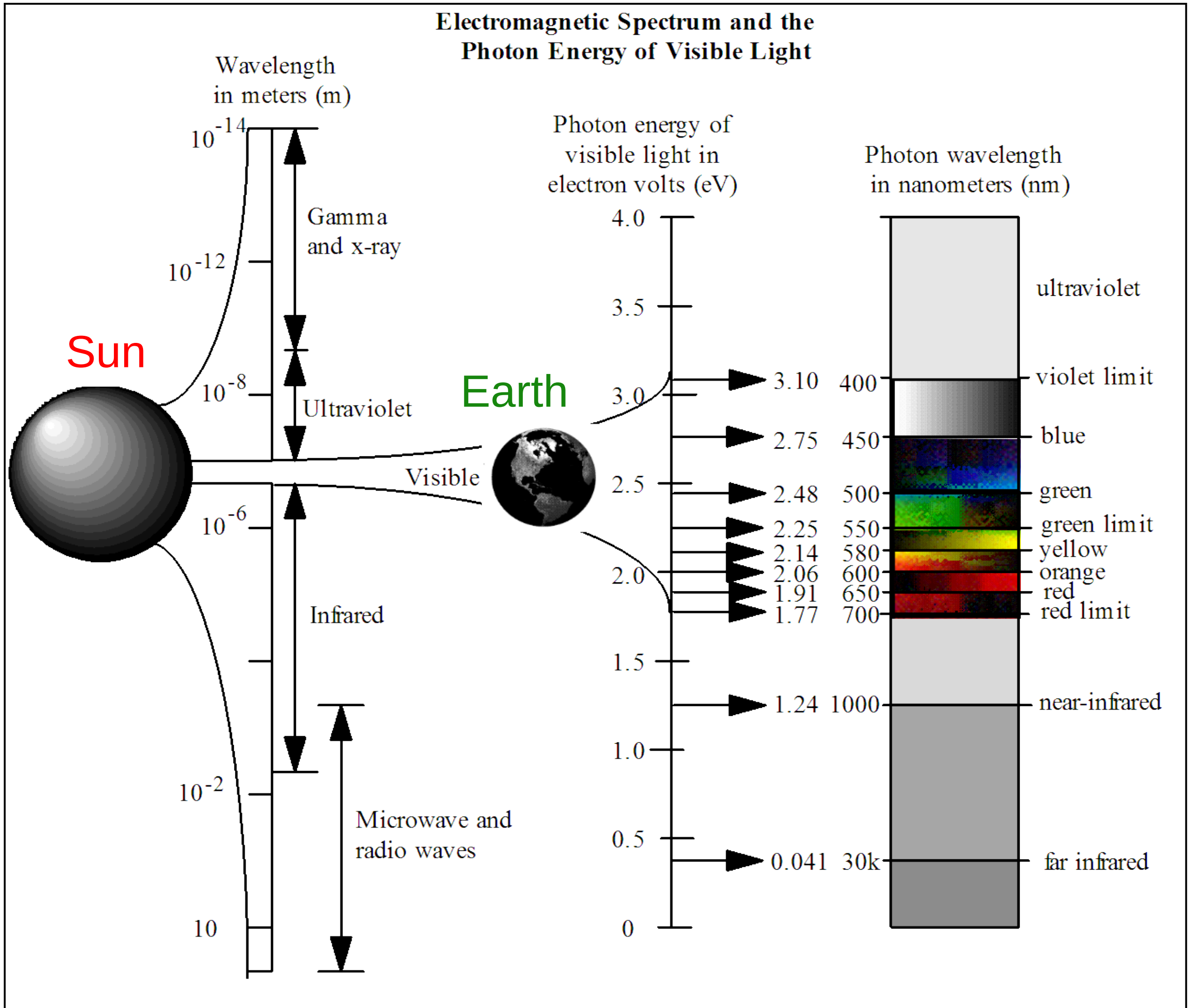
2012 Update

Outline

1. **Solar Radiation Spectrum**
2. **Microwave Radiometry System**
3. **History of Microwave Instruments**
4. **Calibration and Validation**
5. **Microwave Data, Products and Applications**
6. **Future Challenges**
7. **Summary**

Electromagnetic (EM) Spectrum

The Sun produces a *continuous spectrum* of energy from gamma rays to radio waves that continually bathe the Earth in energy.

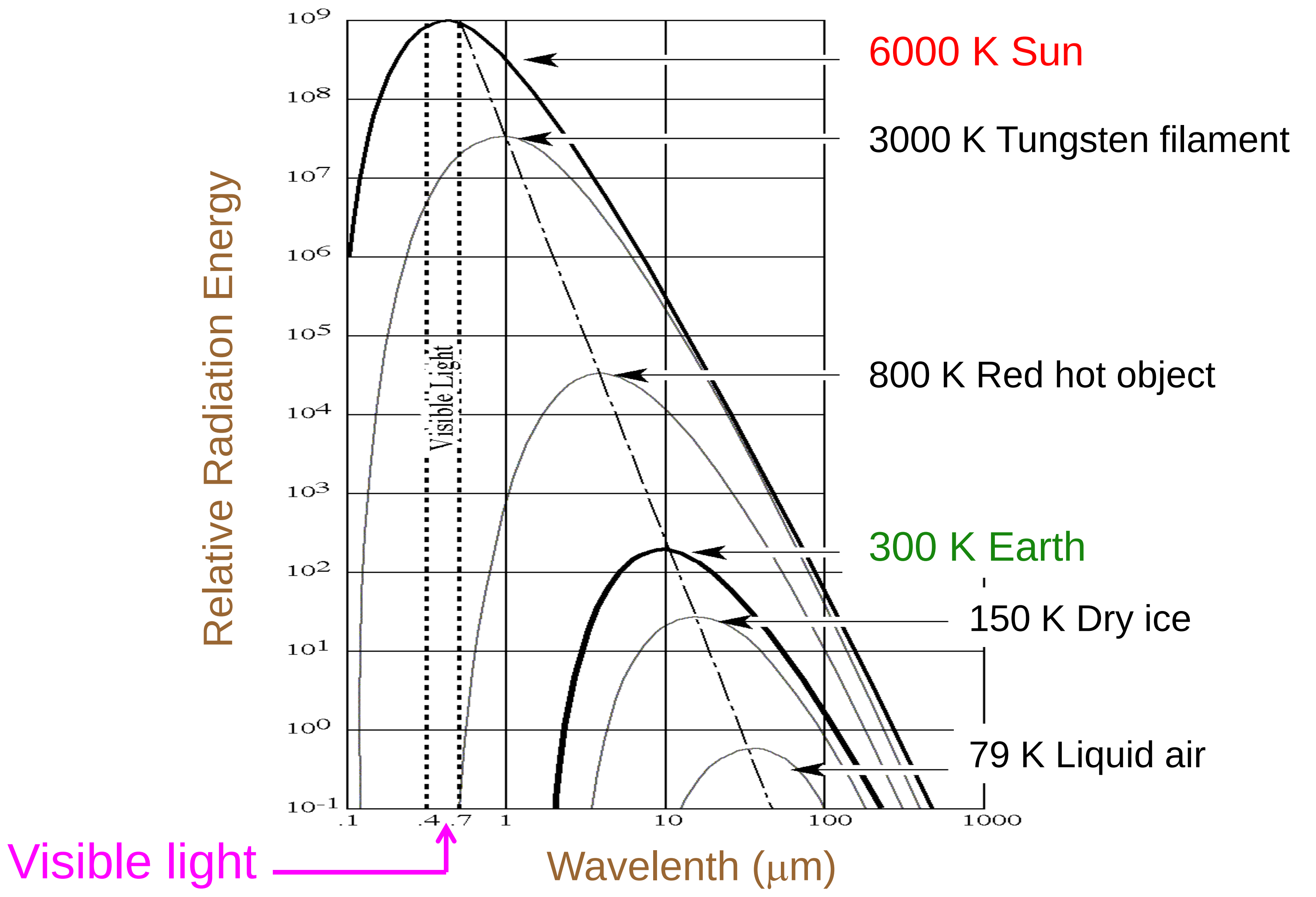


The visible portion of the spectrum may be measured using wavelength in unit of

- μm
- nm
- eV (electron volts)

All units are Interchangeable.

Blackbody Radiation Curves



Advantages of Microwave Remote Sensing from Space

1. Penetration through non-precipitating clouds

2. Highly stable instrument calibration

3. Radiance is linearly related to temperature
   (i.e. the retrieval is nearly linear)

4. O_2 concentration is uniformly distributed in the atmosphere

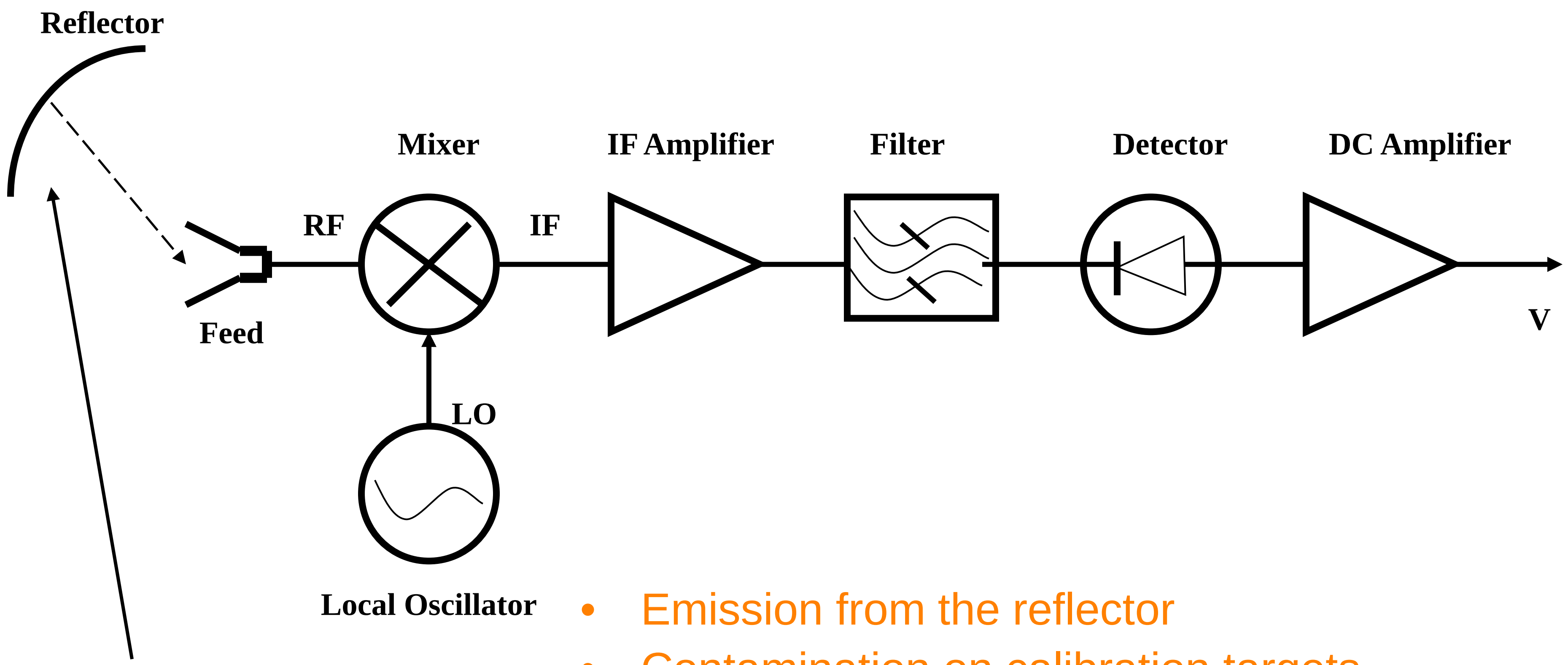
5. Major impacts on NWP and climate research

Microwave Radiometers

Satellite	Sensor	Center Frequencies(GHz)	Nadir IFOV(km)[1]	Primary Application[2]
Cosmos-243 1969	-	3.5,8.8,22.2,37	13 (nadir)	V,L,F,T,S
Cosmos-384 1970	-	3.5,8.8,22.2,37	13 (nadir)	V,L,F,T,S
Nimbus-5 1972	ESMR	19.35	25 (x-scan)	F,S,R
Nimbus-5 1972	NEMS	22.23,31.40 53.65,54.90,58.80	200 (nadir)	t,V,L
Nimbus-6 1975	SCAMS	22.23,31.65 52.85,53.85,55.45	150 (nadir)	t,V,L
Nimbus-6 1975	EMSR	37.0(V+H)	25 (c-scan)	F,R,W
Nimbus-7 1978	SMMR	6.6,10.69,18.0(V+H) 21.0,37.0(V+H)	25 (c-scan) 20-100(c-scan)	F,S,R,C V,L,W,T
TIROS 1978-1995	MSU	50.30,53.74,54.96,57.95	110(x-scan)	t,L
DMSP 1979-	SSM/T	50.50,53.20,54.35,54.90 58.40,58.82,59.40	175(x-scan)	t,L
MOS-1 1987	MSR	23.80,31.40	23-32(x-scan)	V,L,F,W
DMSP 1987-	SSM/I	19.35,37.0,85.5(V+H) 22.235(V)	15-60(c-scan)	F,R,C,V L,W
DMSP 1991-	SSM/T2	90.0,150.0,183±7 183±3,183±1	50 (x-scan)	v,V,R
NOAA 1998-	AMSU/A	23.8,31.4,89.0,50.3 52.8,53.6,54.4,59.54 55.50,F = 57.29 F±0.217 F±0.322±0.048 F±0.322±0.022 F±0.322±0.010 F±0.322±0.045	50(x-scan)	t,v,F,R, C,V,L
NOAA 1998-	AMSU/B	90.0,150.0,183±7 183±3,183±1	15 (x-scan)	v,V,I,R
TRMM 1998-	TMI	10.7,19.35,37.0, 85.5 (V+H),22.235(V)	5-30(c-scan)	R,V,T L,W
EOS 2002	AMSR	6.7,10.6,19.35,37.0, 85.5 (V+H),23.8(V)	15-60(c-scan)	T,W,S,F,C, R,L,V
Navy 2002	WINDSAT	6.9,10.7(V+H),23.8(V) 18.7,37 (Stokes)	30-60(c-scan)	T,S,L,V,R W,D
DMSP 1987-	SSM/IS	19.35,37.0,91.6 (V+H) 22.23(V)+SSM/T&T2	15-75(c-scan)	F,R,C,V L,W,t,v,
NPP 2009	ATMS	AMSU/A channels AMSU/B channels	50(x-scan) 15(x-scan)	t,F,R,L,V v,R,C,I

1 x-scan:cross-track scanner,c-scan:conical scanner
2 R:rain rate, L:cloud liquid water, I:cloud ice water, V:total precipitable water
2 T:surface temperature, W (D):surface wind speed (direction), F:sea ice concentration
2 S:soil moisture, C:snow cover, t:temperature sounding, v:water vapor sounding

Microwave Radiometry System



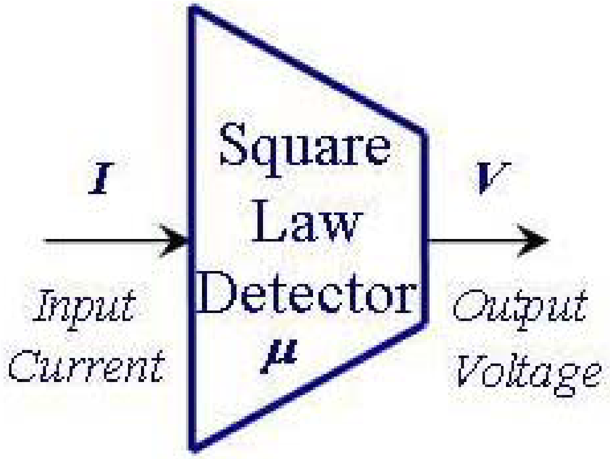
- Emission from the reflector
- Contamination on calibration targets
- Non-linearity factor
- Spill-over effects (e.g. side lobe, cross-pol)

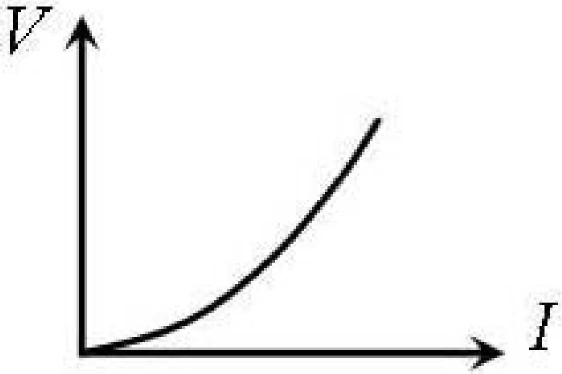
What are calibration and validation?

- **Calibration is a process of quantitatively defining the system or instrument response to known, controlled signal inputs**

- **Validation is a process of assessing the quality of the data products derived from the system outputs by independent means**

Calibration
Including Non-Linearity Effect



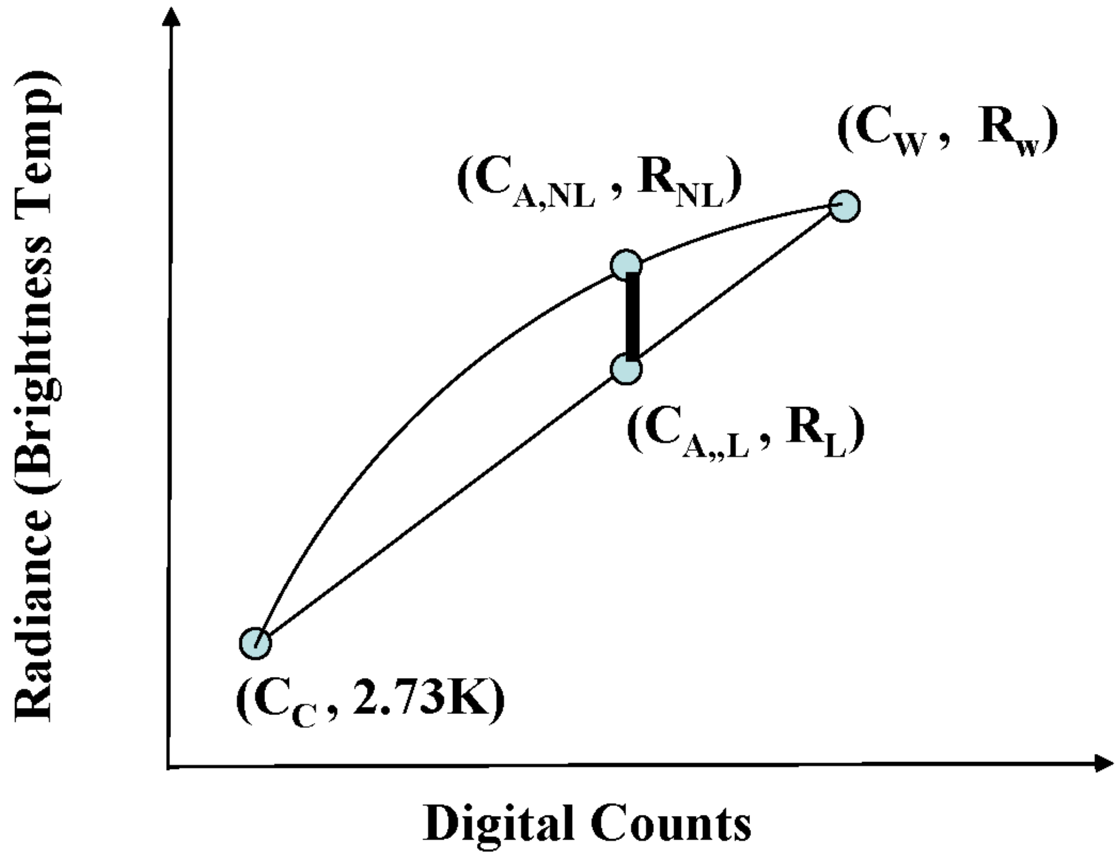


$$V = a_1 I + a_2 I^2 + a_3 I^3 + a_4 I^4$$

$$I^2 = \mathrm{KBG}\left[R(T_A) + R(T) \right]$$

$$V = b_0 + b_1 R(T_A)\left[1 + \mu R(T_A) \right]$$

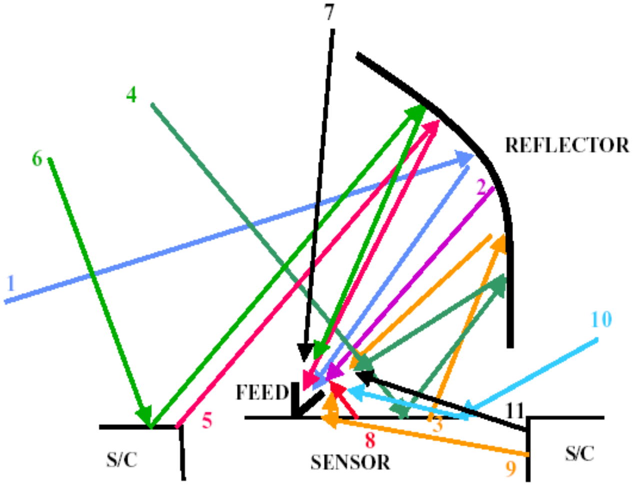
Microwave Radiometry Calibration



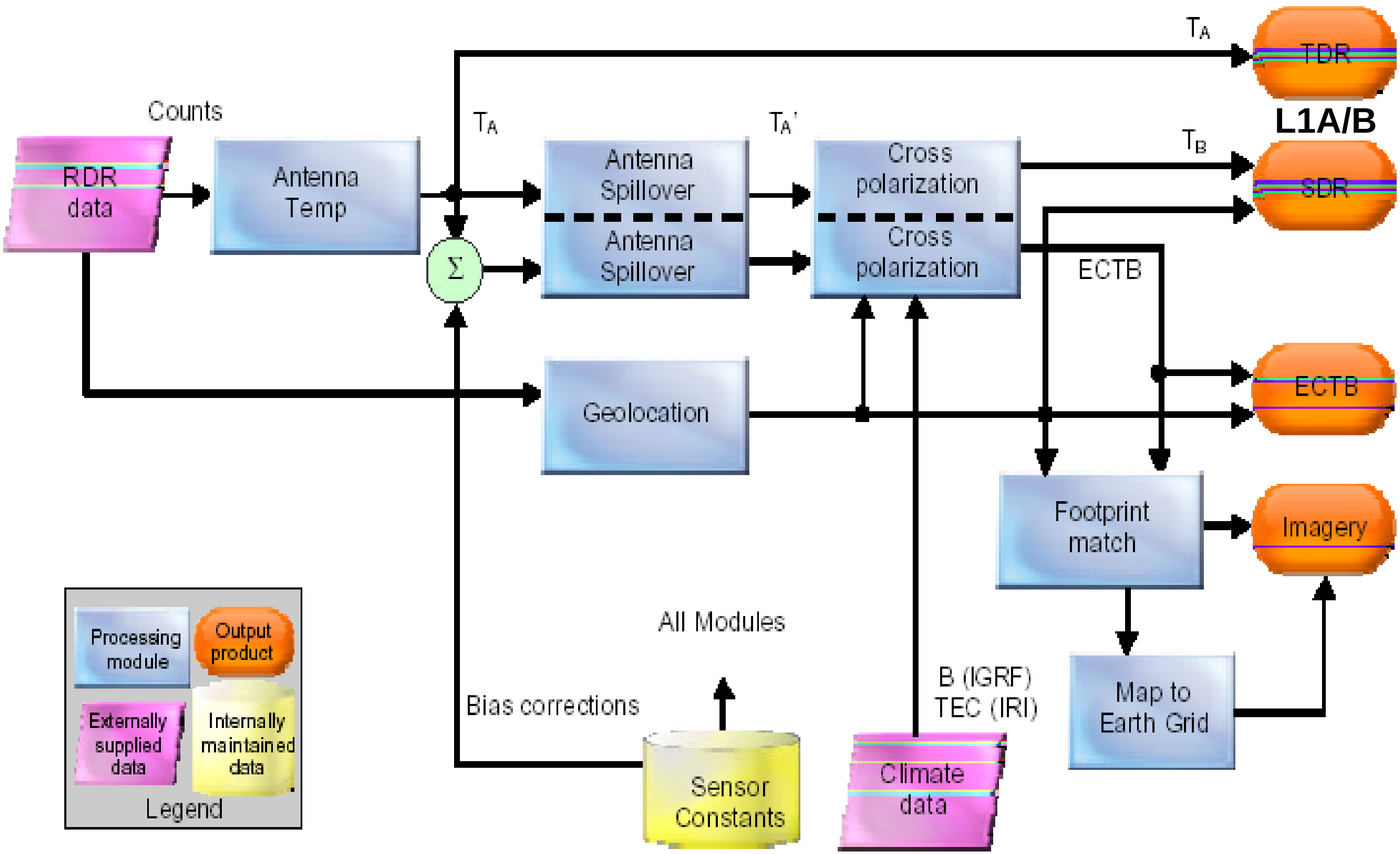
$$R_A = R_C + S(C_A - C_C) + \mu S^2 (C_A - C_C)(C_A - C_W)$$

Microwave Instrument Calibration Components

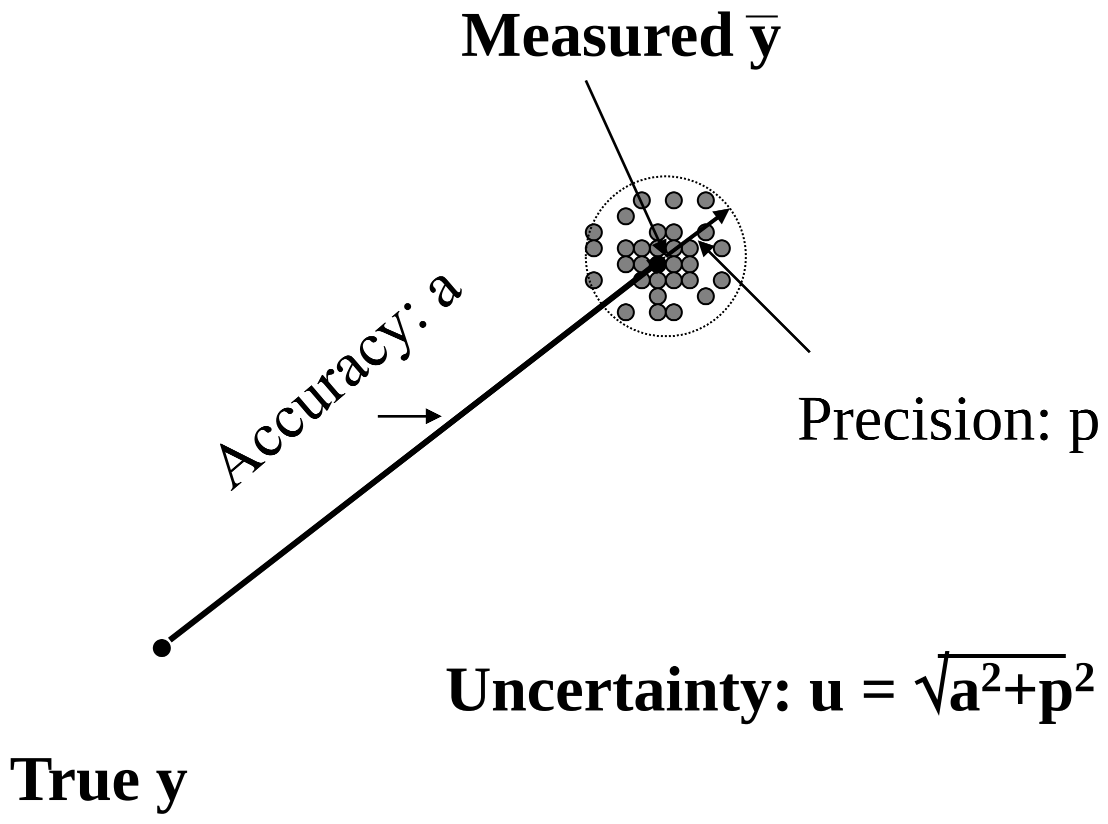
- Energy sources entering feed for a reflector configuration
- Earth scene component
- Reflector emission
- Sensor emission viewed through reflector
- Sensor reflection viewed through reflector
- Spacecraft emission viewed through reflector
- Spacecraft reflection viewed through reflector
- Spillover directly from space
- Spillover emission from sensor
- Spillover reflected off sensor from spacecraft
- Spillover reflected off sensor from space
- Spillover emission from spacecraft



Microwave Measurement Data Records

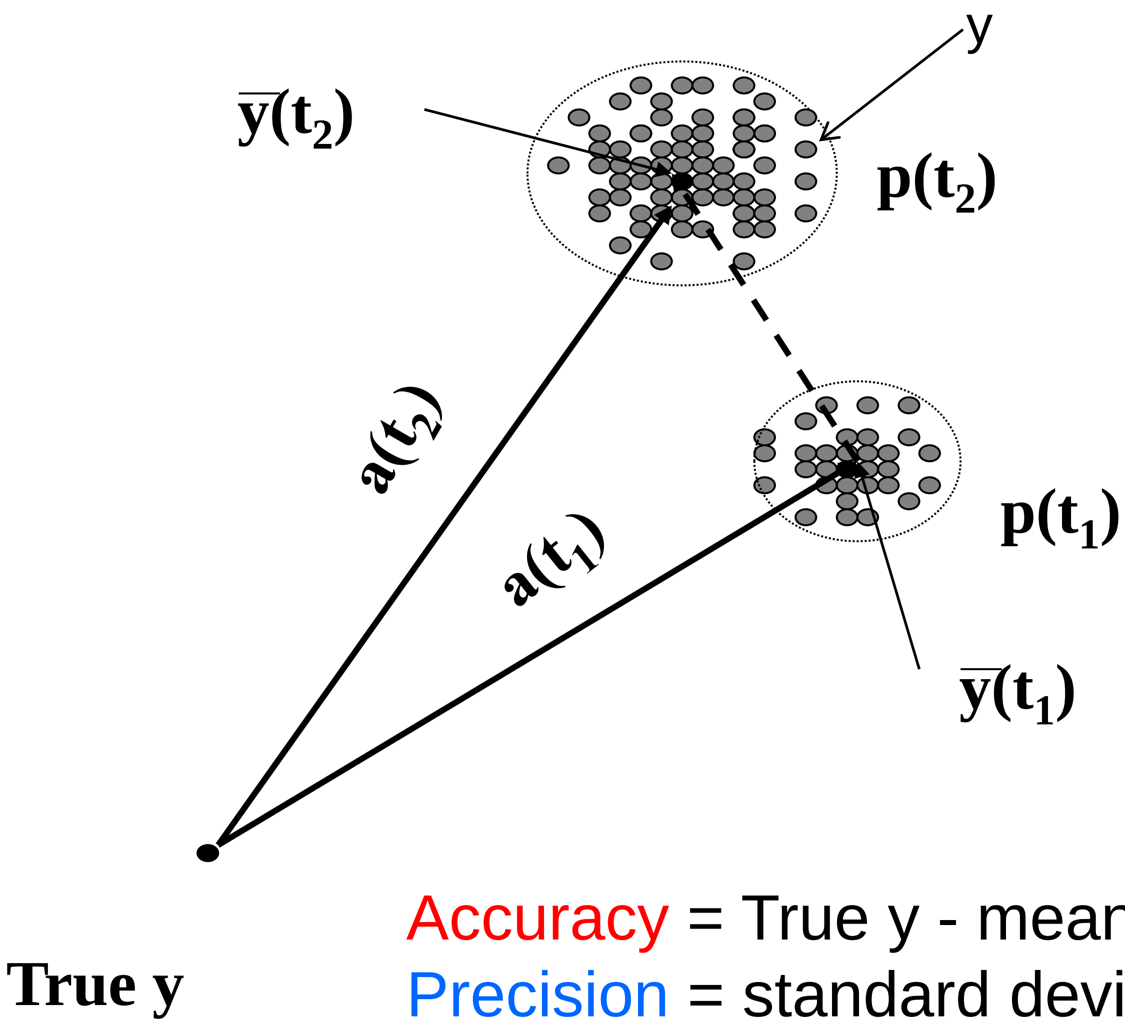


Traits: Accuracy, Precision and Uncertainty (After Stephens, 2003)



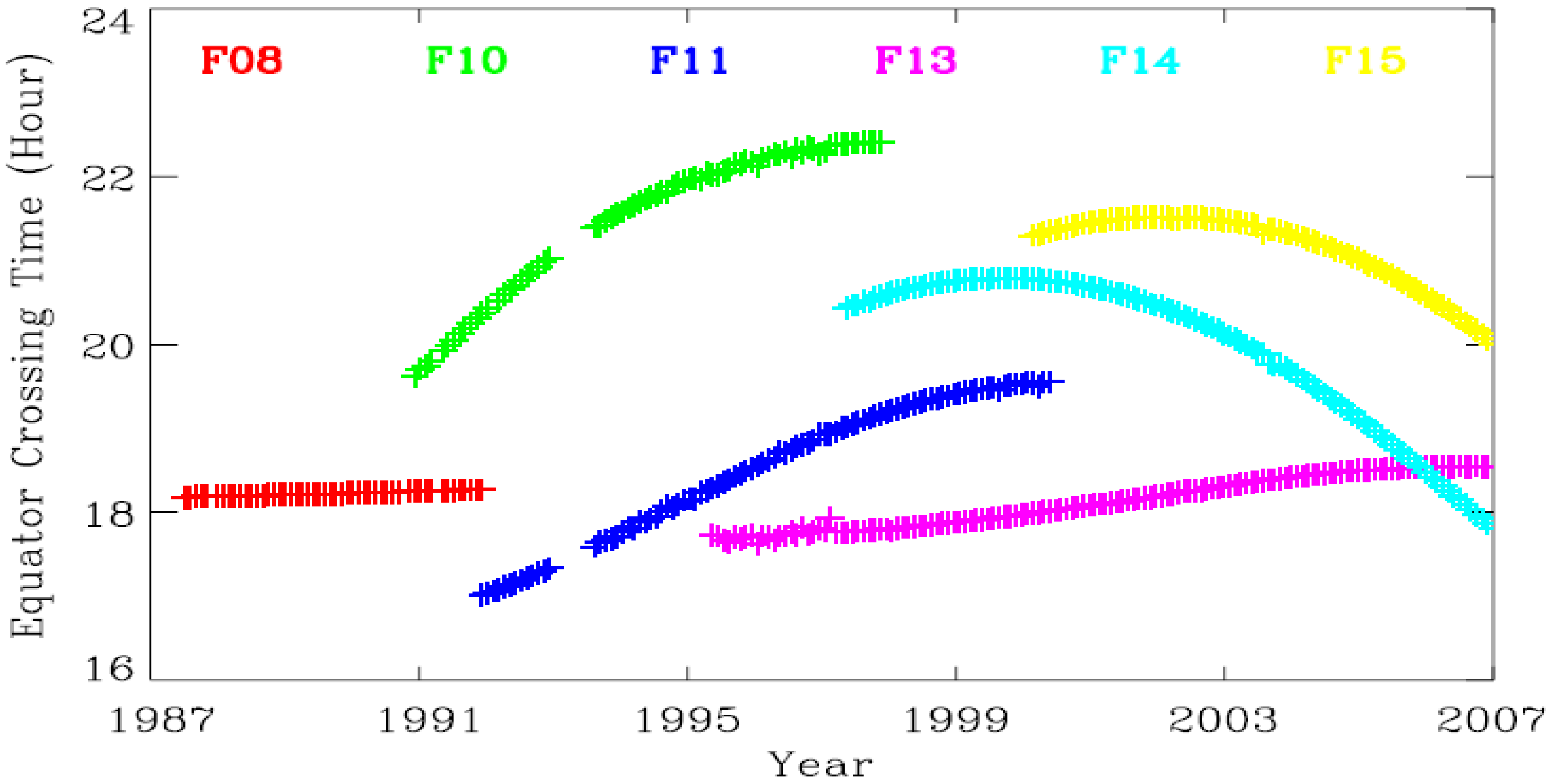
Uncertainty: $u = \sqrt{a^2+p^2}$

Accuracy, Precision, Stability
(after Stephens)



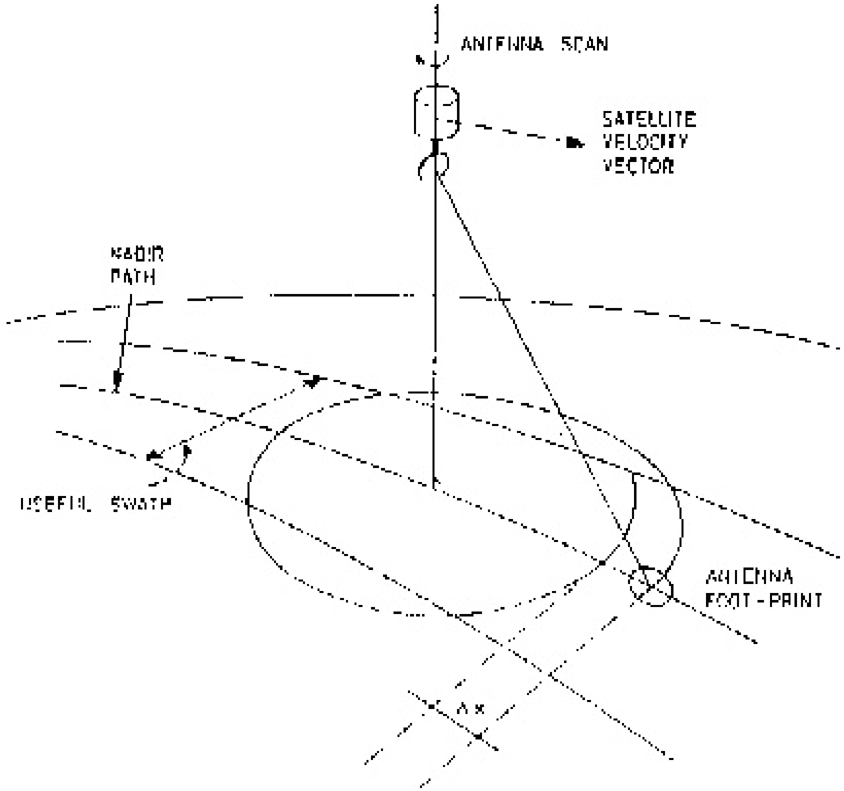
Accuracy = True y - mean y
Precision = standard deviation of y
Stability = change of accuracy with time

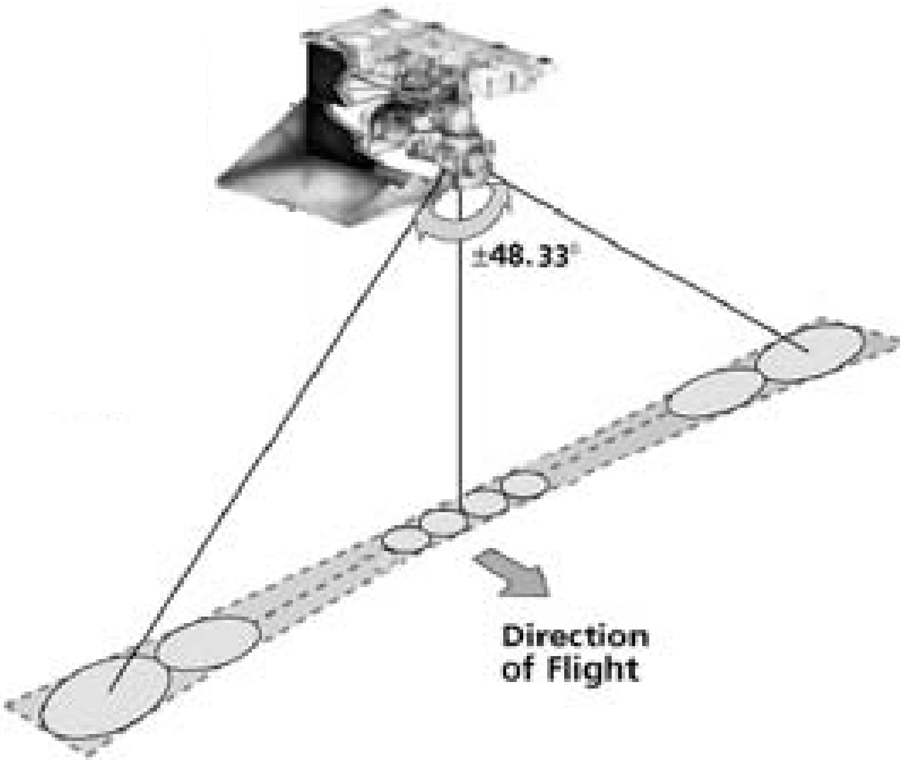
DMSP SSM/I Orbital Draft



F13 provided a stable and longest time series for inter-sensor calibration!

Conical vs Cross Track Sounding

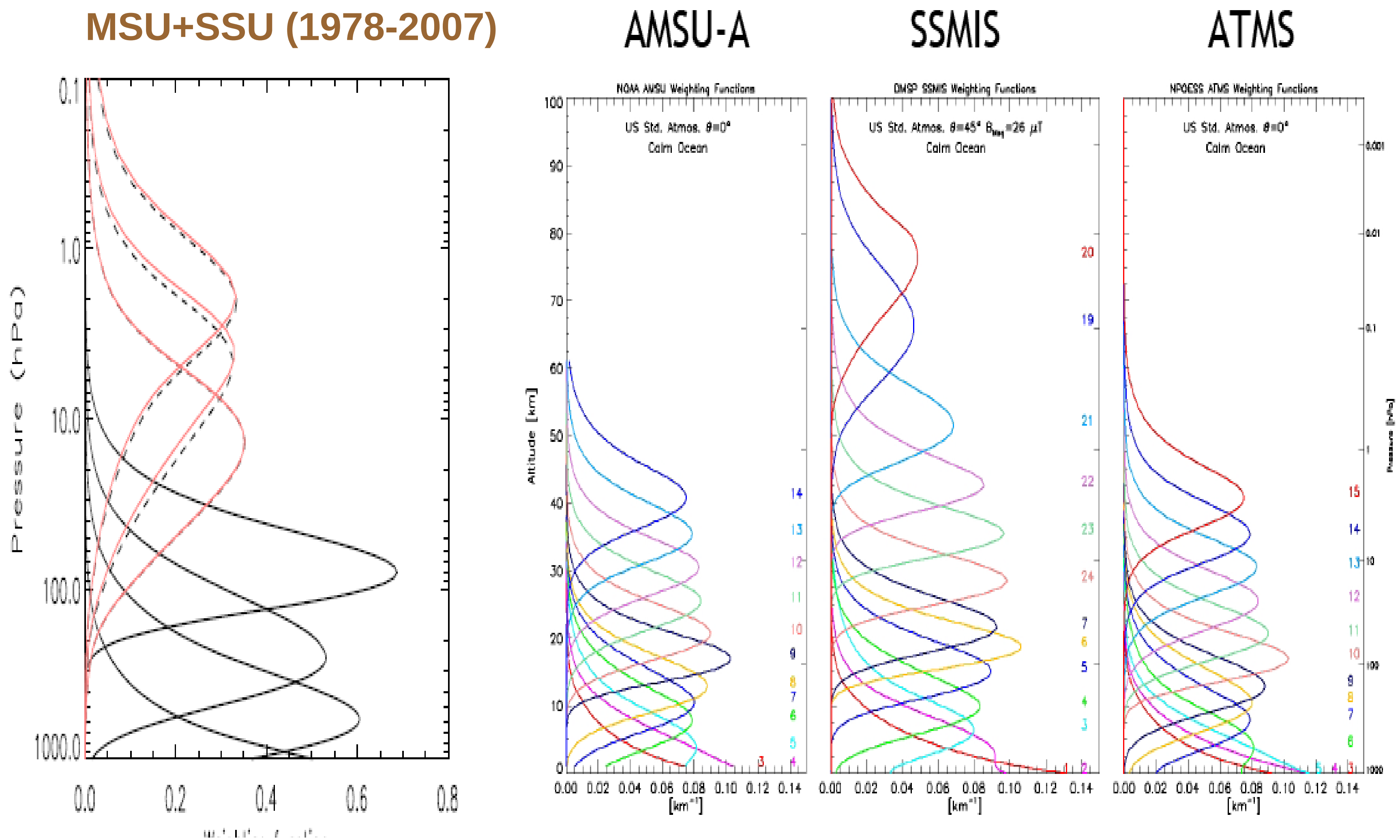




- Narrow scan swath with orbit gap
- FOV size is the same everywhere but varies with frequencies
- Same pol for all scan positions

- Large scan swath width (no orbit gap)
- Same resolution for all frequencies
- Mixing pol as scan from nadir to limb
- Res varies with scan angle

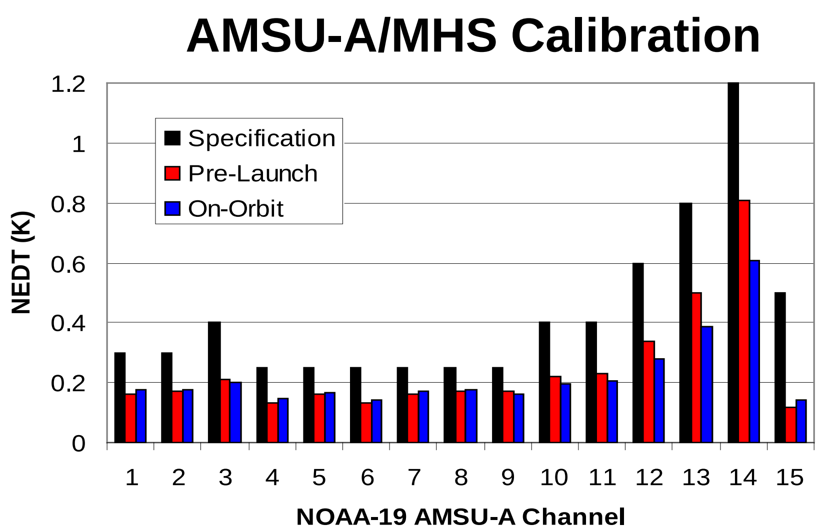
Microwave Temperature Sounding Vertical Resolution

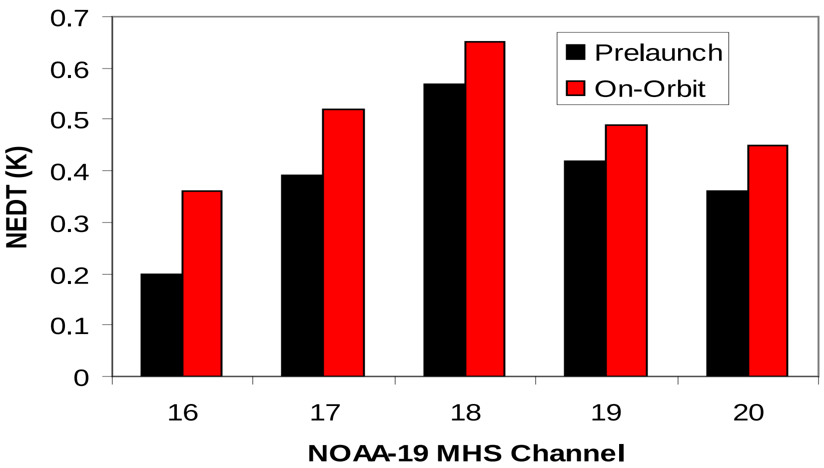


Weighting Function

MSU/AMSU/MHS Calibration Precision & Accuracy & Stability

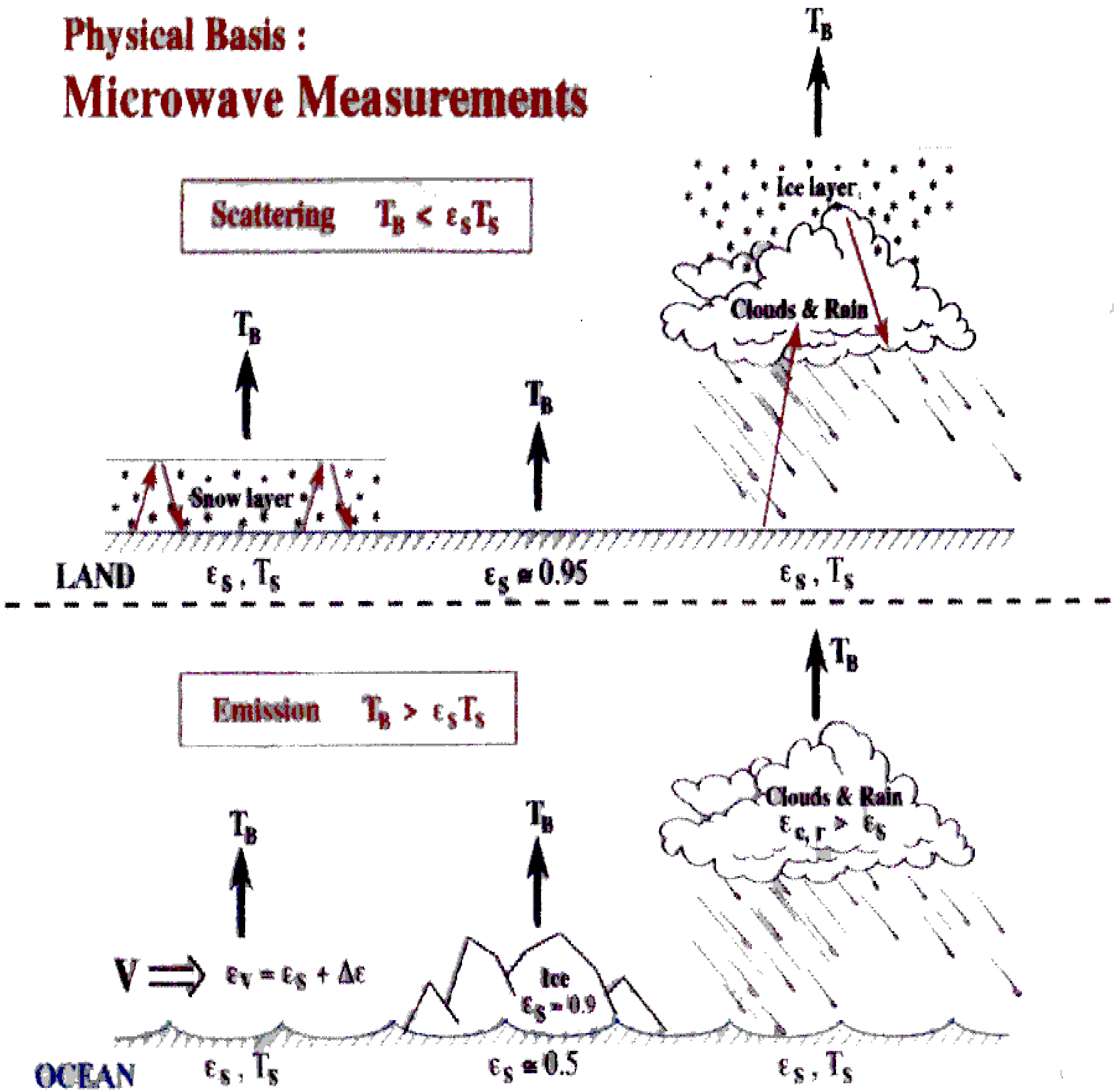
- Requirements for current system (AMSU/MHS)
  - Accuracy: 1.0 K
  - Precision (NEDT): 0.25 – 1.2K
  - Stability: None
- Requirements for future system
  - Accuracy: 0.5 K
  - Precision (NEDT): <0.1K
  - Stability: 0.04K





Physical Basis :

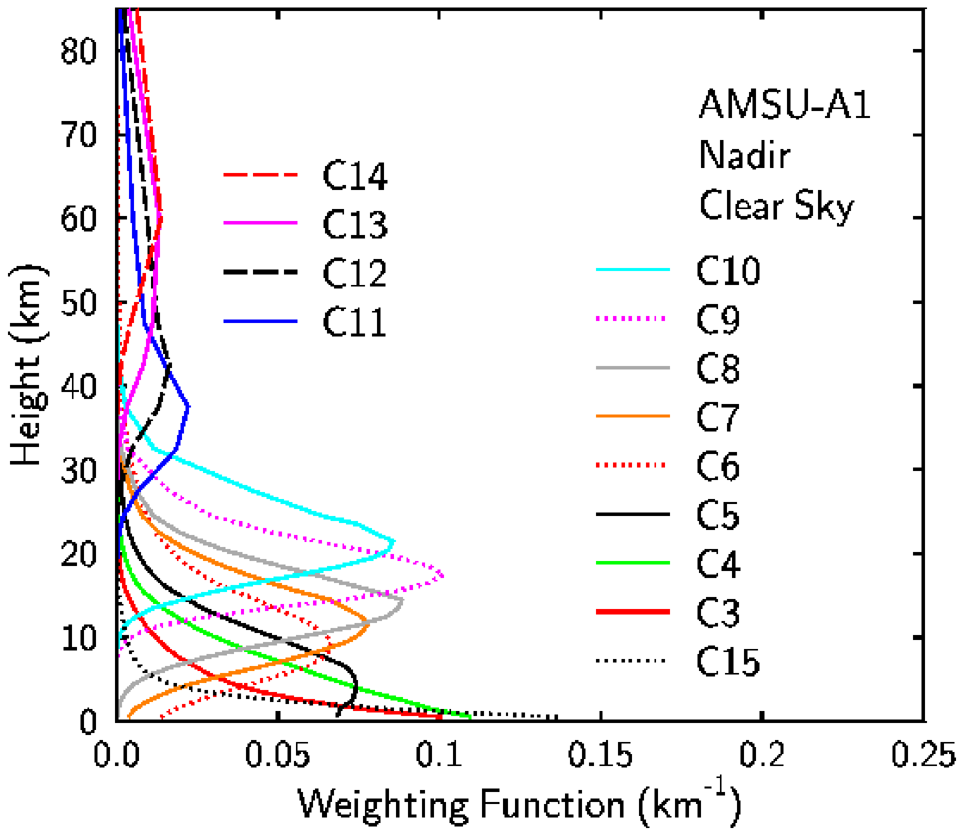
Microwave Measurements



Physical Basis and Phenomenology

- In microwave region, surface emissivity over oceans is typically low and therefore emits less thermal radiation
- Clouds and raindrops in atmosphere absorb the emitted radiation from surface and re-emit higher radiation
- A retrieval of a lower amount of cloud liquid water is significantly affected by sea surface conditions
- The absorption coefficient of cloud liquid water is dependent on cloud temperature
- Accuracy in remote sensing of cloud retrieval over land is poor due to large variability of emissivity

Microwave Sounding Principle Under All Weather Conditions



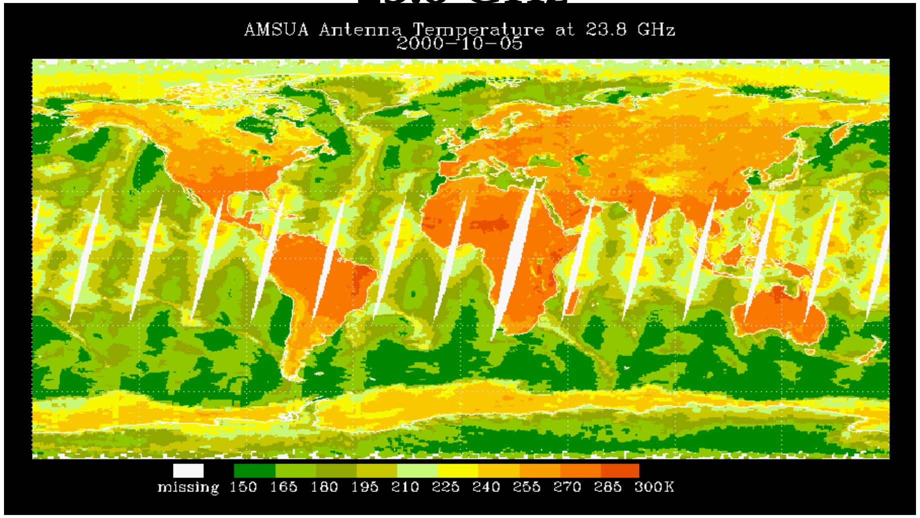
- Satellite microwave radiation at each sounding channel primarily arises from a particular altitude, indicated by its weighting function

- The vertical resolution of sounding is dependent on the number of independent channel measurements

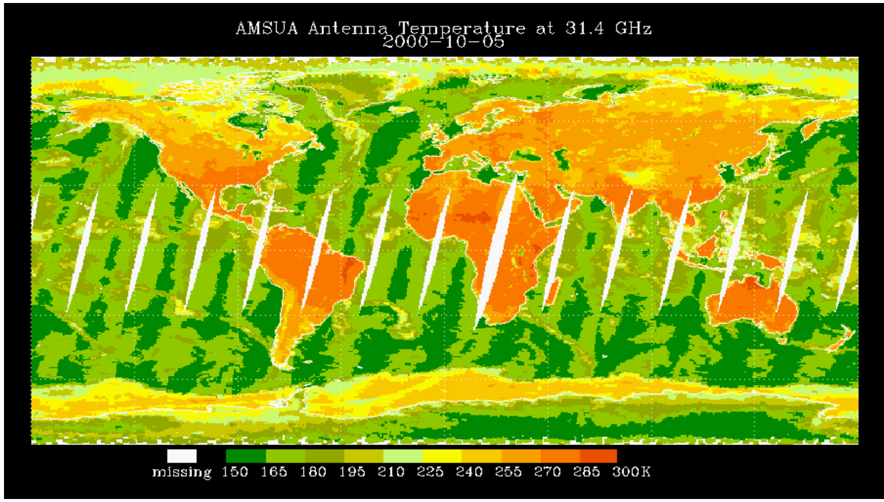
- Lower tropospheric channels are also affected by the surface radiation which is quite variable over land

Advanced Microwave Sounding Unit Window Channels

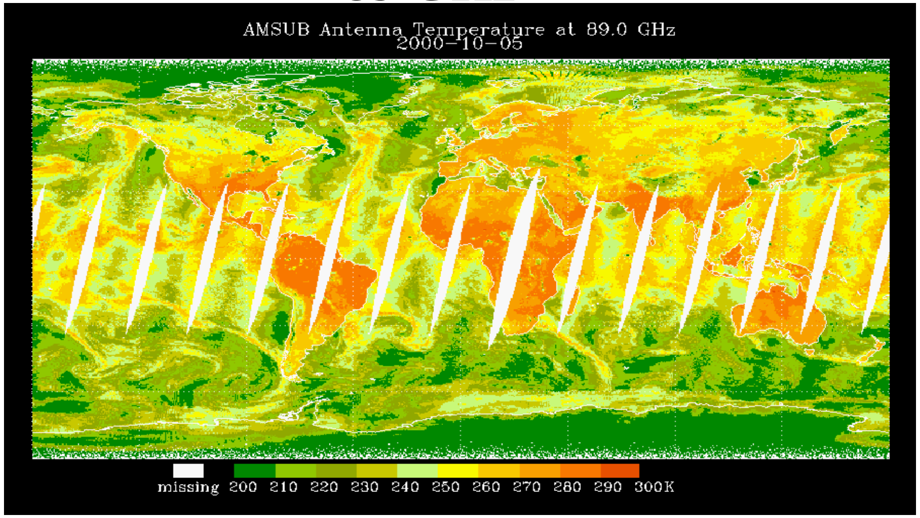
23.8 GHz



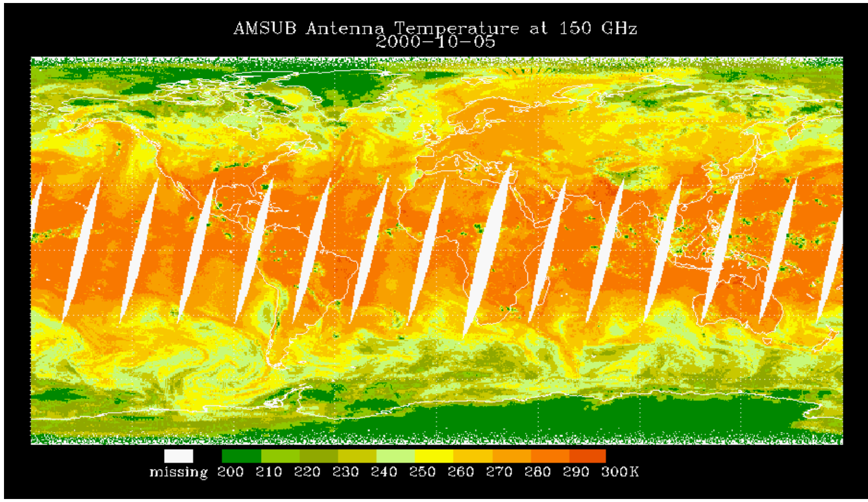
31.4 GHz



89 GHz

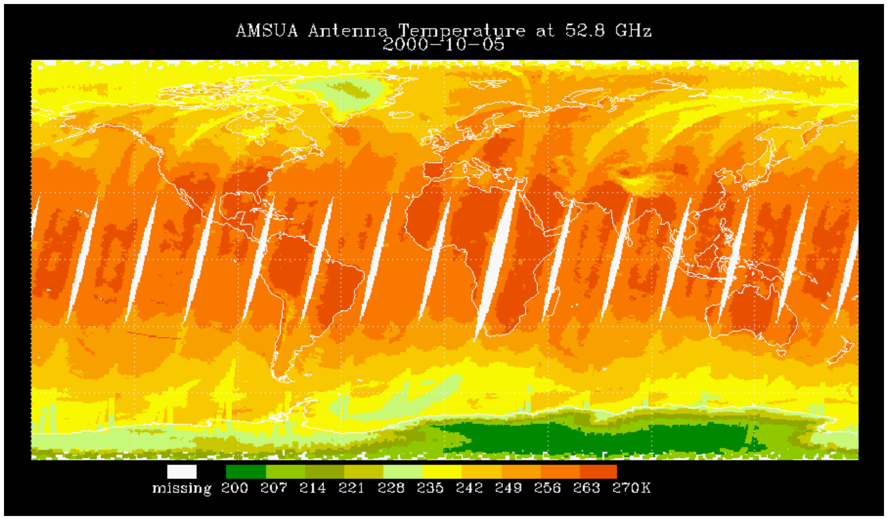


150 GHz

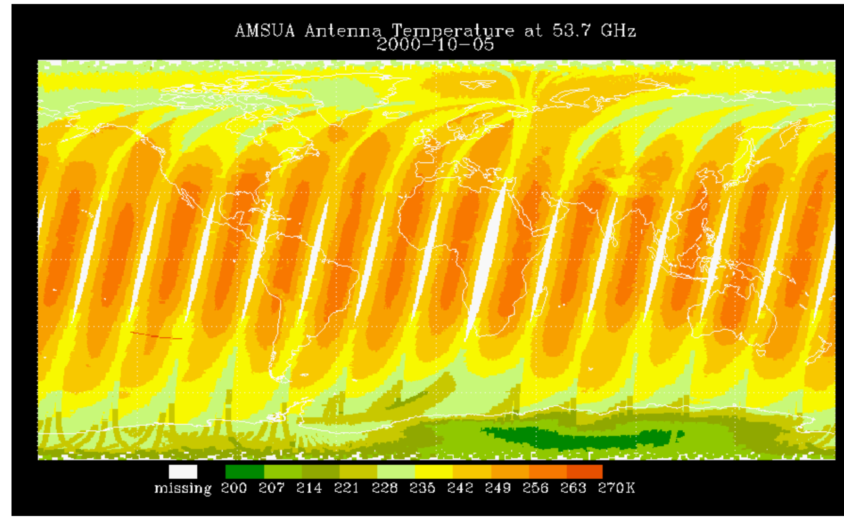


Advanced Microwave Sounding Unit
Sounding Channels

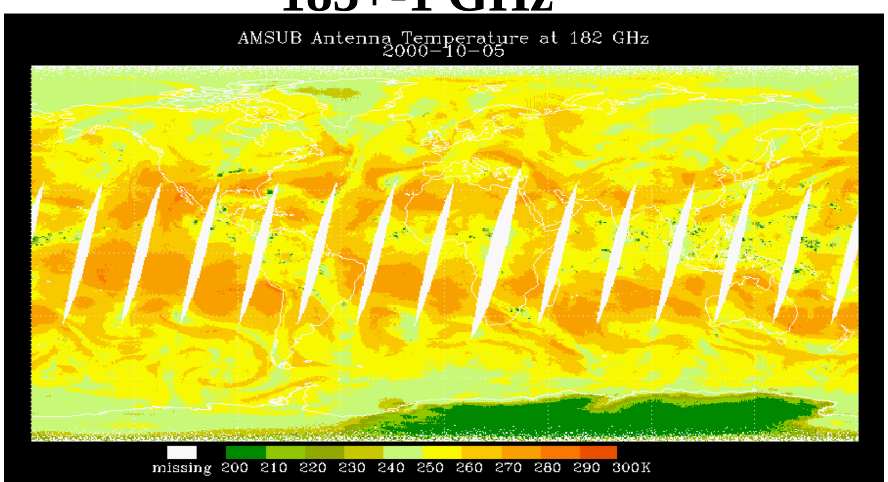
52.8 GHz



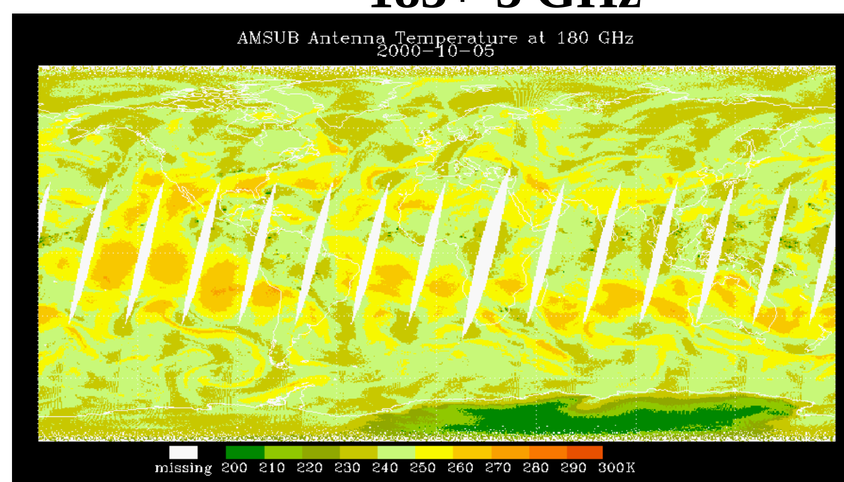
53.7 GHz



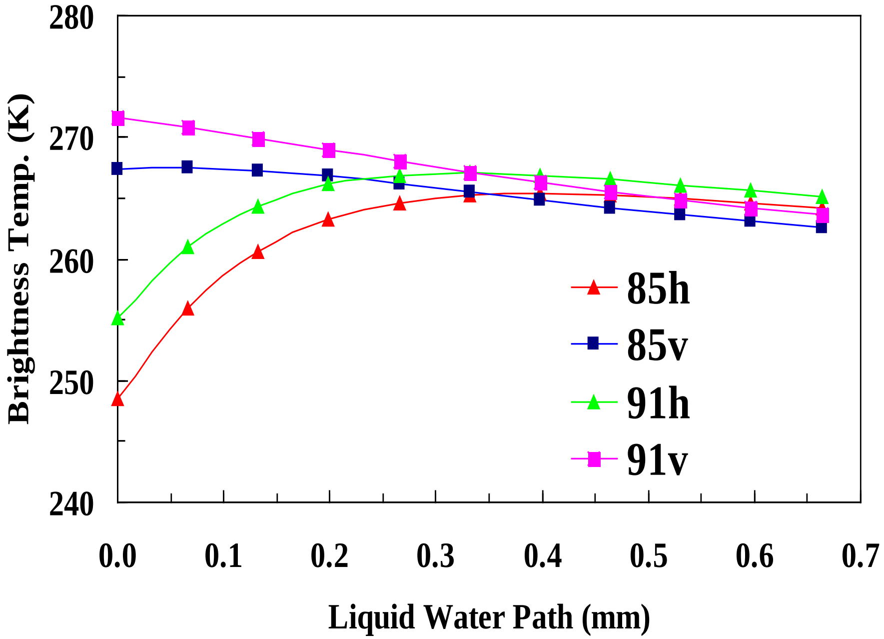
183+-1 GHz

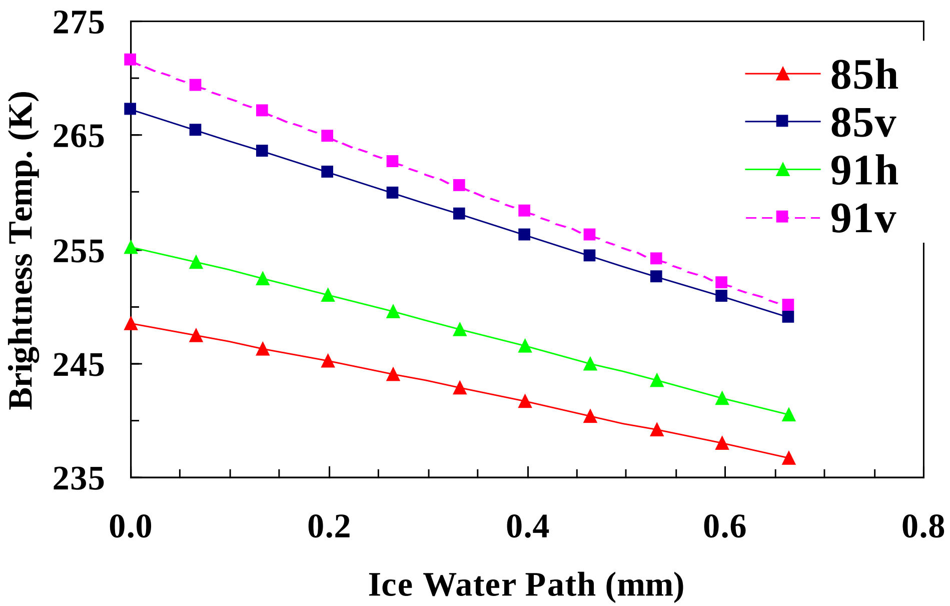


183+-3 GHz

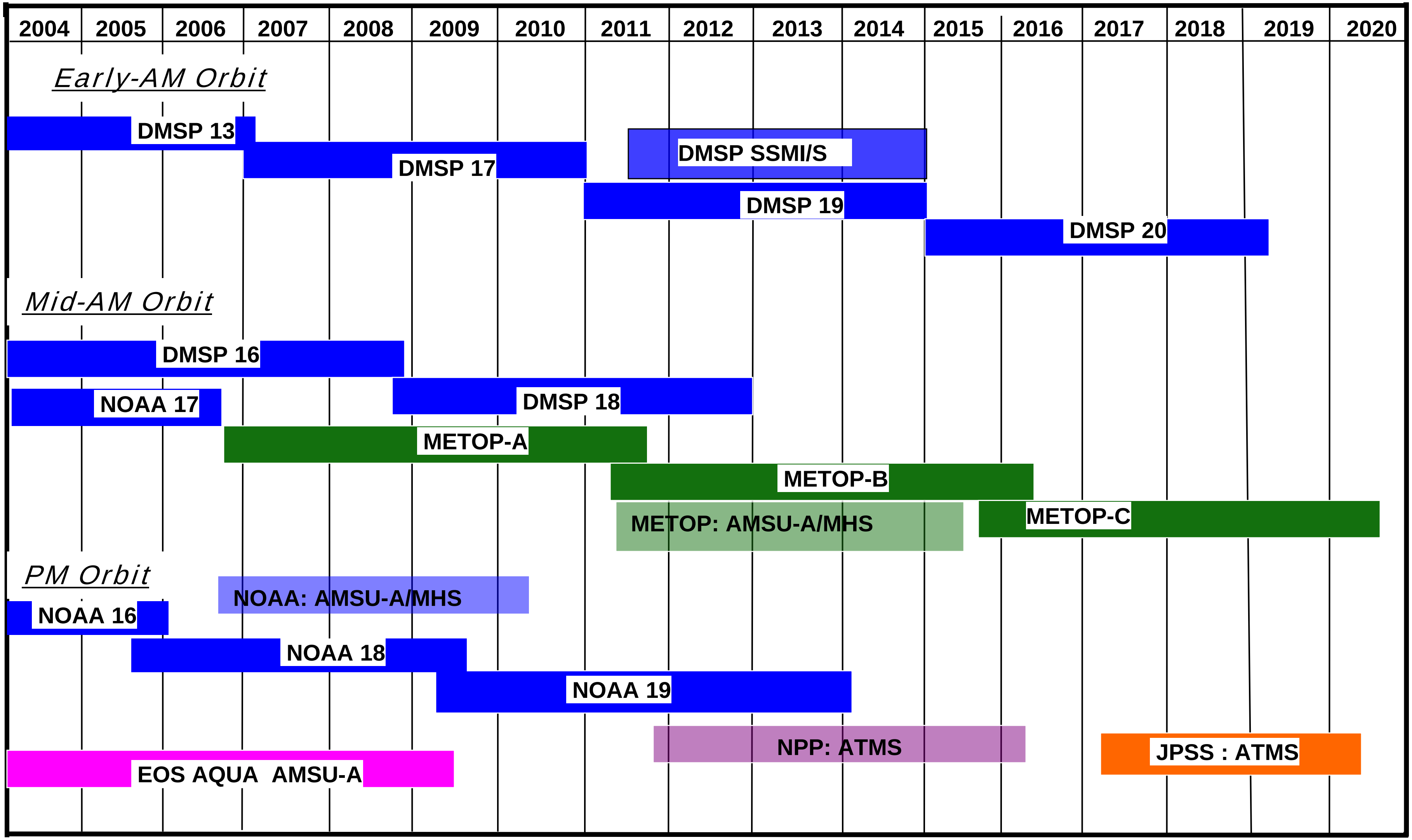


Cloud Emission and Scattering (over Oceans)



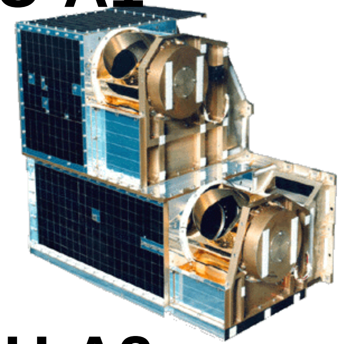


US Polar Missions with MW Sensors for Operational Uses



From AMSU/MHS to ATMS

AMSU-A1

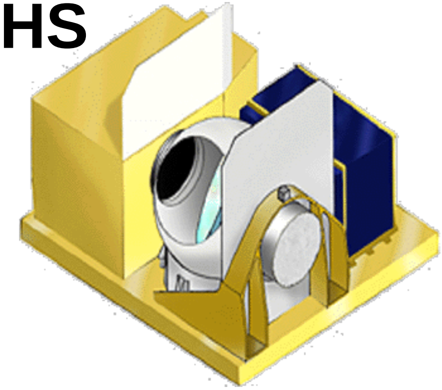


- 73x30x61 cm
- 67 W
- 54 kg
- 3-yr life

AMSU-A2

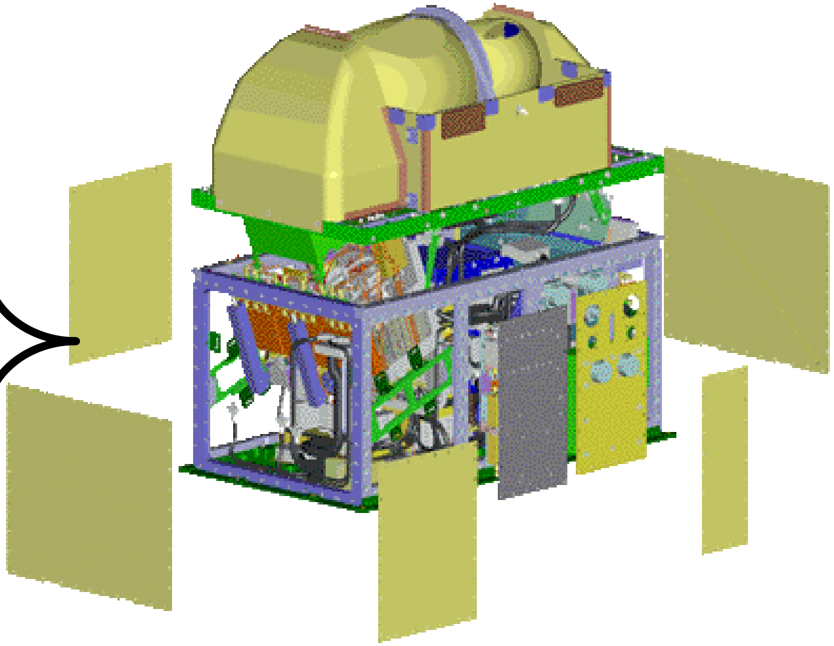
- 75x70x64 cm
- 24 W
- 50 kg
- 3-yr life

MHS



- 75x56x69 cm
- 61 W
- 50 kg
- 4-yr life

Reduce the volume by 3x



- 70x40x60 cm
- 110 W
- 85 kg
- 8 year life

From Bill Blackwell, MIT

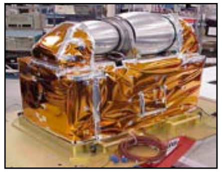
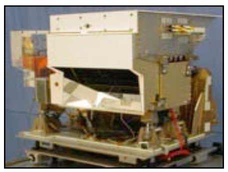
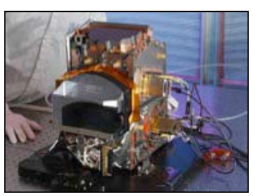
Content

- **Long-Term Monitoring System for Suomi NPP/JPSS Operational CalVal**
- **Suomi NPP SDR Product Maturity**
- **CalVal Results and New Sciences**
- **Summary and Conclusions**

Vern Suomi

Suomi NPP satellite was successfully launched on October 28, 2011!!!!

Suomi NPP Instruments (the Same as JPSS-1)

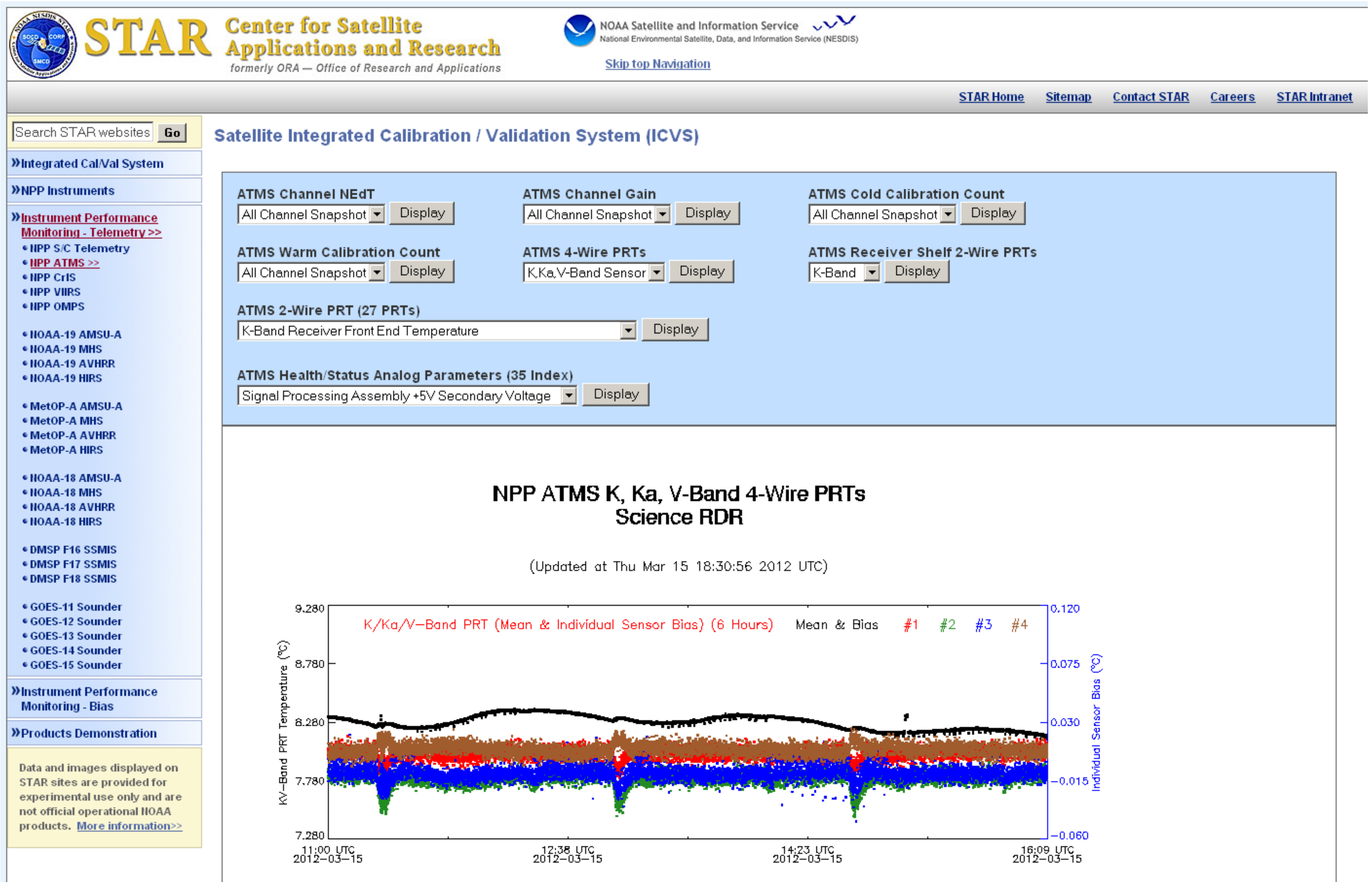
JPSS Instrument		Measurement
	**ATMS** - Advanced Technology Microwave Sounder	ATMS and CrIS together provide high vertical resolution **temperature** and **water vapor information needed to maintain and improve forecast skill** out to 5 to 7 days in advance for extreme weather events, including hurricanes and severe weather outbreaks
	**CrIS** - Cross-track Infrared Sounder	
	**VIIRS** – Visible Infrared Imaging Radiometer Suite	VIIRS provides many **critical imagery products** including snow/ice cover, clouds, fog, aerosols, fire, smoke plumes, vegetation health, phytoplankton abundance/chlorophyll
	**OMPS** - Ozone Mapping and Profiler Suite	Ozone spectrometers for **monitoring ozone** hole and recovery of stratospheric ozone and for UV index forecasts
	**CERES** - Clouds and the Earth's Radiant Energy System	Scanning radiometer which supports studies of Earth Radiation Budget

Summary of Suomi NPP TDR/SDR Algorithm Schedule

Sensor	Beta	Provisional (planned)	Validated (planned)
CrIS	M ay 7, 2012	October, 2012	2013
ATMS	February 22, 2012	July, 2012	2013
OMPS	March 12, 2012	March, 2013	2013
VIIRS	May 2, 2012	October, 2012	2013

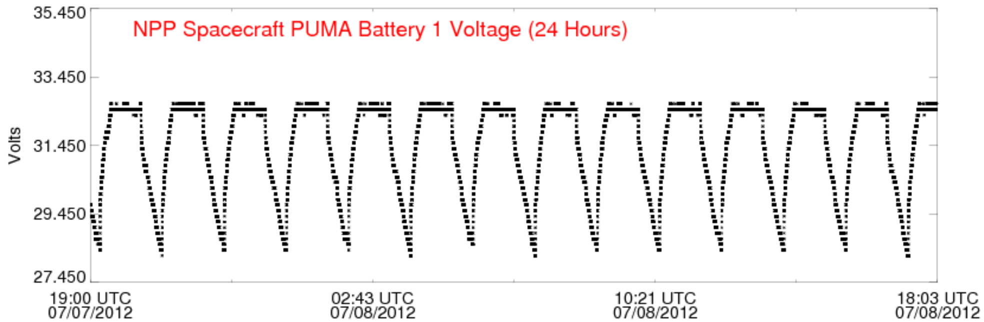
NPP SDR Product Maturity Levels
1. Beta • Early release product. • Initial calibration applied. • Minimally validated and may still contain significant errors (rapid changes can be expected. Version changes will not be identified as errors are corrected as on-orbit baseline is not established) • Available to allow users to gain familiarity with data formats and parameters • Product is not appropriate as the basis for quantitative scientific publications studies and applications
2. Provisional • Product quality may not be optimal • Incremental product improvements are still occurring as calibration parameters are adjusted with sensor on-orbit characterization (versions will be tracked) • General research community is encouraged to participate in the QA and validation of the product, but need to be aware that product validation and QA are ongoing • Users are urged to contact NPOESS NPP Cal/Val Team representatives prior to use of the data in publications
3. Validated/ Calibrated • On-orbit sensor performance characterized and calibration parameters adjusted accordingly • Ready for use by the Centrals and in scientific publications • There may be later improved versions • There will be strong versioning with documentation

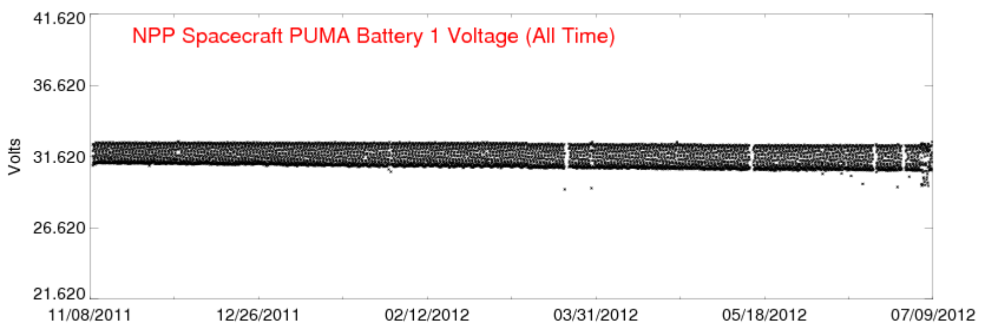
NOAA Instrument Long-Term Monitoring System

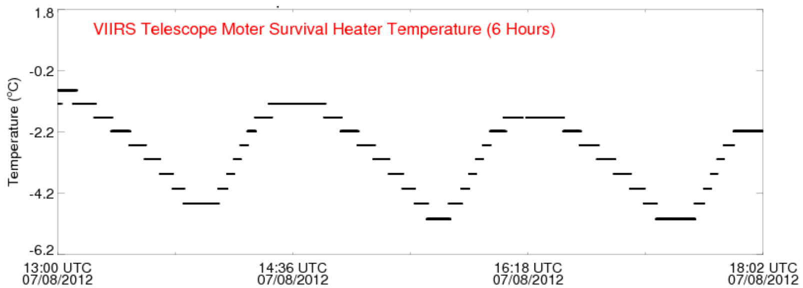


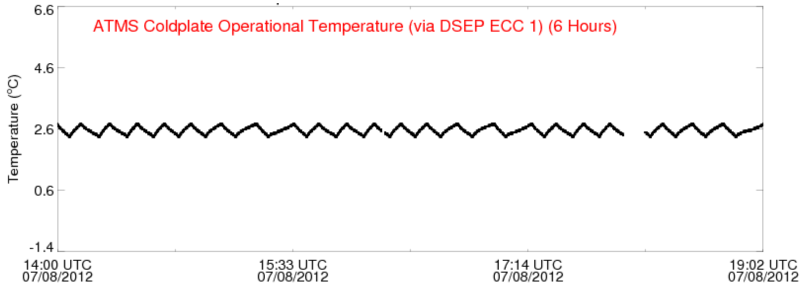
NPP Spacecraft Monitoring Example

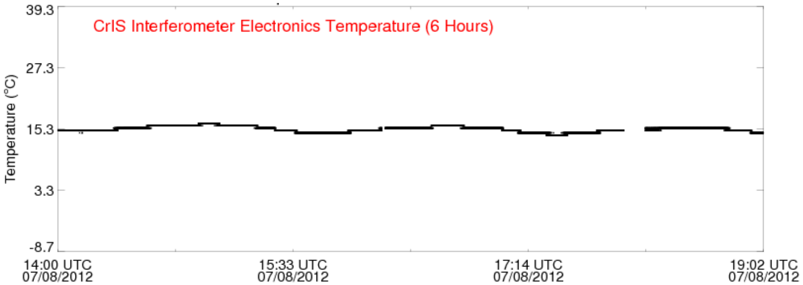
- Instrument temperatures obtained from S/C telemetry (right)
- S/C PUMA Battery 1 Voltage real time variation during the last 24 hours and LTM trending since launch (below)

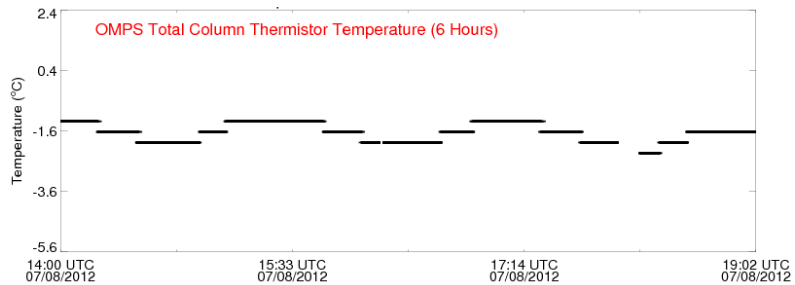




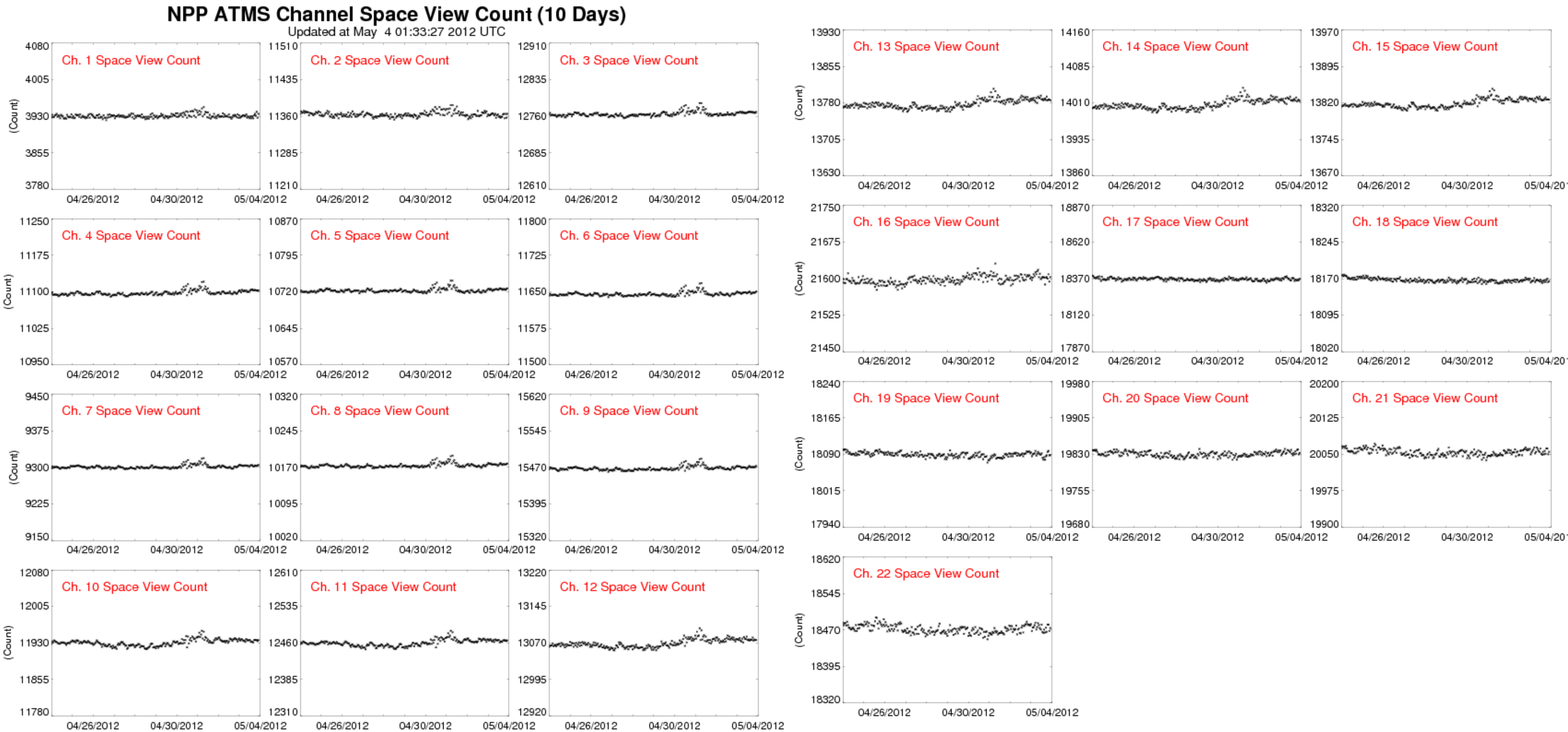








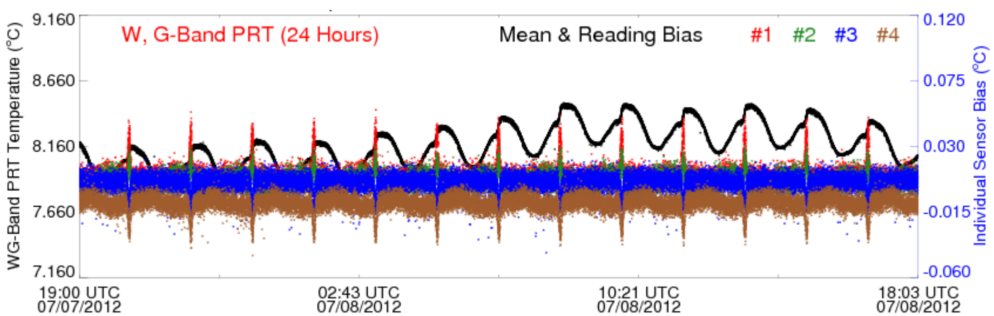
ATMS Space View Count

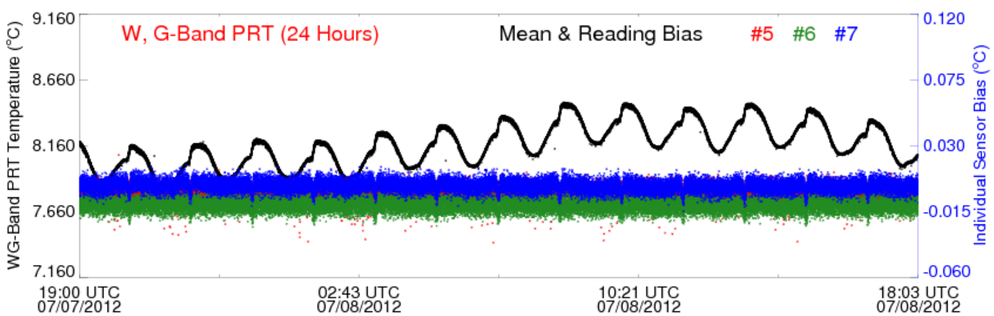


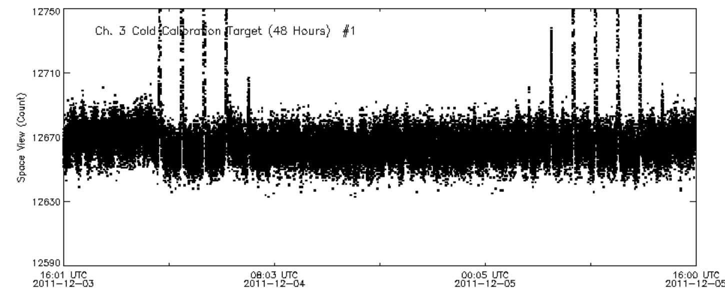
- NPP ATMS space view calibration counts are stable
- NPP ATMS warm load calibration counts and gain are also stable (not shown)

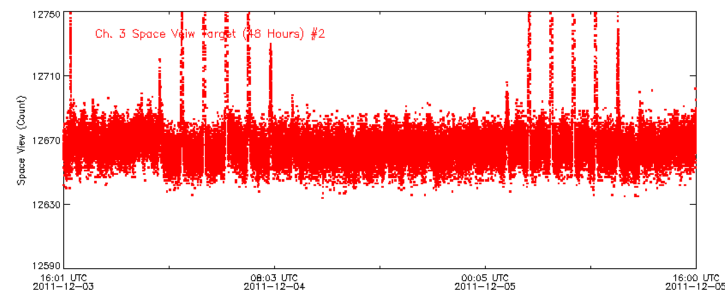
ATMS Calibration Target Monitoring

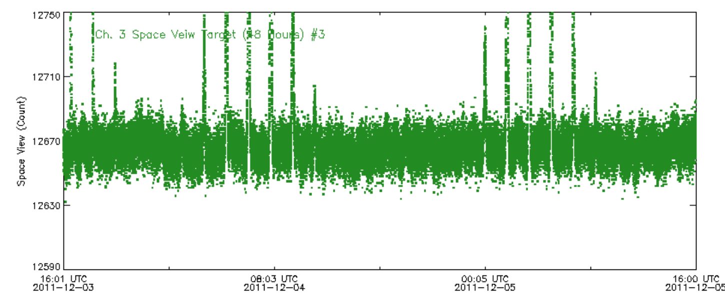
- Lunar intrusion effects on ATMS space view readings and channels are different (right)
- ATMS 4-Wire PRTs anomalies are observed in individual readings of all bands (below)

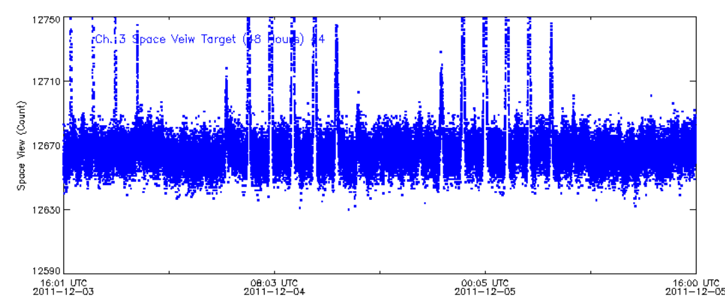






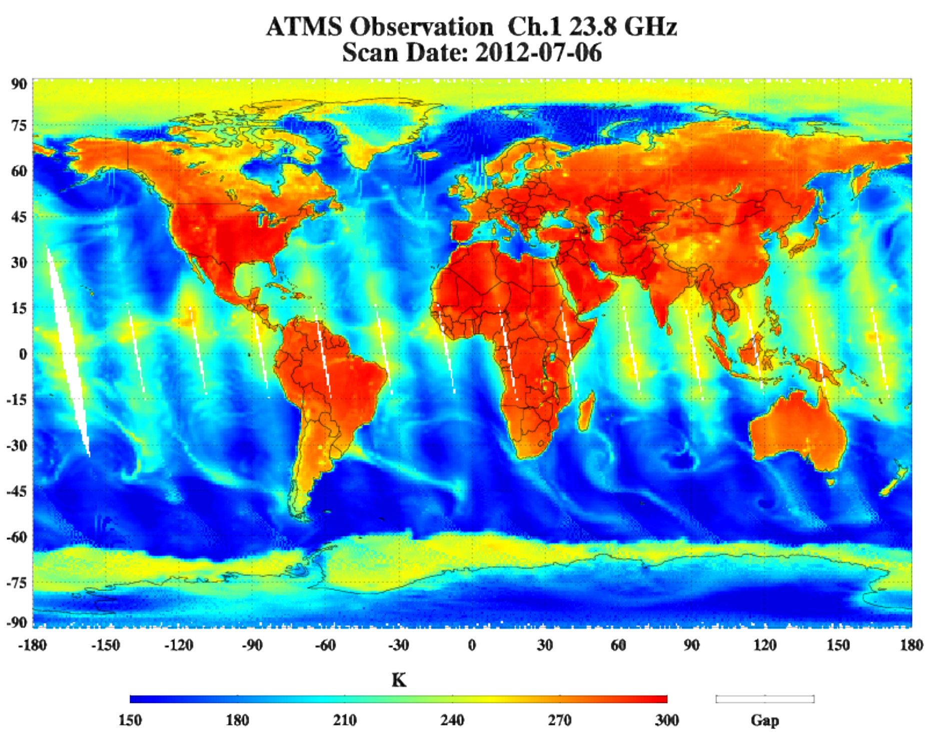


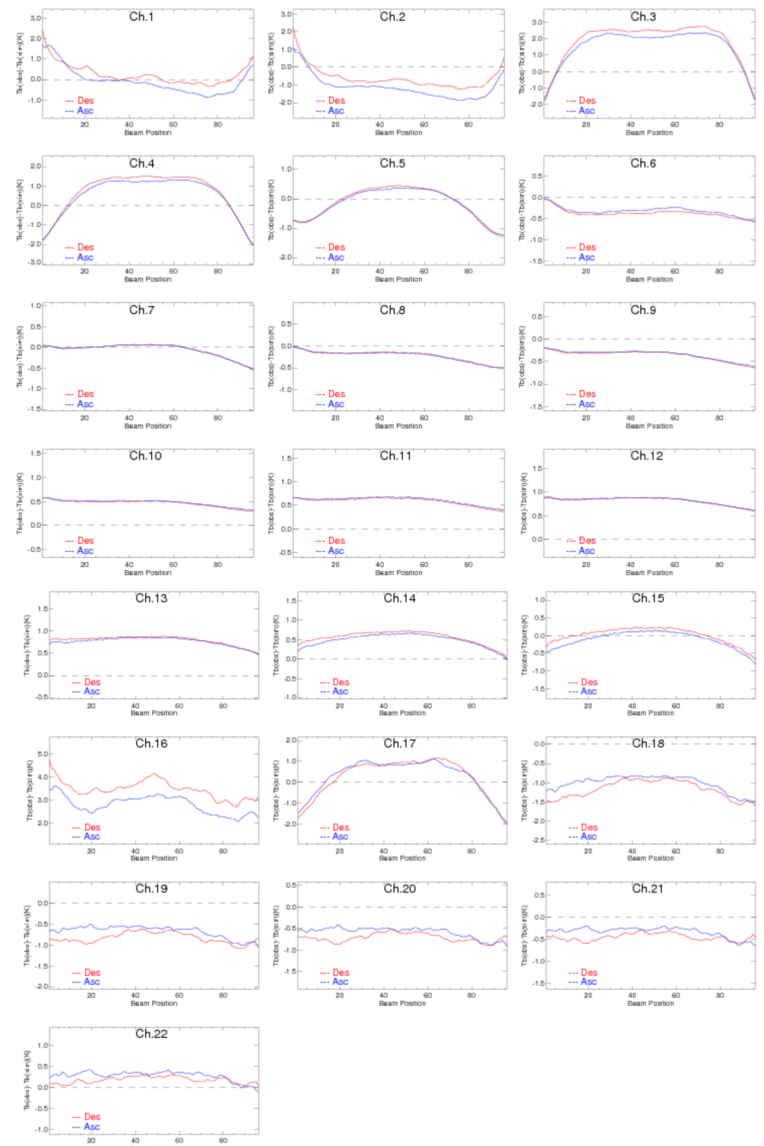




ATMS Bias Monitoring

- ATMS angular dependent bias character obtained from RTM (right)
- ATMS daily global images (below) and data quality distribution





ATMS Data Types

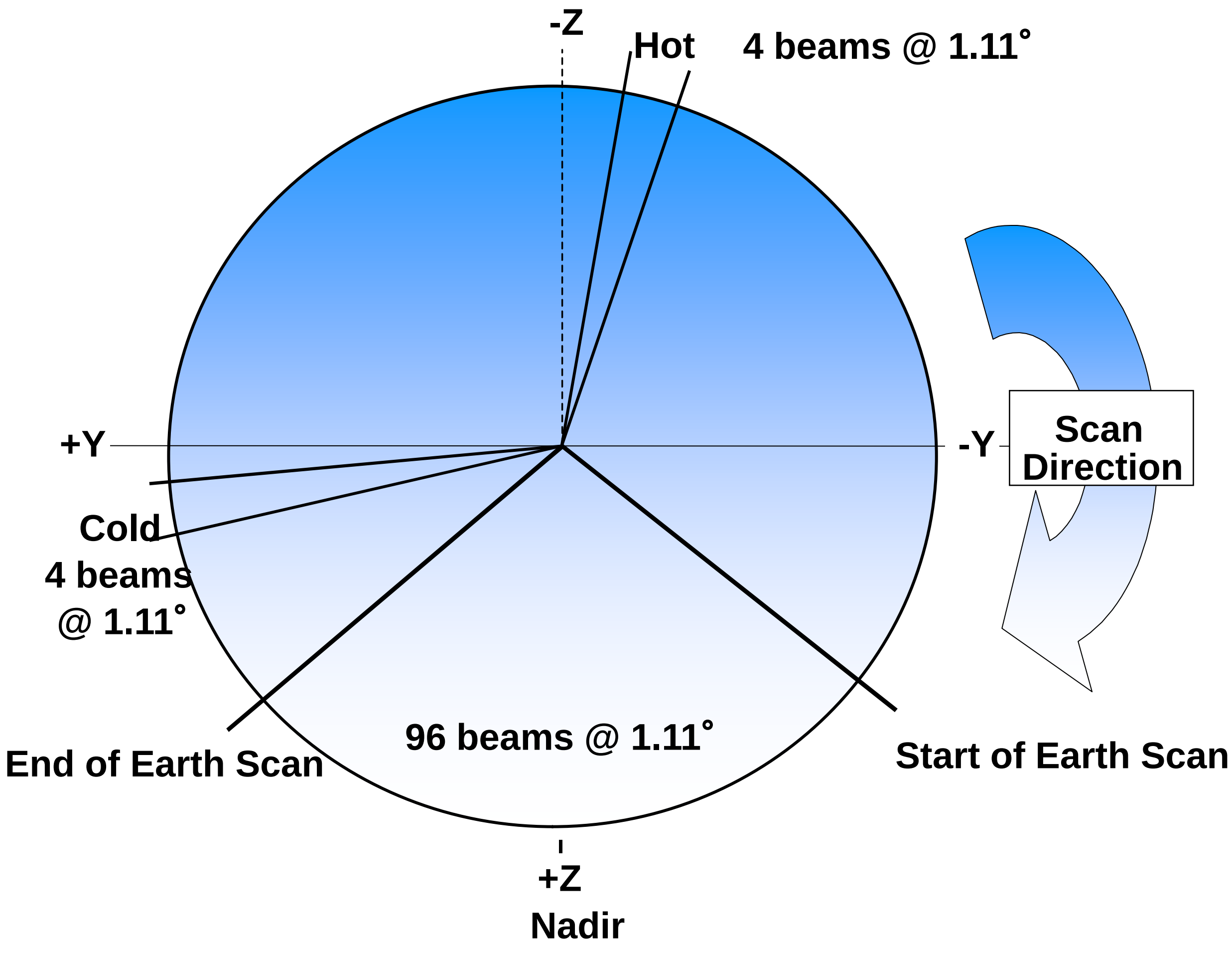
Raw Data Record (RDR): digital counts with full calibration and geo-location information ***for all 22 channels at the original field of view (FOV)***

Antenna Data Record (TDR): ***brightness temperatures at all 22 channels at the original field of view (FOV) derived from two-point calibration with non-linearity correction and geolocation***

Sensor Data Record (SDR): ***brightness temperatures with all 22 channels at their original field of view resolution with corrections of antenna gain and side-slope effects to TDR data***

Remap **Sensor Data Record (RSDR):** ***SDR data at each channel other than ch 1 and 2 are resampled to the CrIS field of regard (3x3 field of views) which is equivalent to about AMSU-A antenna beam width (3.3 degree)***

ATMS Scanning Characteristics



Spectral Differences

ATMS has 22 channels and AMSU/MHS have 20, with polarization differences between some channels

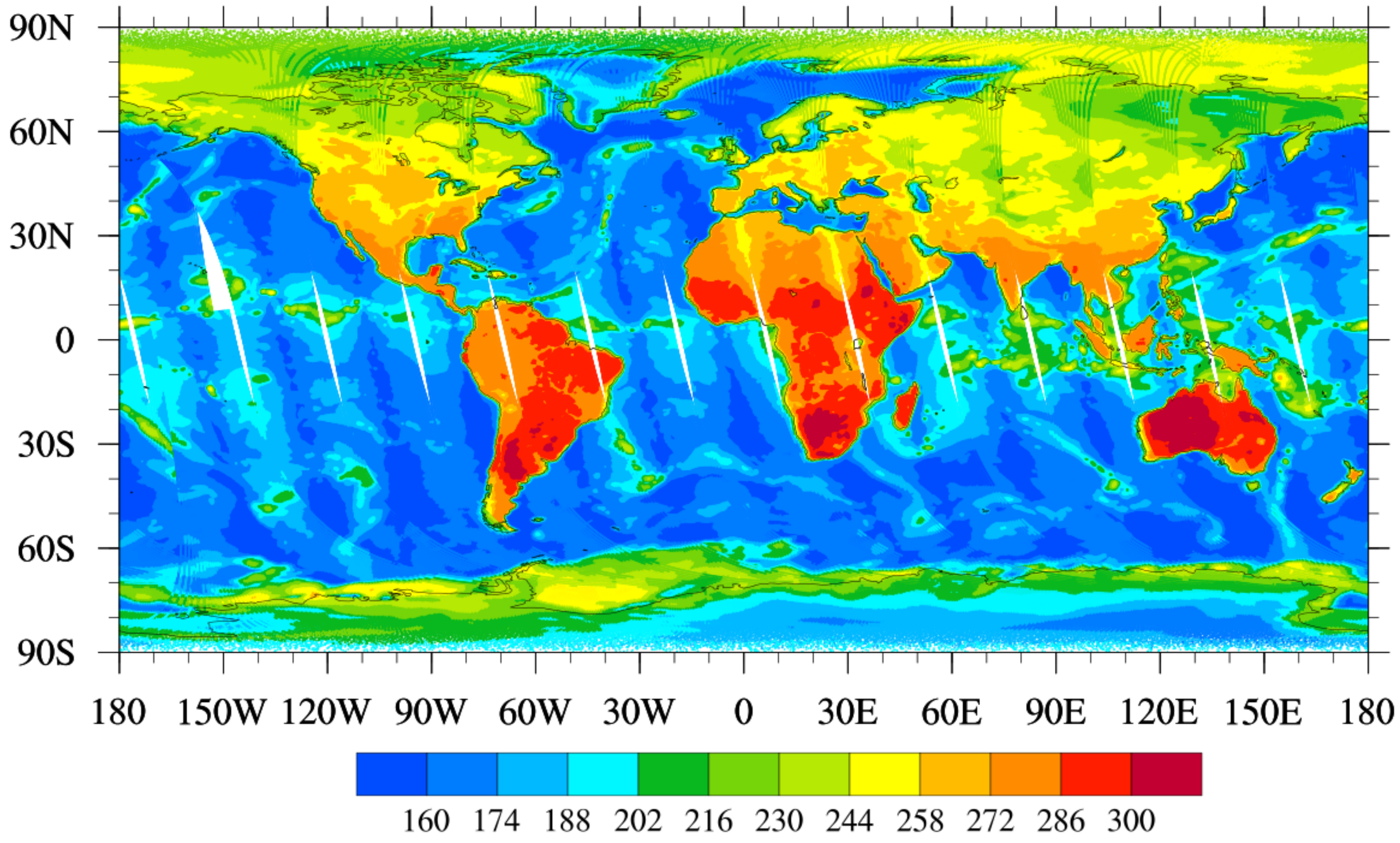
– QV = Quasi-vertical *polarization vector is parallel to the scan plane at nadir*

– QH = Quasi-horizontal *polarization vector is perpendicular to the scan plane at nadir*

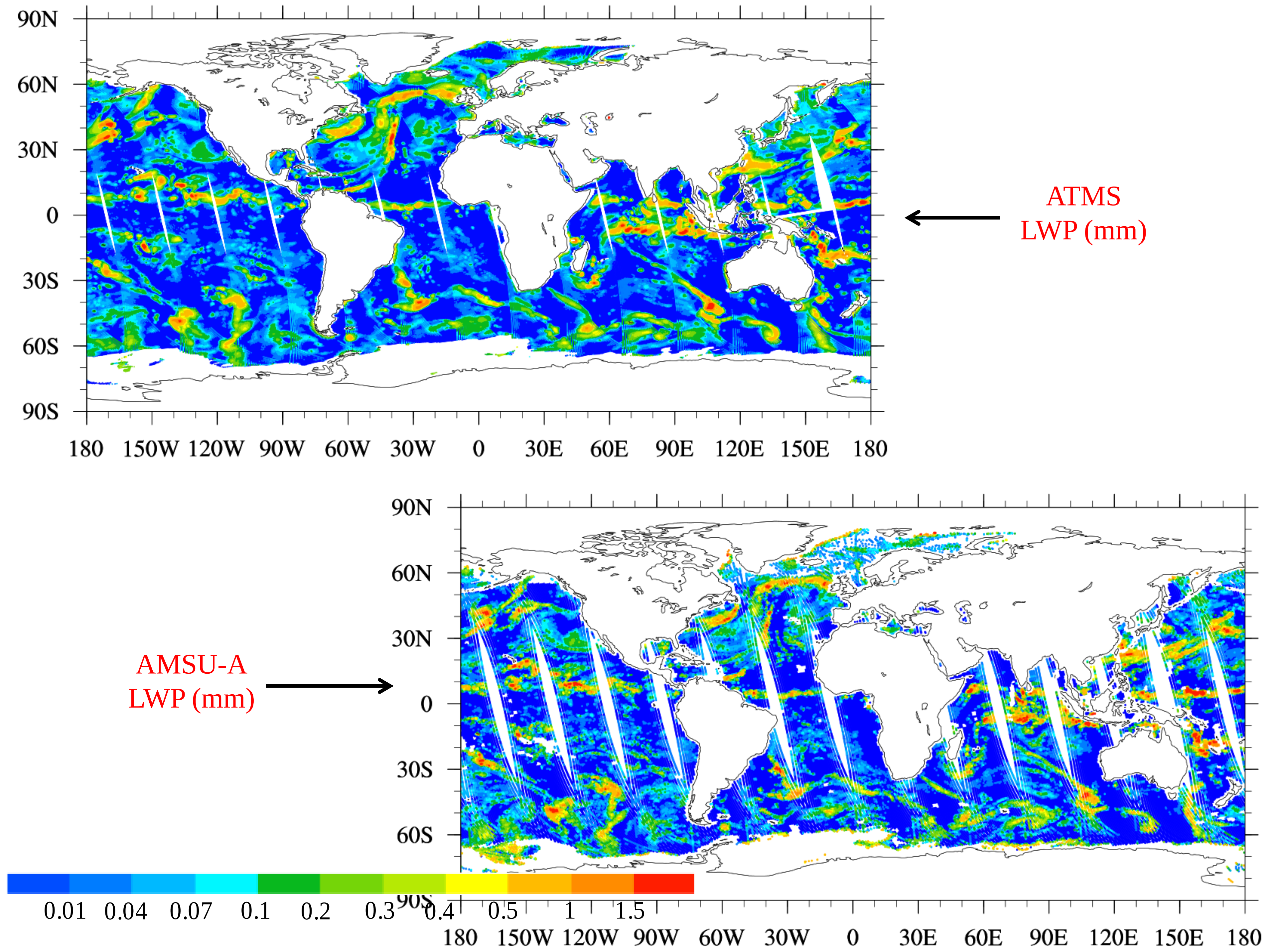
	AMSU/MHS			ATMS		
	Ch	GHz	Pol	Ch	GHz	Pol
AMSU-A	1	23.8	QV	1	23.8	QV
	2	31.399	QV	2	31.4	QV
	3	50.299	QV	3	50.3	QH
				4	51.76	QH
	4	52.8	QV	5	52.8	QH
	5	53.595 ± 0.115	QH	6	53.596 ± 0.115	QH
	6	54.4	QH	7	54.4	QH
	7	54.94	QV	8	54.94	QH
	8	55.5	QH	9	55.5	QH
	9	fo = 57.29	QH	10	fo = 57.29	QH
	10	fo ± 0.217	QH	11	fo±0.3222±0.217	QH
	11	fo±0.3222±0.048	QH	12	fo± 0.3222±0.048	QH
	12	fo ±0.3222±0.022	QH	13	fo±0.3222±0.022	QH
	13	fo± 0.3222±0.010	QH	14	fo±0.3222 ±0.010	QH
	14	fo±0.3222±0.0045	QH	15	fo± 0.3222±0.0045	QH
	15	89.0	QV			
MHS	16	89.0	QV	16	88.2	QV
	17	157.0	QV	17	165.5	QH
	18	183.31 ± 1	QH	18	183.31 ± 7	QH
	19	183.31 ± 3	QH	19	183.31 ± 4.5	QH
	20	191.31	QV	20	183.31 ± 3	QH
				21	183.31 ± 1.8	QH
				22	183.31 ± 1	QH

- Exact match to AMSU/MHS
- Only Polarization different
- Unique Passband
- Unique Passband, and Pol. different from closest AMSU/MHS channels

ATMS Brightness Temperature at CH 2

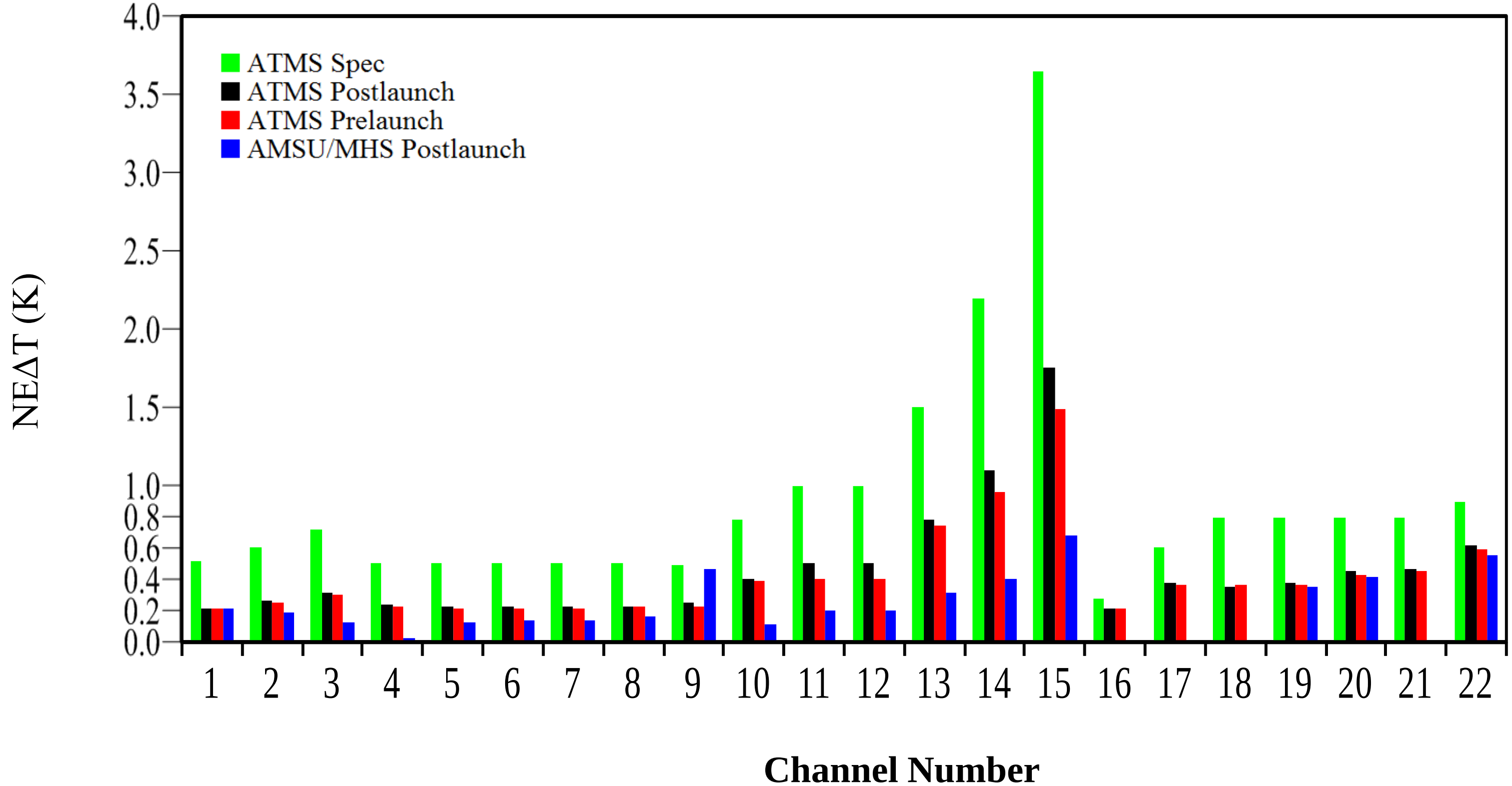


December 20, 2011



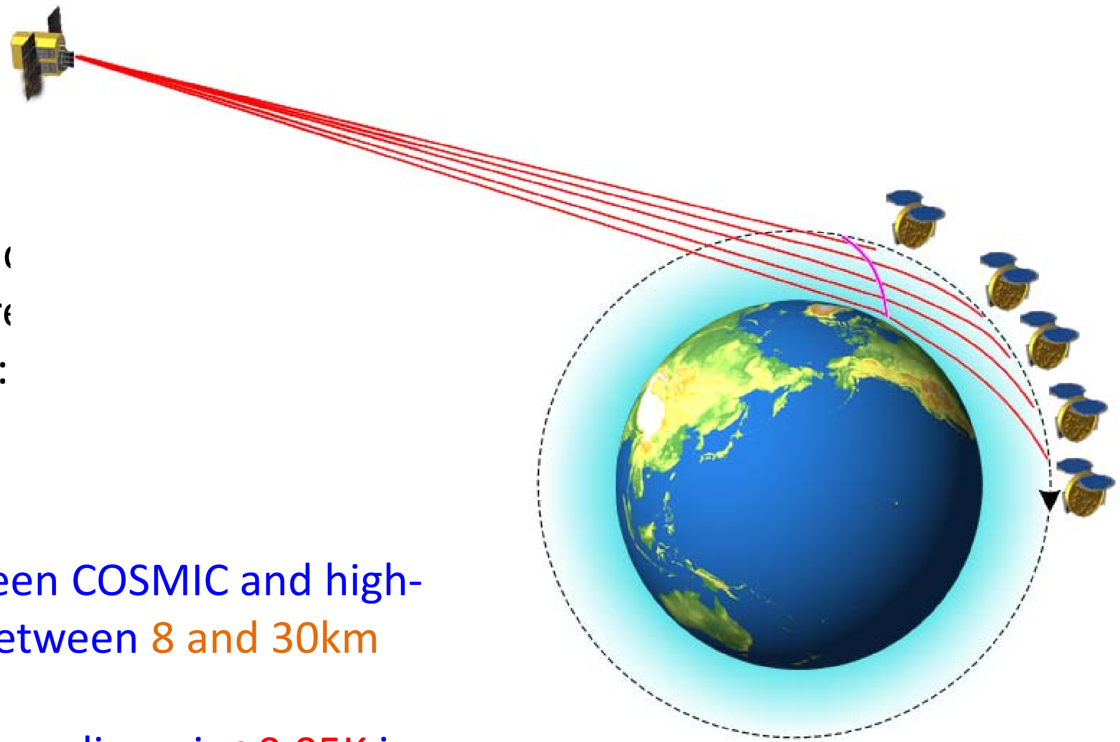
ATMS
LWP (mm)
AMSU-A
LWP (mm)
90N
60N
30N
0
30S
60S
90S
180
150W
120W
90W
60W
30W
0
30E
60E
90E
120E
150E
180
0.01
0.04
0.07
0.1
0.2
0.3
0.4
0.5
1
1.5

ATMS Noise Equivalent Differential Temperature (NEDT)



On-orbit ATMS noise magnitudes are about twice as large as those AMSUMHS but much lower than specification. The re-sampled ATMS data within CrIS FOR or equivalent AMSU-A FOV would result in noise much lower than that of AMSU-A/MHS

Building High Quality NPP SDR Products for Science Community: Or-Orbit ATMS Absolute Calibration Using COSMIC and LBL RT Model



1. High vertical resolution
2. No contamination from clou
3. No system calibration requir
4. High accuracy and precision:

The global mean differences between COSMIC and high-quality reanalyses is ~0.65K between 8 and 30km (Kishore et al. 2008)

The precision of COSMIC GPS RO soundings is ~0.05K in the upper troposphere and lower stratosphere (Anthes et al. 2008)

NPP Data Collocation with COSMIC

- **Time period of data search:**

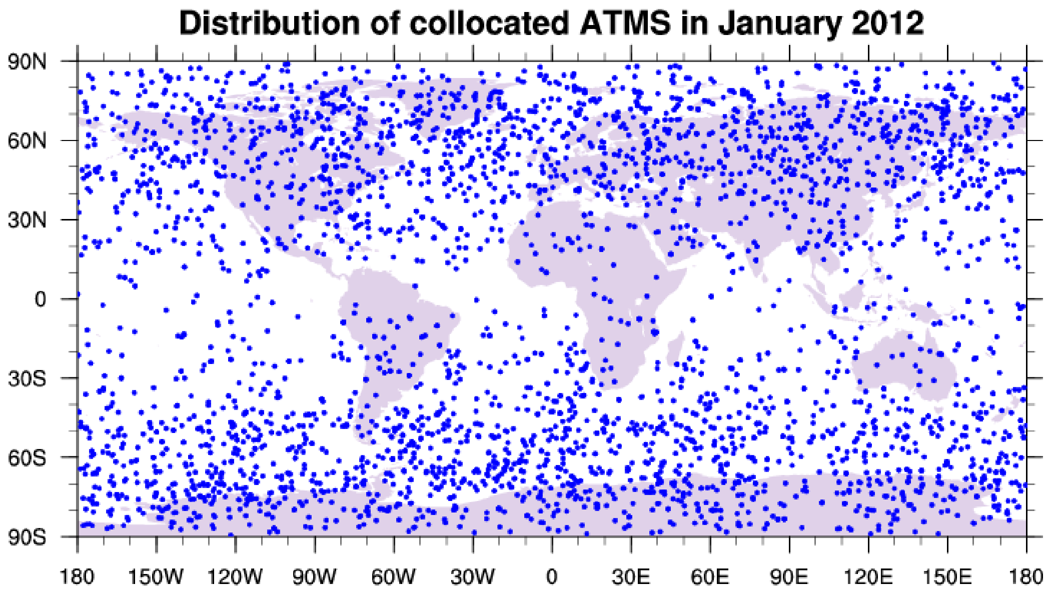
  January, 2012

- **Collocation of CloudSat and COSMIC data:**

  Time difference < 0.5 hour

  Spatial distance < 30 km

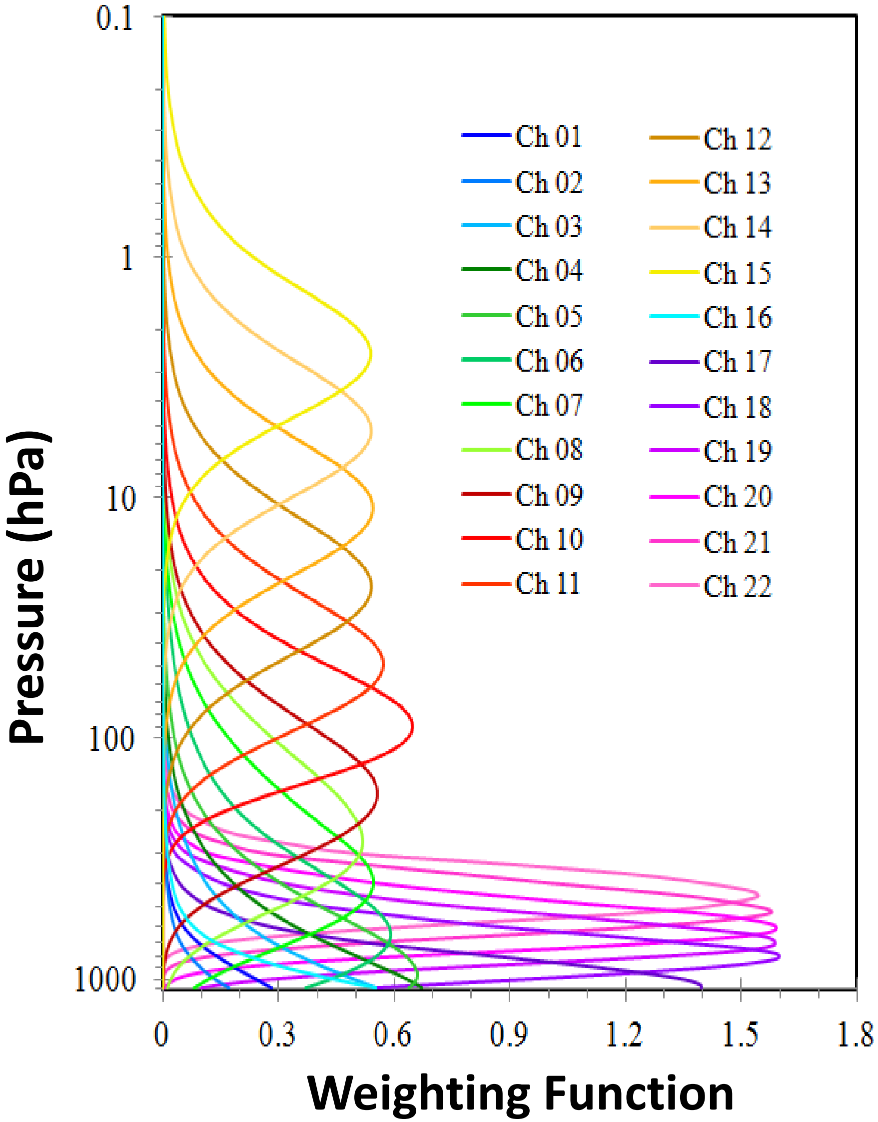
(GPS geolocation at 10km altitude is used for spatial collocation)



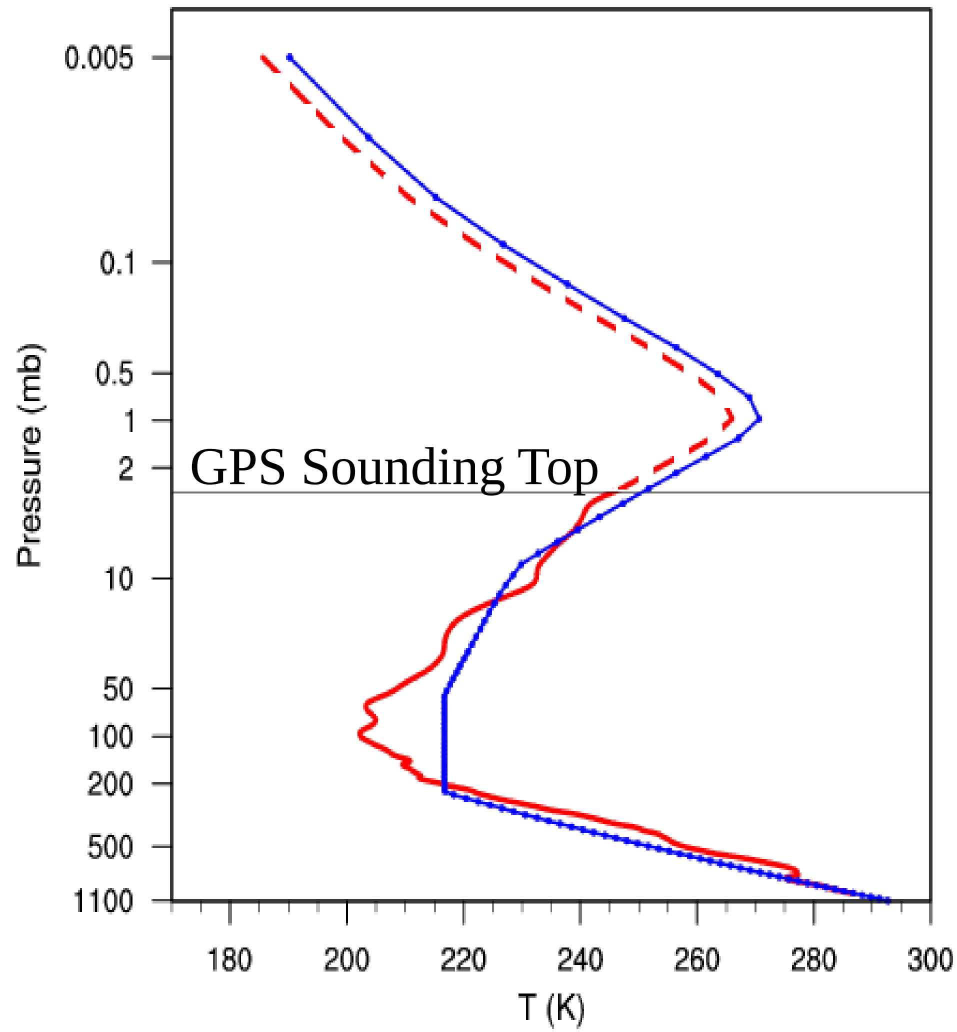
3056 collocated measurements

Courtesy of Lin Lin, STAR

ATMS WF (U.S. Standard Atmosphere)



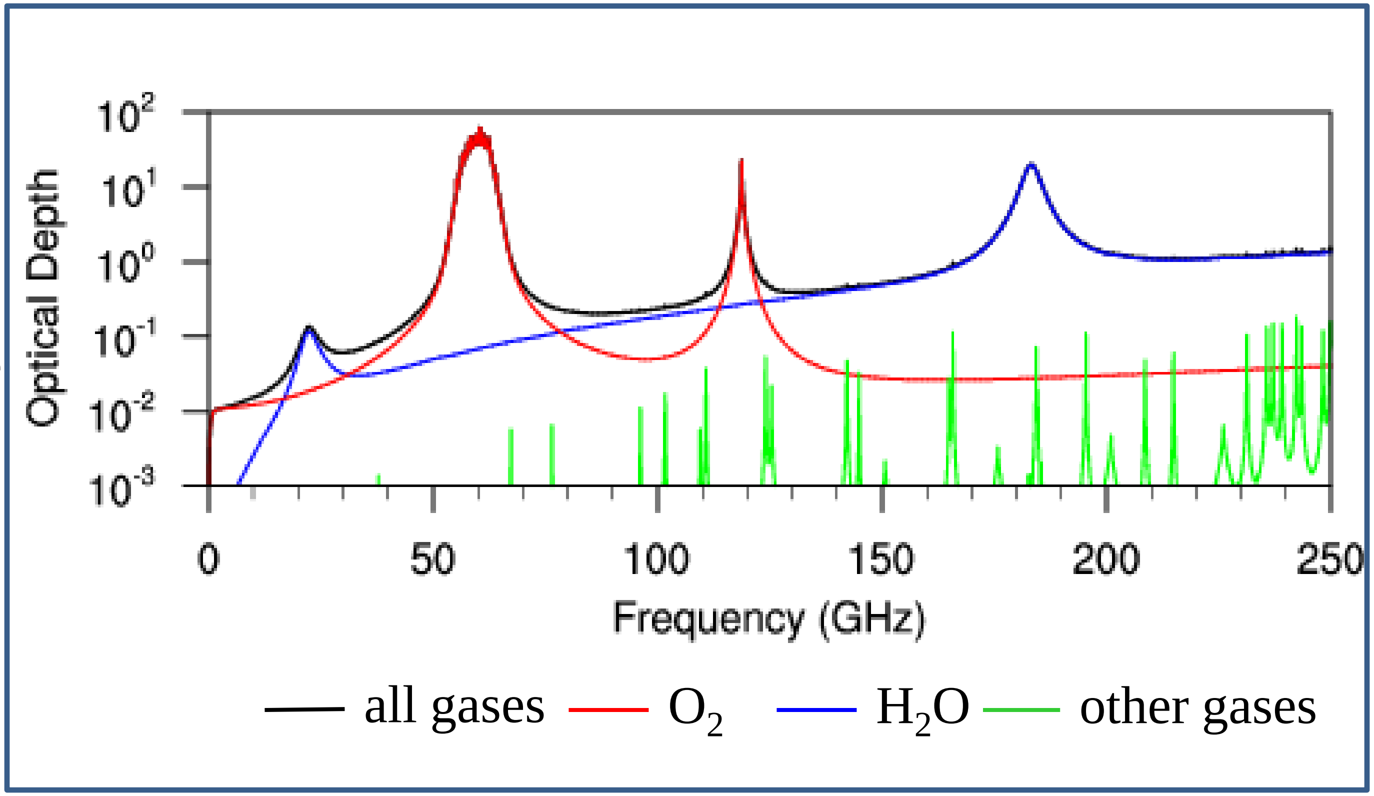
Add 1976 U.S. Standard Atmosphere State to GPS Soundings



1051 UTC on January 1, 2012

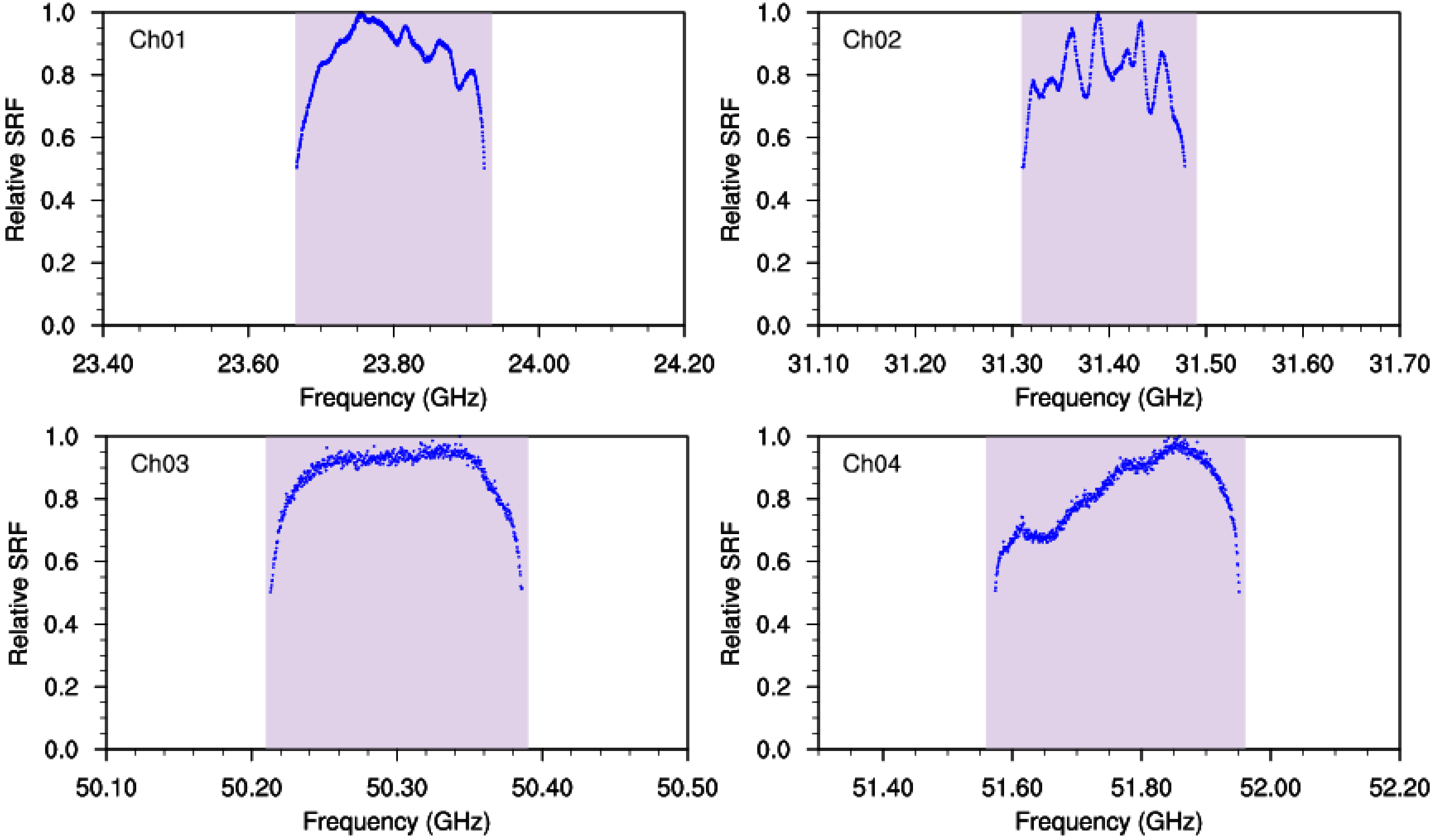
MonoRTM

- Perform a line by line radiative transfer calculation
- Accurate atmospheric spectroscopy data base
- Only gaseous absorption
- Vertical stratification

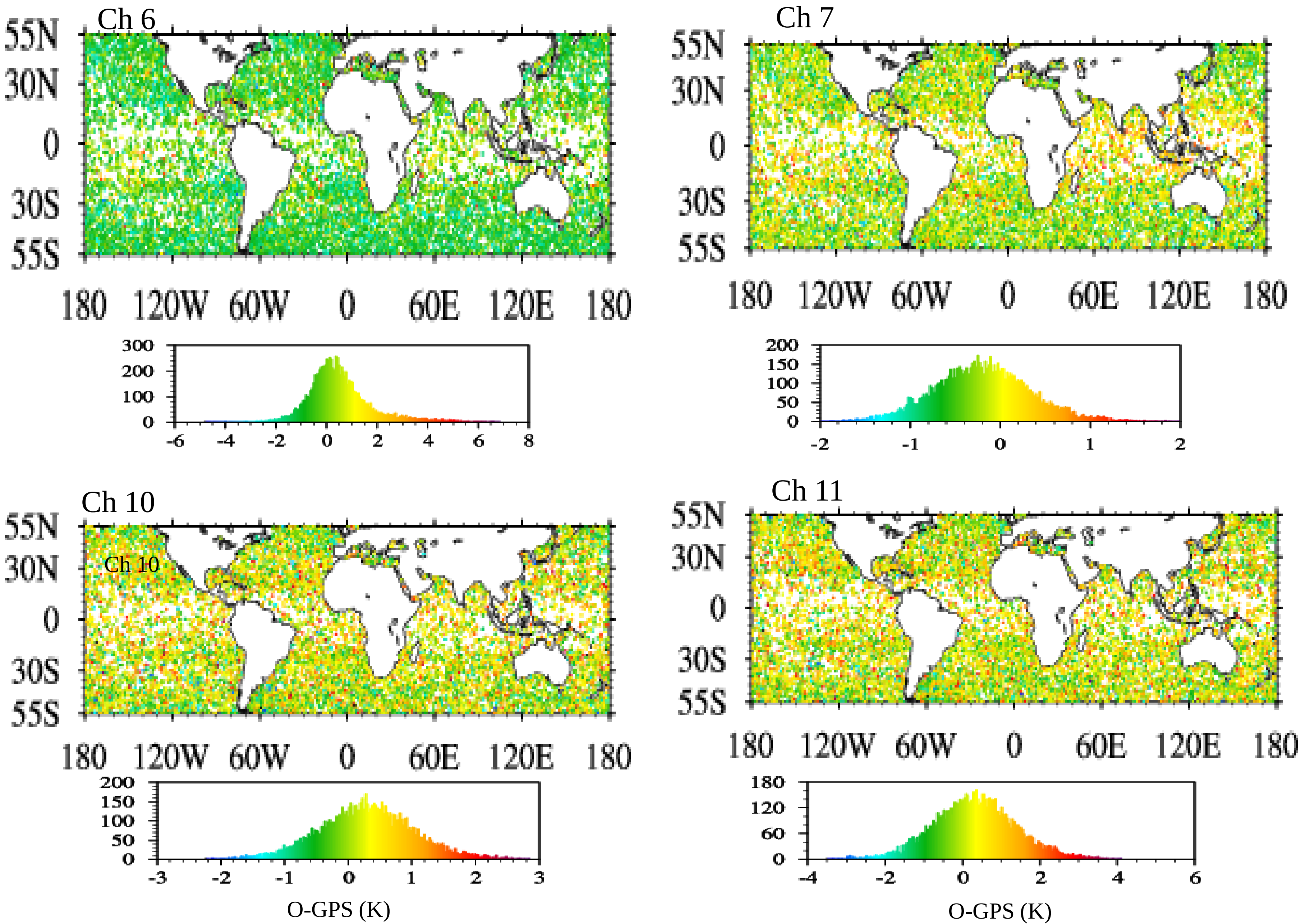


Microwave sounding channels at 50-60 GHz O_2 absorption band can be best simulated under a cloud-free atmosphere using line by line calculation

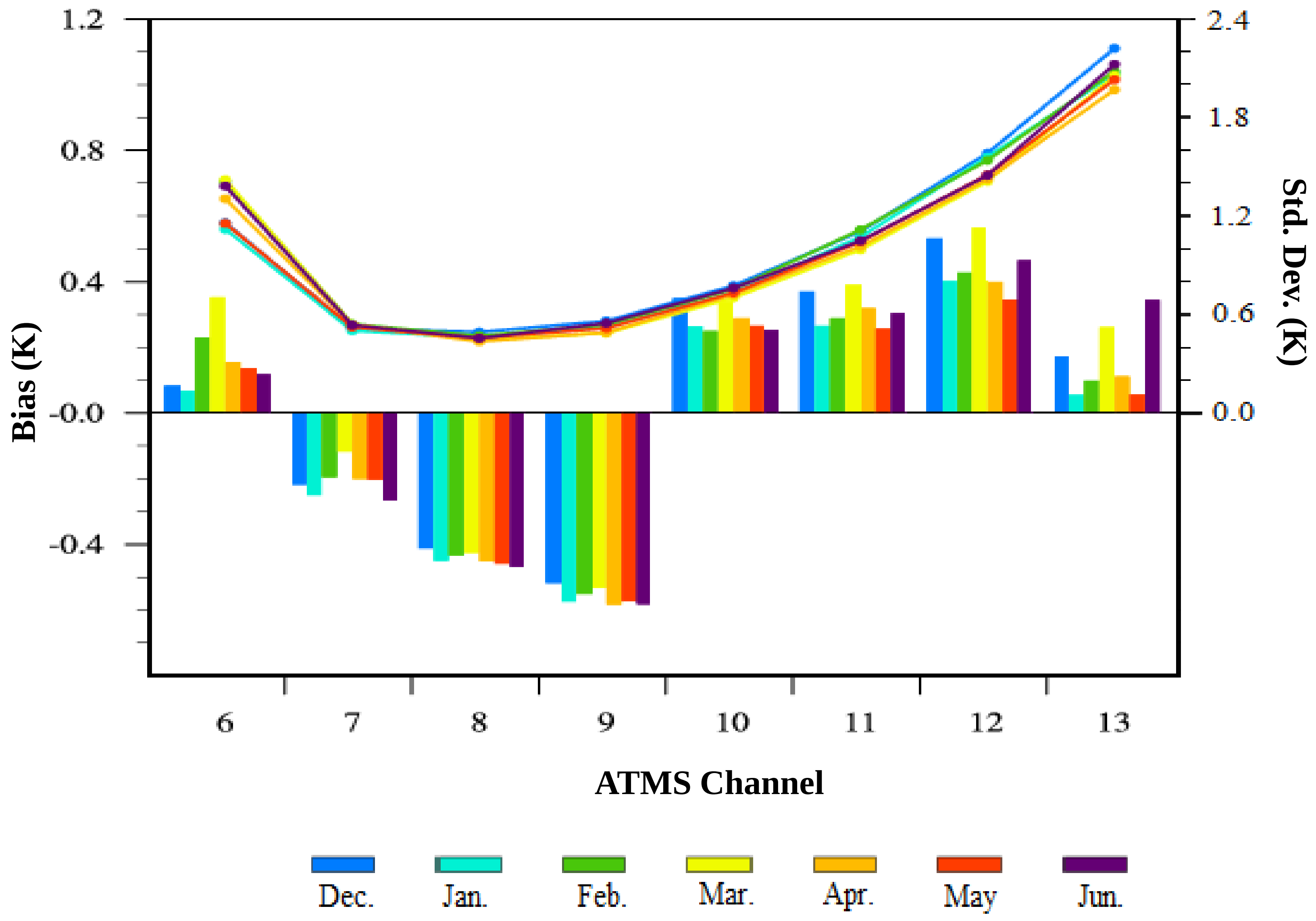
Effects of ATMS Spectral Response Function



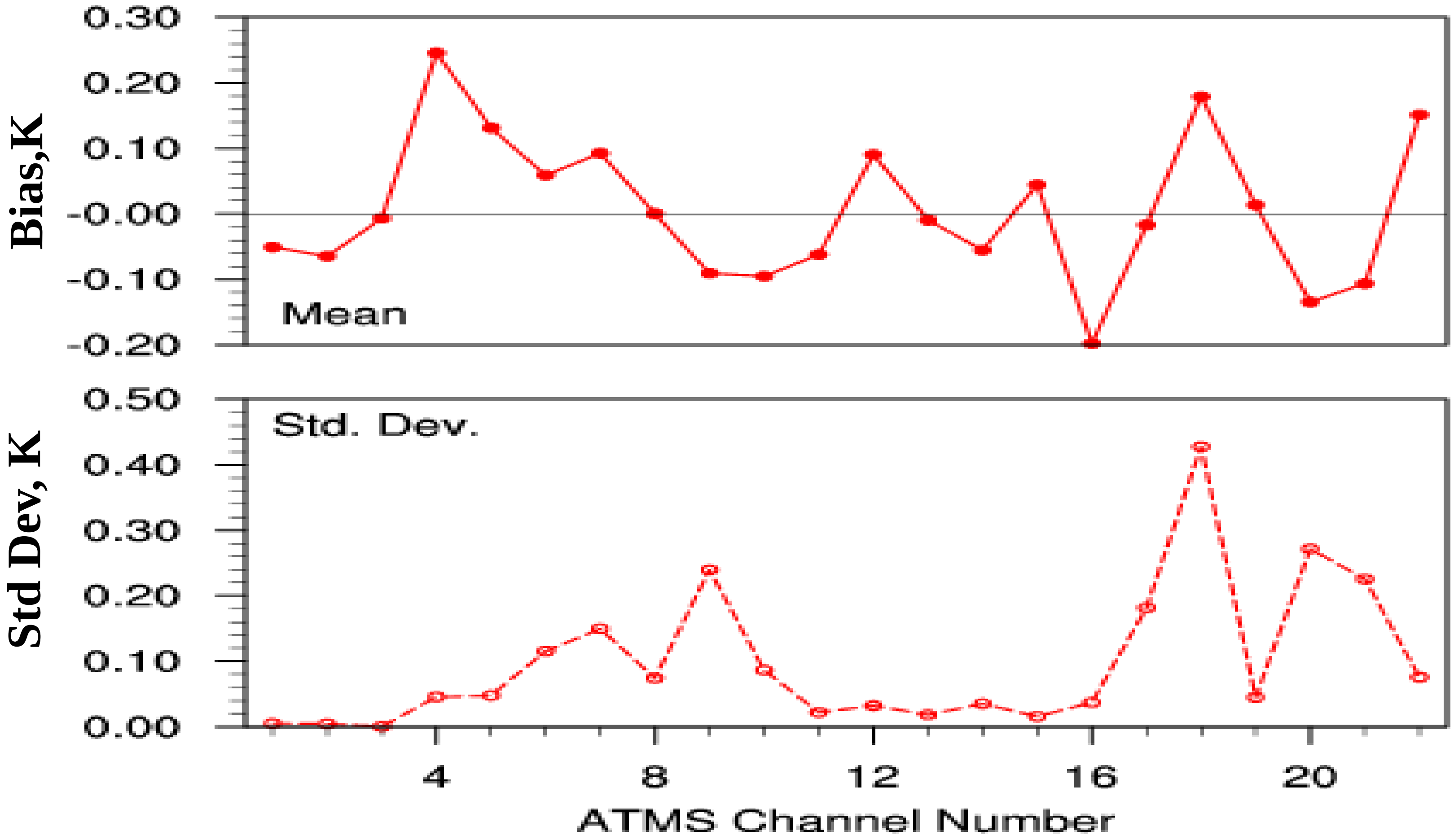
ATMS Bias Obs (TDR) - GPS Simulated



ATMS Bias Obs (TDR) - GPS Simulated

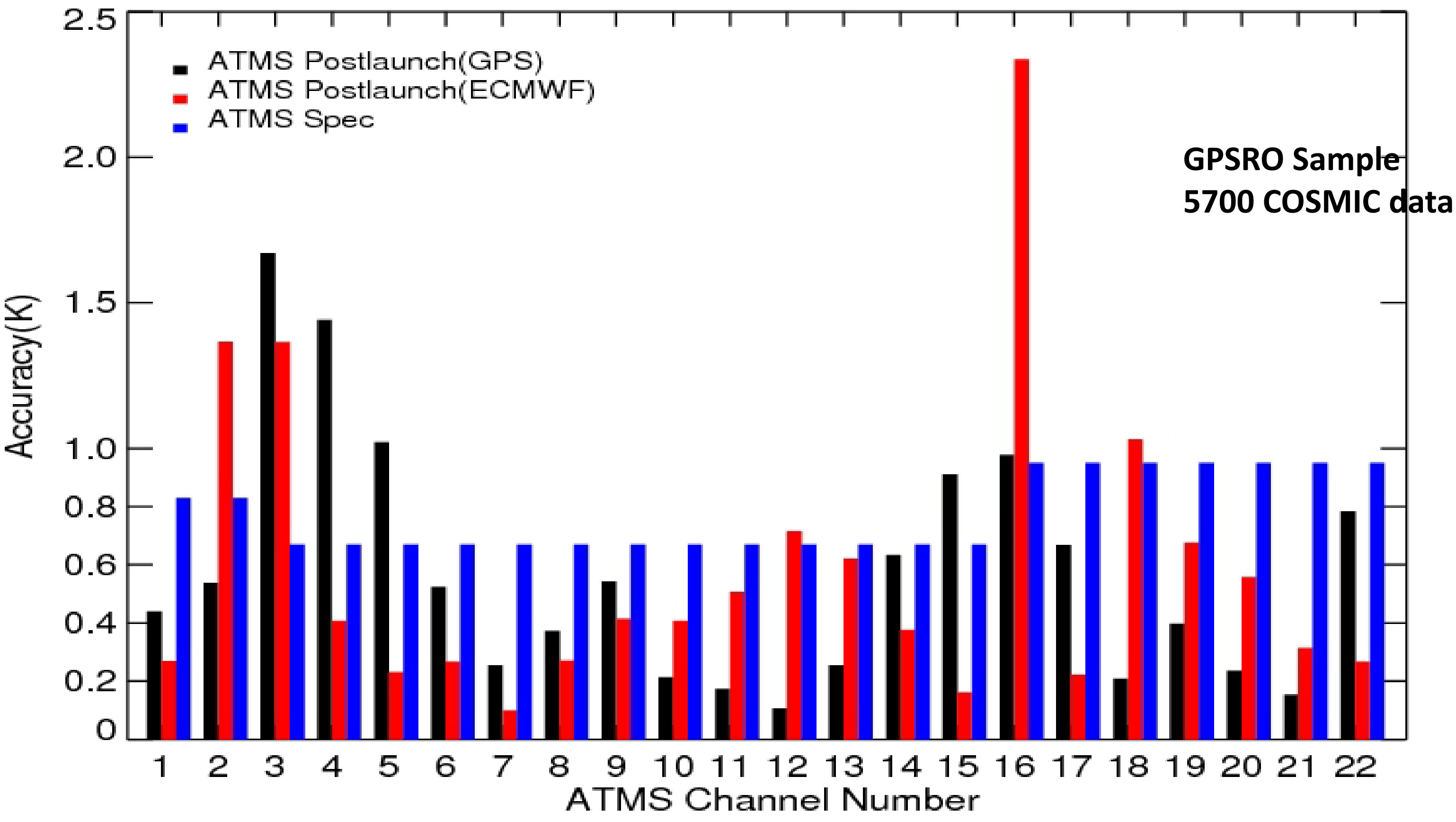


Difference of Antenna Brightness Temperature between Measured SRF and Boxcar



Shown is the means bias of ATMS simulations using boxcar to the measured SRF and the standard deviation of the bias. The simulations are computed from GPSRO profiles and LBLRTM.

ATMS Calibration Accuracy Using GPSRO Data



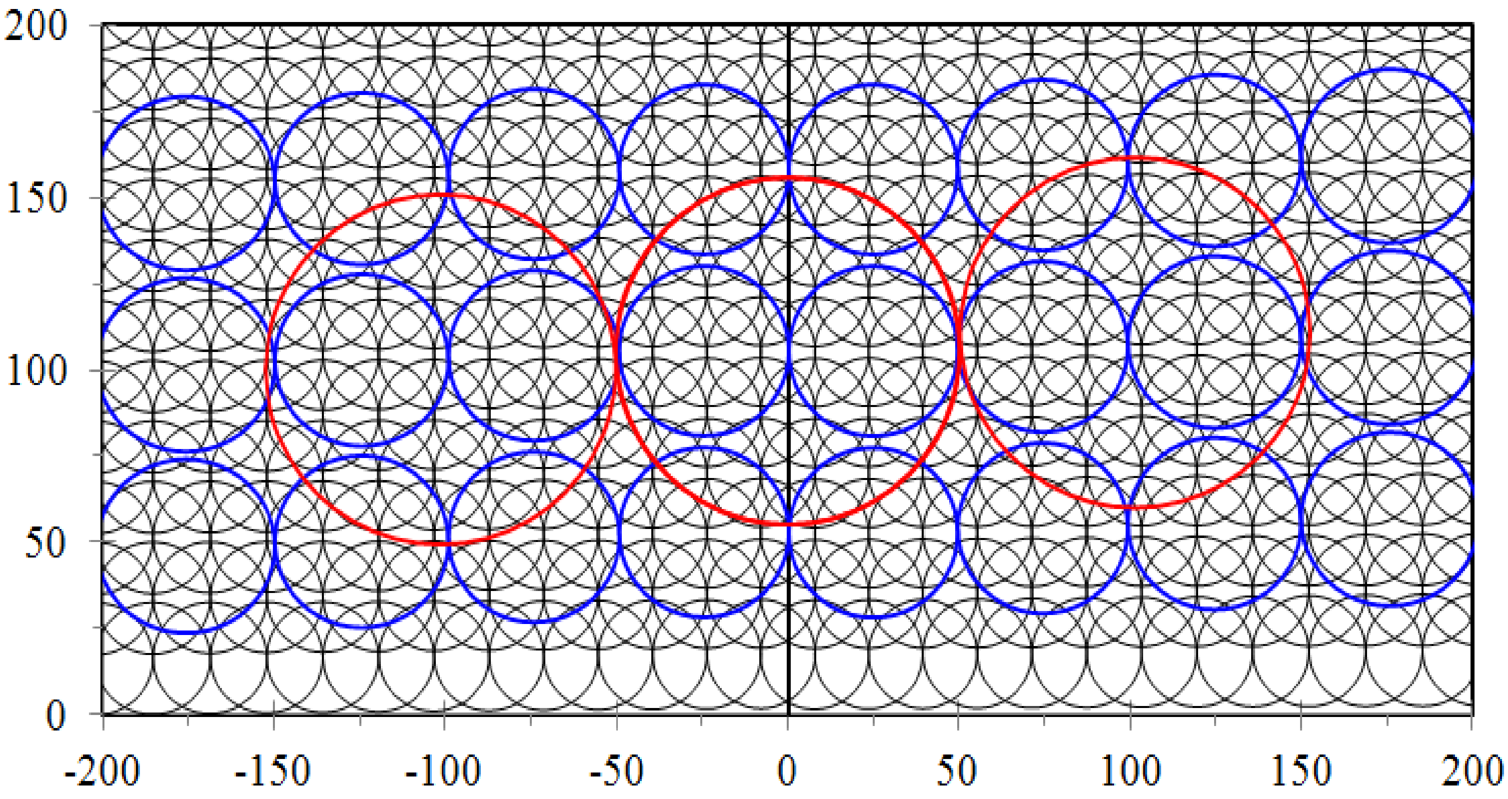
On-orbit ATMS calibration accuracy is quantified using GPSRO data as input to RT model and is better than specification for most of sounding channels.

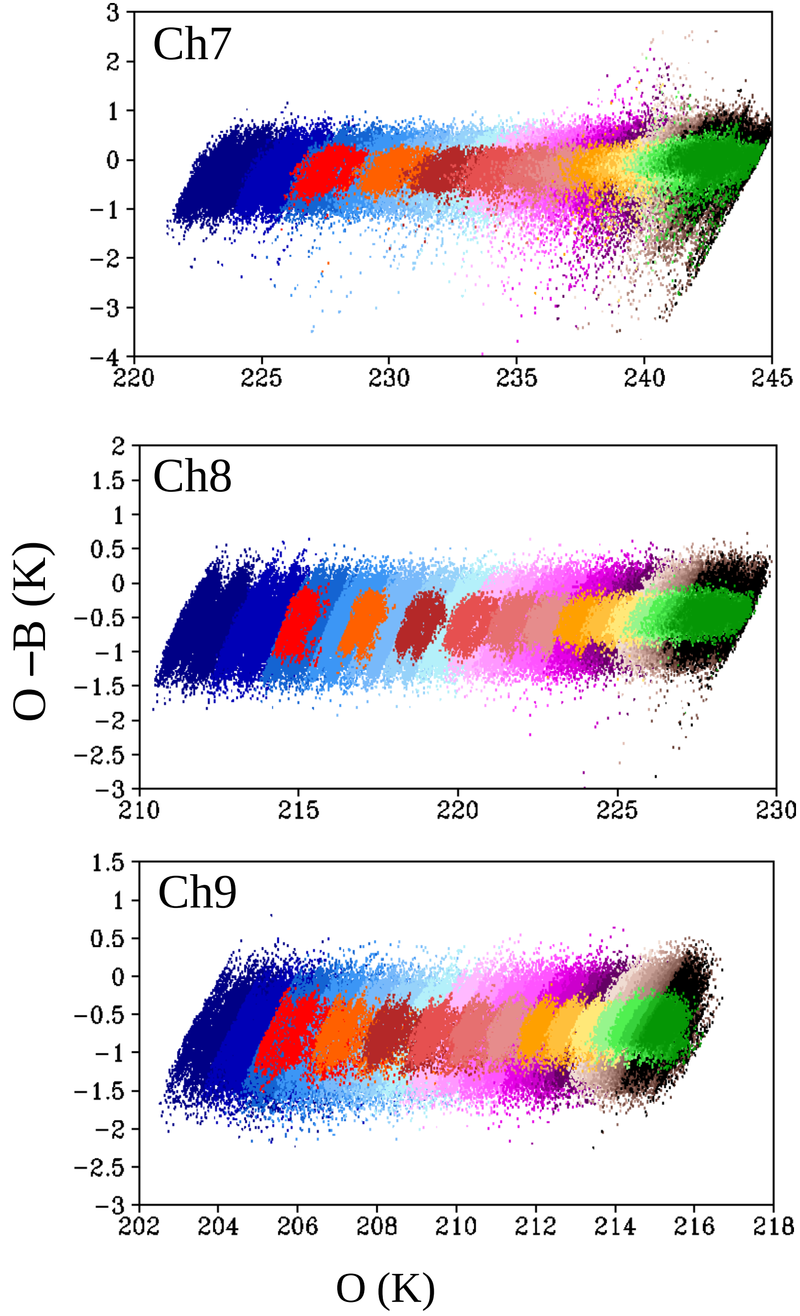
Courtesy of Xiaolei Zou, FSU/STAR

Impacts of ATMS Spatial Re-sampling on NWP O-B

ATMS Field of View Size for the beam width of 2.2° – black line

ATMS Resample to the Field of View Size for the beam width of 3.3°- blue line

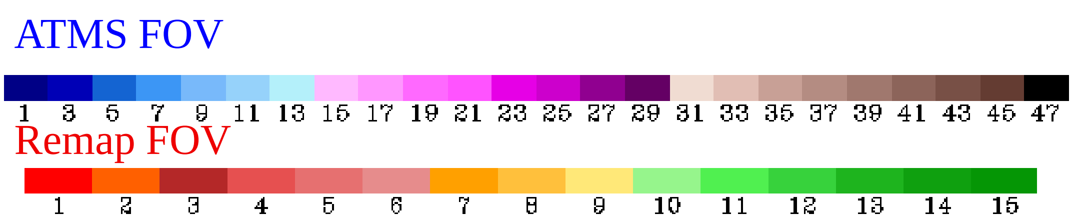




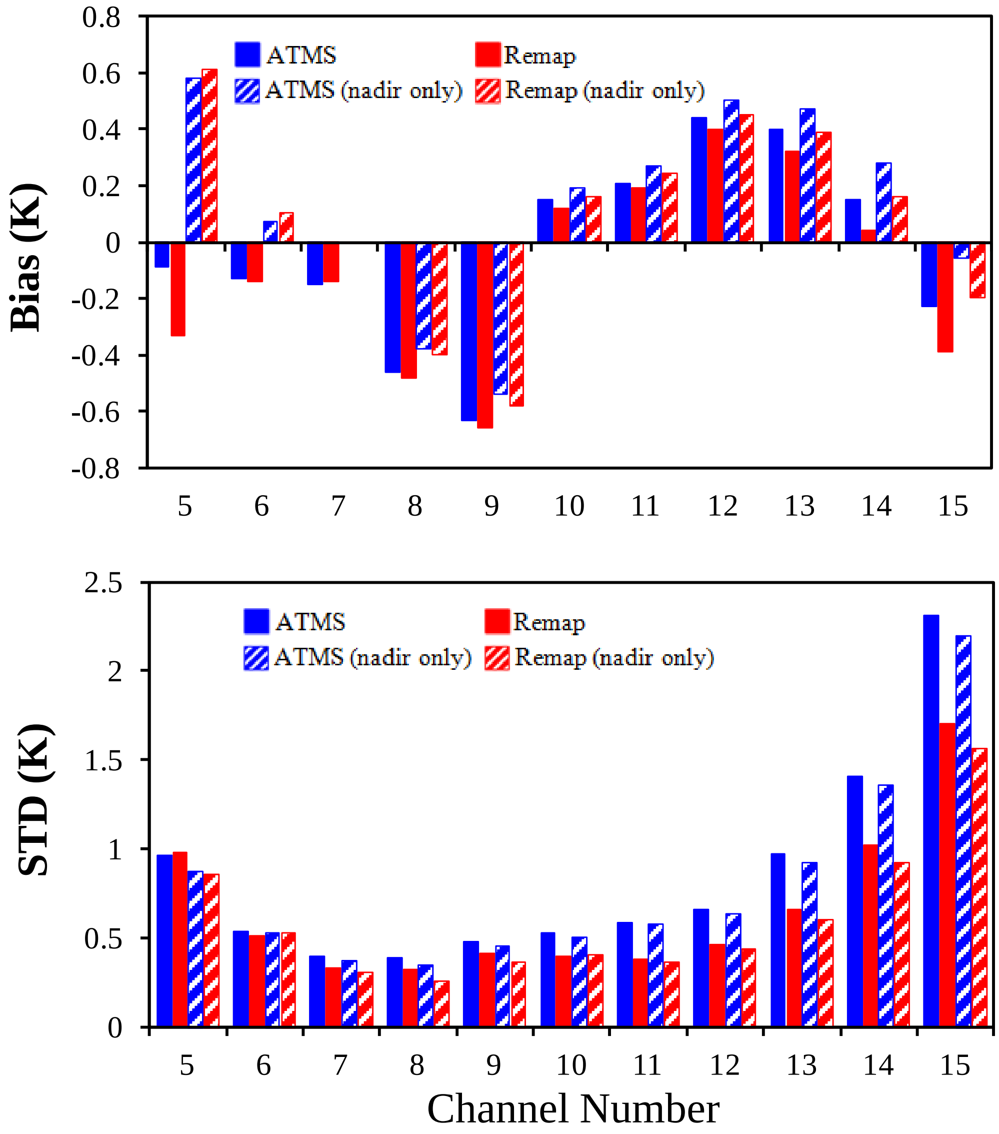
Scene-Temperature Dependence of Biases

Notice the differences between ATMS raw and remap data:

- Dynamics range
- Biases
- Noises

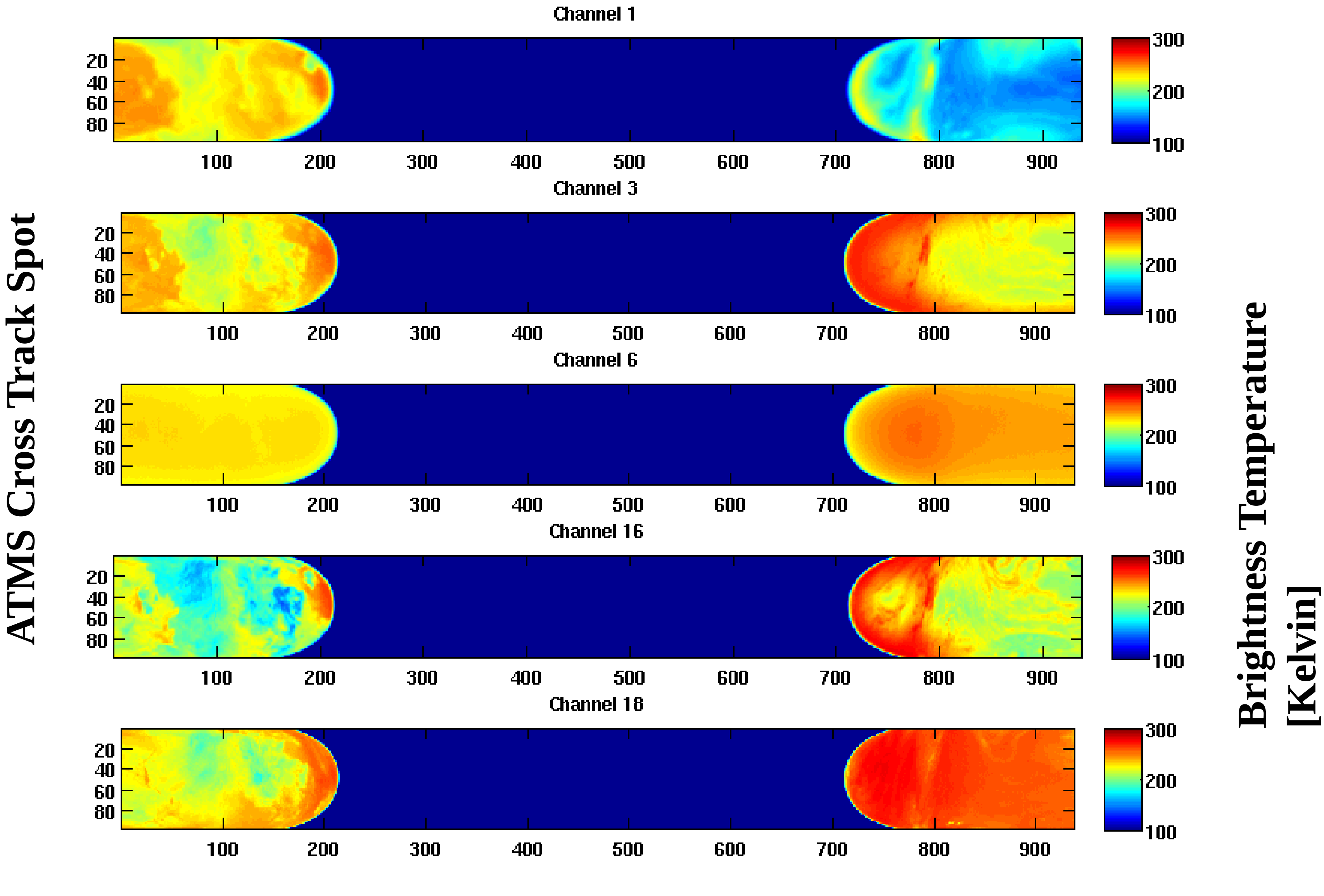


ATMS SDR Global Biases and Standard Deviations



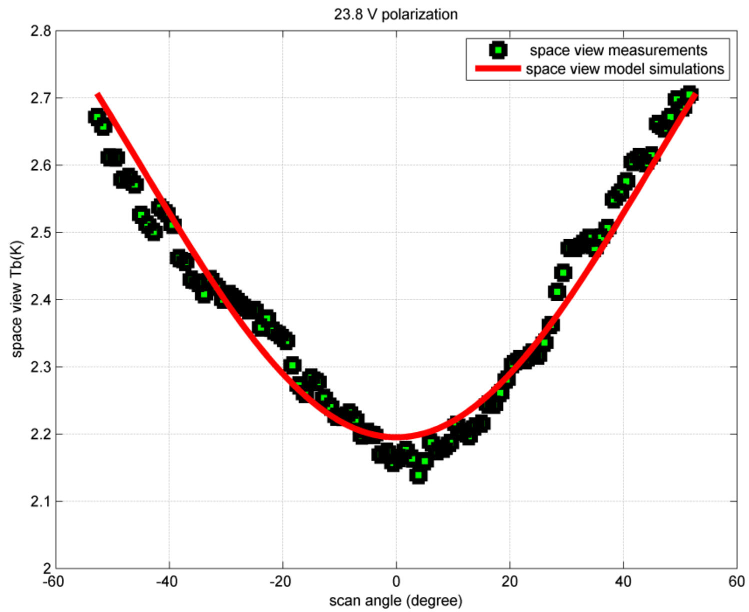
Within 60S-60N, clear-sky, ocean only, 20-27 December 2011

ATMS Pitch Maneuver February 20, 2012

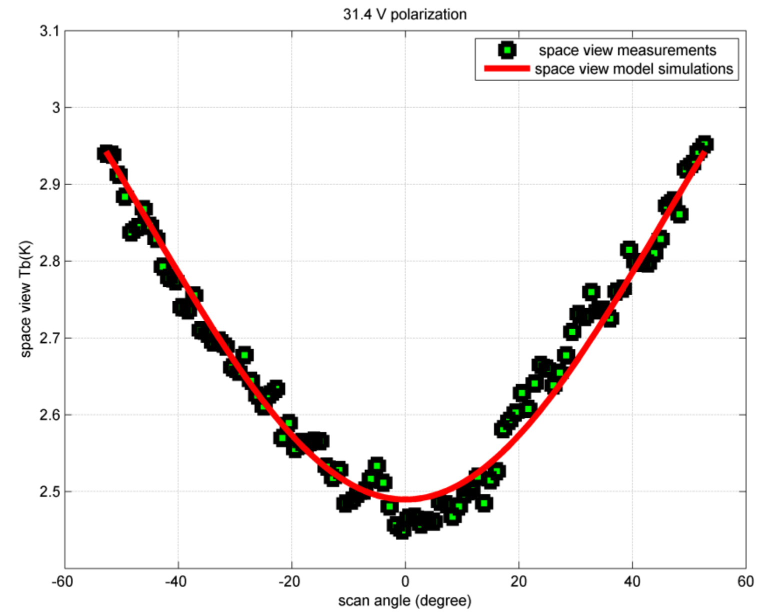


courtesy of Vince Leslie, MITLL

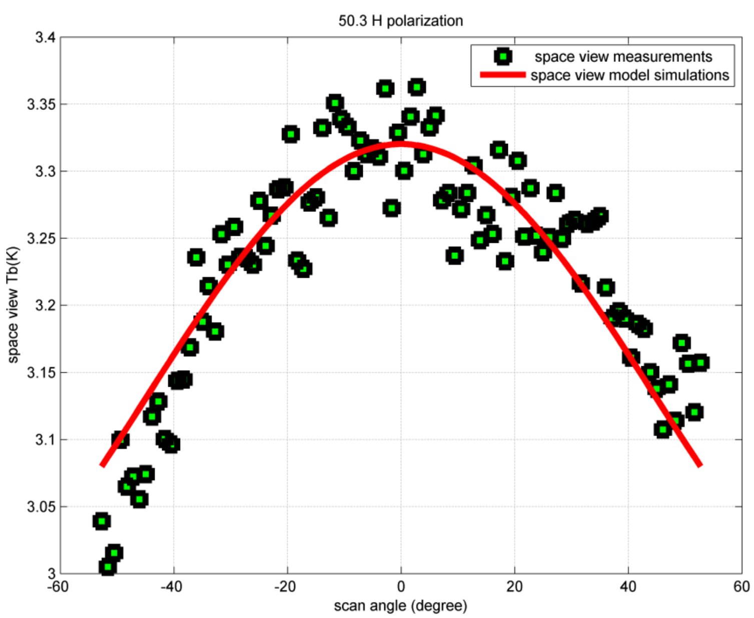
Channel 1



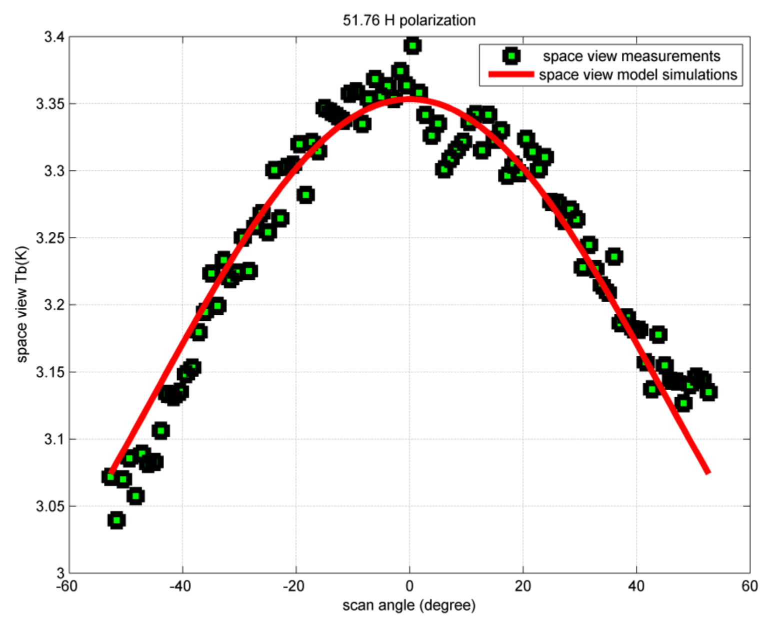
Channel 2



Channel 3



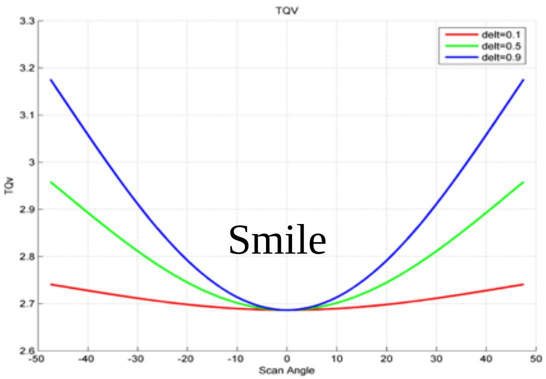
Channel 4



ATMS Pitch Maneuver Antenna Temperature Model

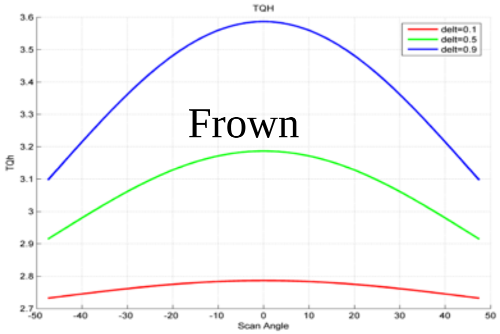
A smile pattern QV- antenna temperature:

$$T_a^{v_q} = (\eta_m^{vv} + \eta_m^{hv})T_b^c + \beta_0^v + \beta_1^v \sin^2\theta$$



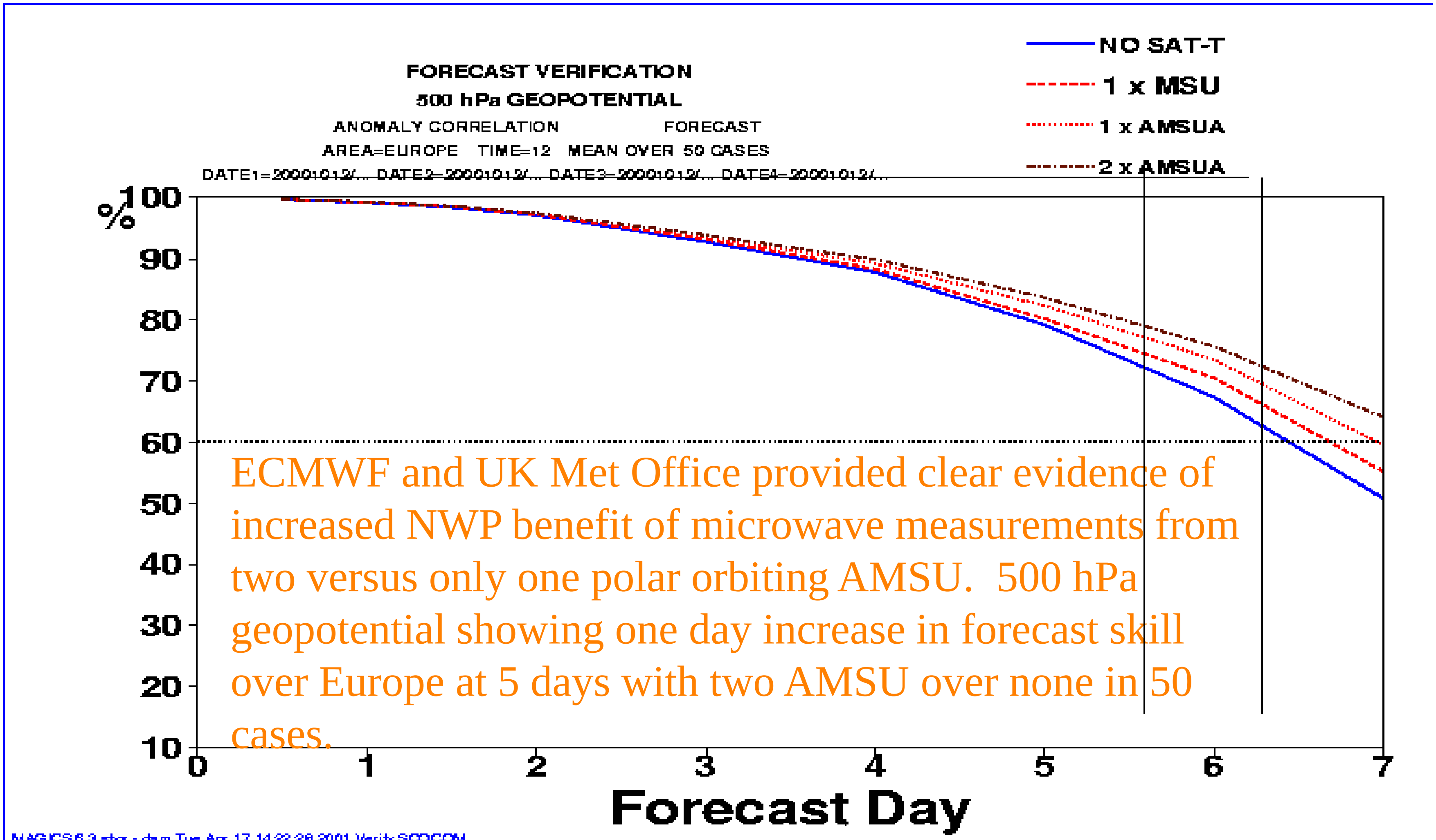
A frown pattern QH- antenna temperature:

$$T_a^{h_q} = (\eta_m^{hh} + \eta_m^{vh})T_b^c + \beta_0^h + \beta_1^h \cos^2\theta$$



β* : *the slope and scale parameters related to spacecraft emission and reflection. It is not well understood in the past. NPP pitch maneuver offers a unique opportunity for us to characterize the term for better characterizations of the earth view bias along the scanline.

Impacts of AMSU on Global Medium Range Forecasting

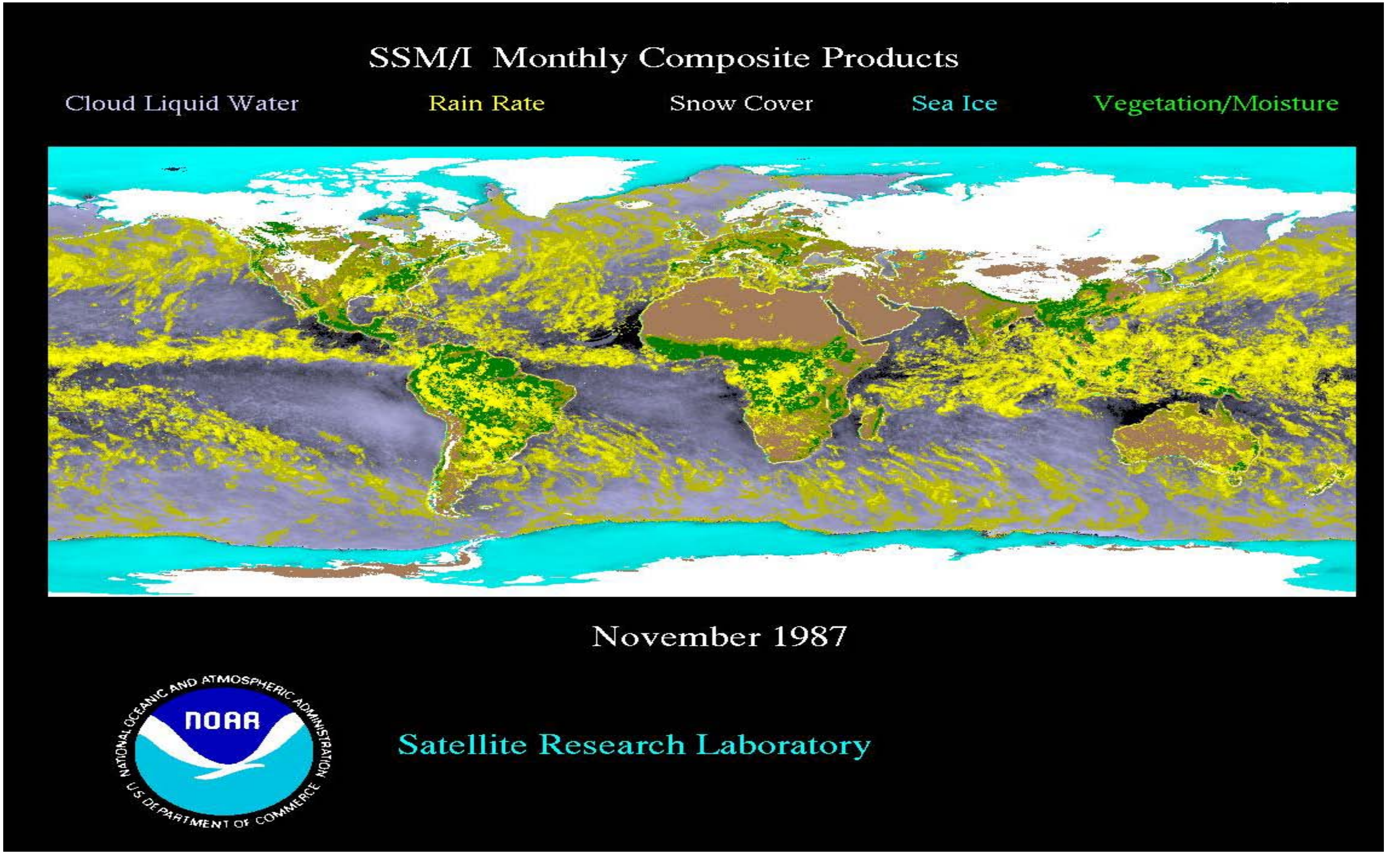


ECMWF and UK Met Office provided clear evidence of increased NWP benefit of microwave measurements from two versus only one polar orbiting AMSU. 500 hPa geopotential showing one day increase in forecast skill over Europe at 5 days with two AMSU over none in 50 cases.

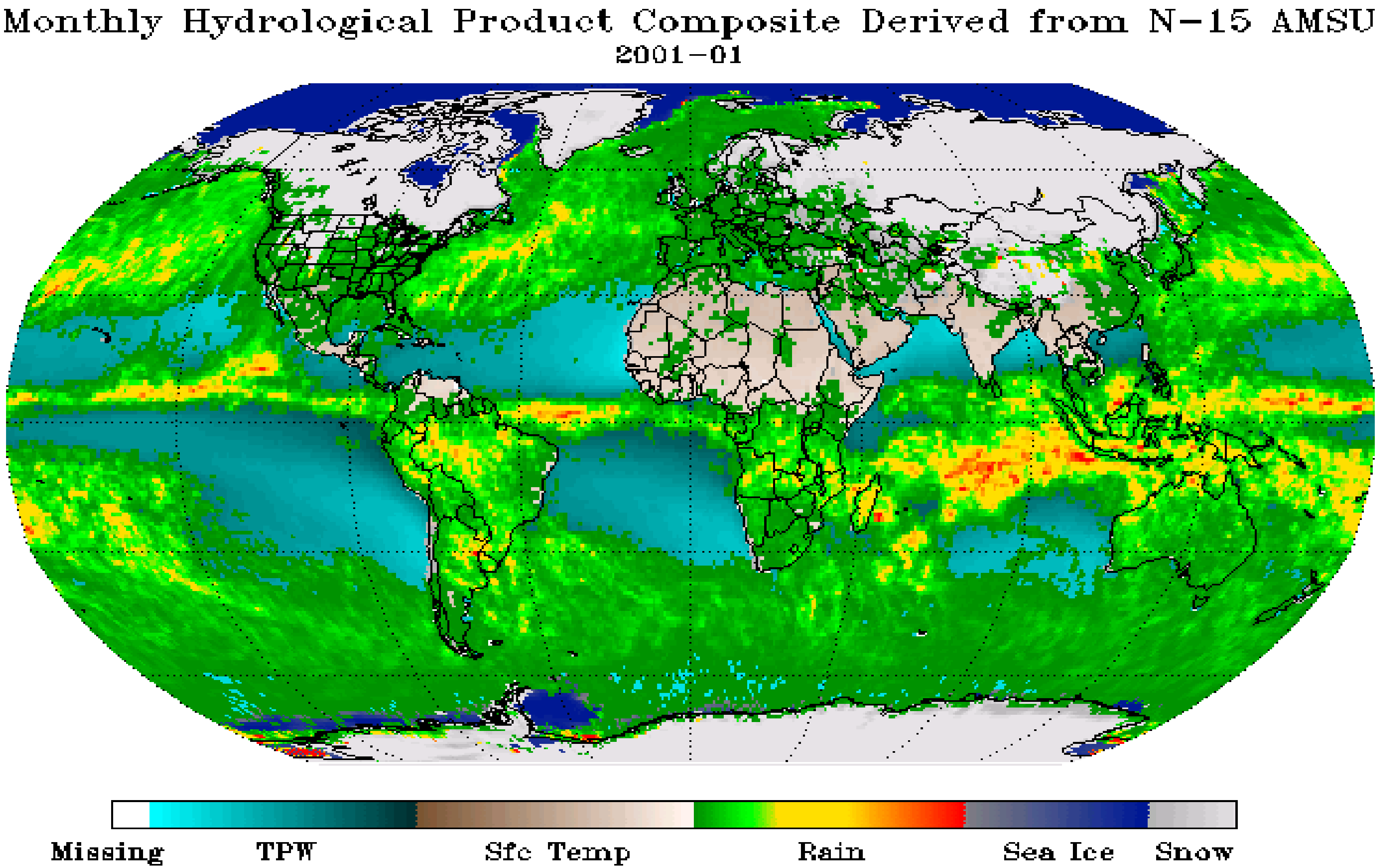
Microwave Environmental Data Records

SDR/EDR	POES/METOP AMSU-A/B; MHS	DMSP SSMIS	NPOESS ATMS/MIS
Radiances	✓	✓	✓
Temp. profile	✓	✓	✓
Moist. profile	✓	✓	✓
Total precipitable water*	✓	✓	✓
Hydr. profile	✓	✓	✓
Precip rate*	✓	✓	✓
Snow cover*	✓	✓	✓
Snow water equivalent*	✓	✓	✓
Sea ice *	✓	✓	✓
Cloud water*	✓	✓	✓
Ice water*	✓	✓	✓
Land temp*	✓	✓	✓
Land emis*	✓	✓	✓
Soil moisture/Wetness Index		✓	✓

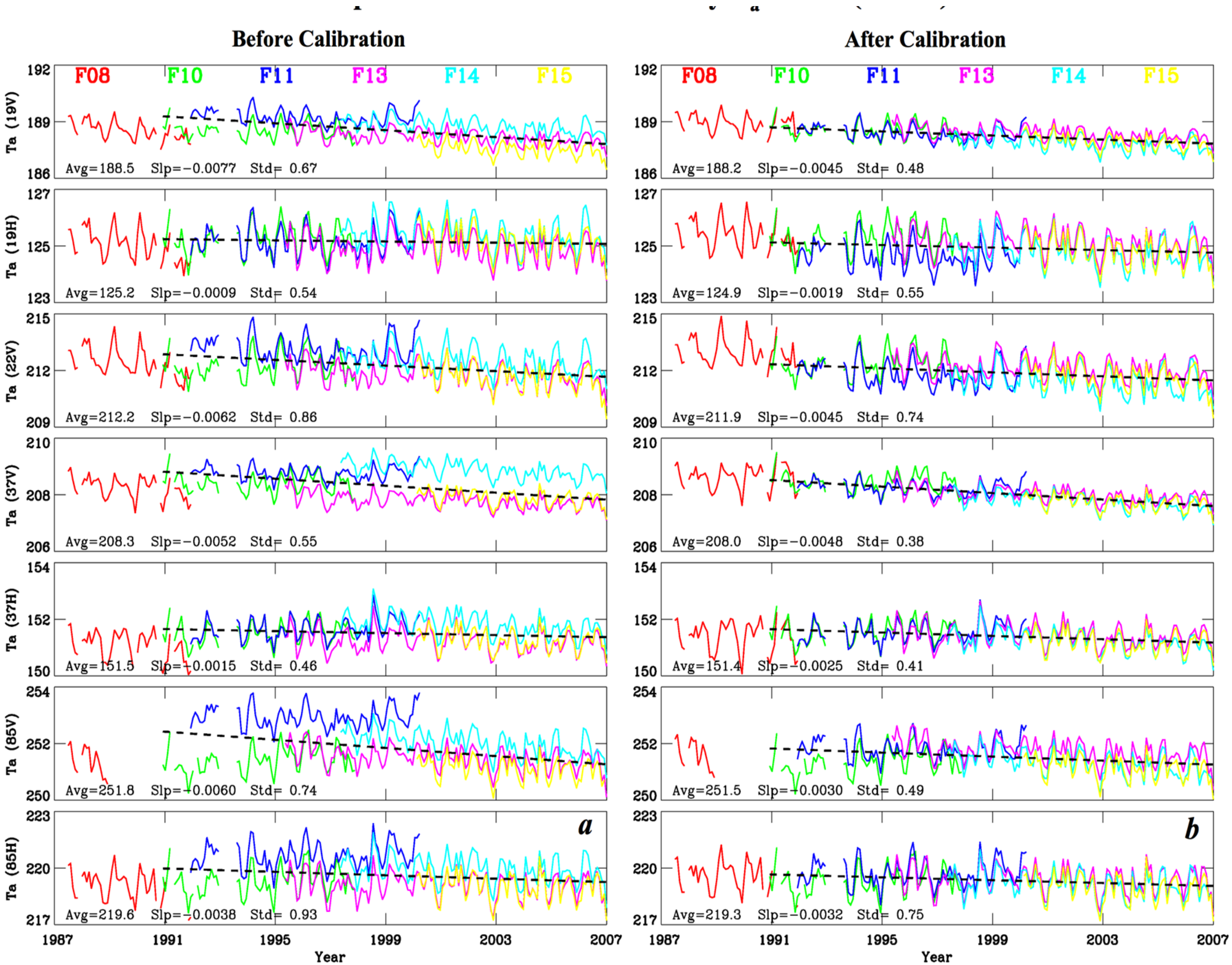
NESDIS SSM/I Climate Data Records Since 1987



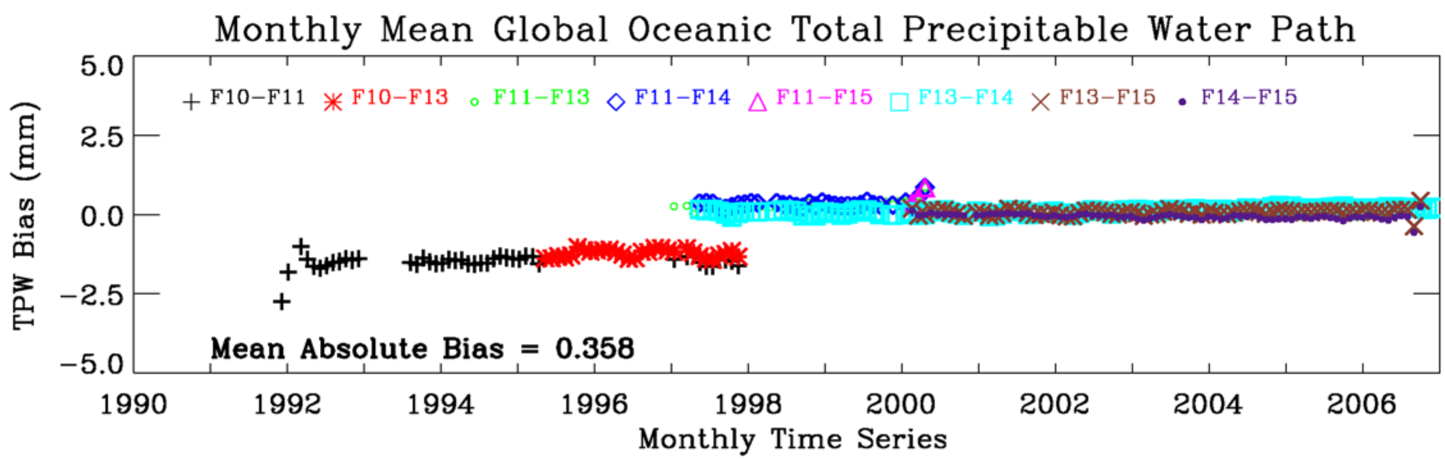
Microwave Products from NOAA Operational Sensor: AMSU

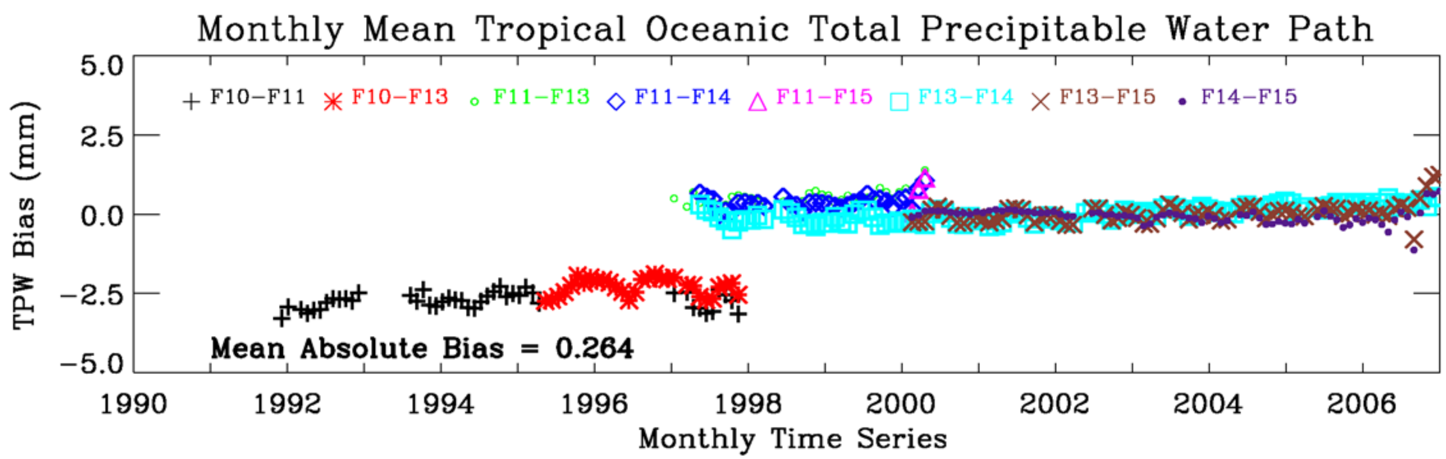


Comparison of SSM/I Monthly Oceanic Rain-free TDR Trend



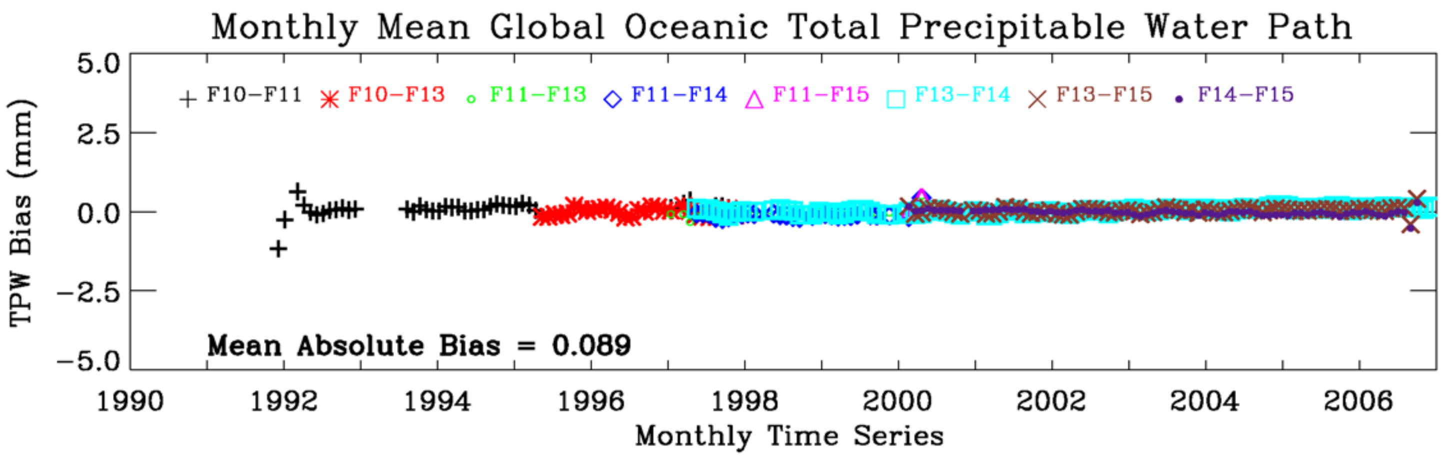
Monthly-Mean TPW Bias between Overlapped Sensors Before Inter-Calibration

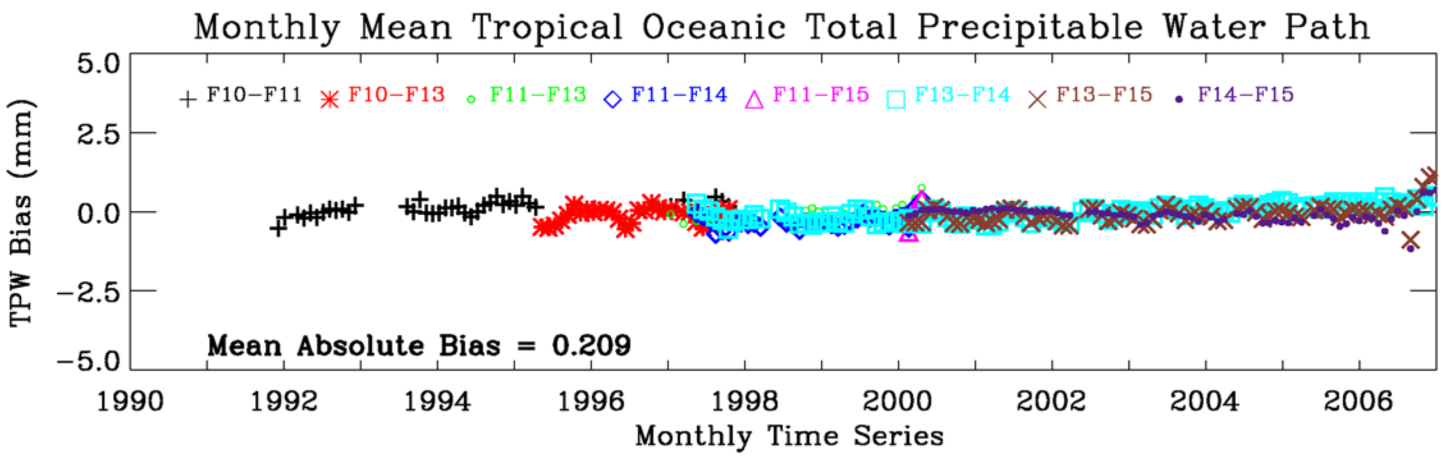




Large TPW biases between F10-F11 and F10-F13 are obvious. Since TPW = 232.89-.1486*TV19-.3695*TV37-(1.8291-.006193*TV22)*TV22, (Alishouse et al., 1991), any radiance biases in lower SSM/I frequencies will be directly translated into TPW biases.

Monthly TPW Bias between Overlapped Sensors After Inter-Calibration





The inter-sensor TPW biases become much smaller and consistent between different sensors. The averaged absolute bias after calibration is reduced by 75% and 21% over global ocean and over tropical ocean, respectively .

Future Advances in Microwave Technology in Space

1. Probe higher atmosphere by adding more sounding channels
2. Polarization or polarimetry for microwave imager
3. Combination of sounder and imager in a single scanning mode
4. Low instrument noise and high instrument stability
5. Longevity (5-10 years) beyond the mission life span

Technology Barriers in Microwave Instrument Developments

1. Course spatial resolutions from uses of solid aperture antenna

2. Slow progress in using low noise amplifier for lower frequencies

3. Difficult uses of microwave imager data in NWP systems through direct radiance assimilation

Summary

1. **Microwave thermal radiation** from the Earth is of much smaller magnitude, compared to VIS/IR
2. **Satellite Microwave Observations** are critical for atmospheric sounding and imaging under all weather conditions
3. **Microwave Sensor Calibration** converts analog signal to physical quantity using both linear and nonlinear systems
4. **Climate Data Record** can be obtained from satellites through cross sensor calibrations that remove inter-sensor biases
5. **Microwave Sensing Principle** is based on imaging clouds over ocean with lower emissivity, and sounding atmosphere from O_2 and H_2O absorption lines