Satellite inter-calibration activities and methods for window channel radiometers

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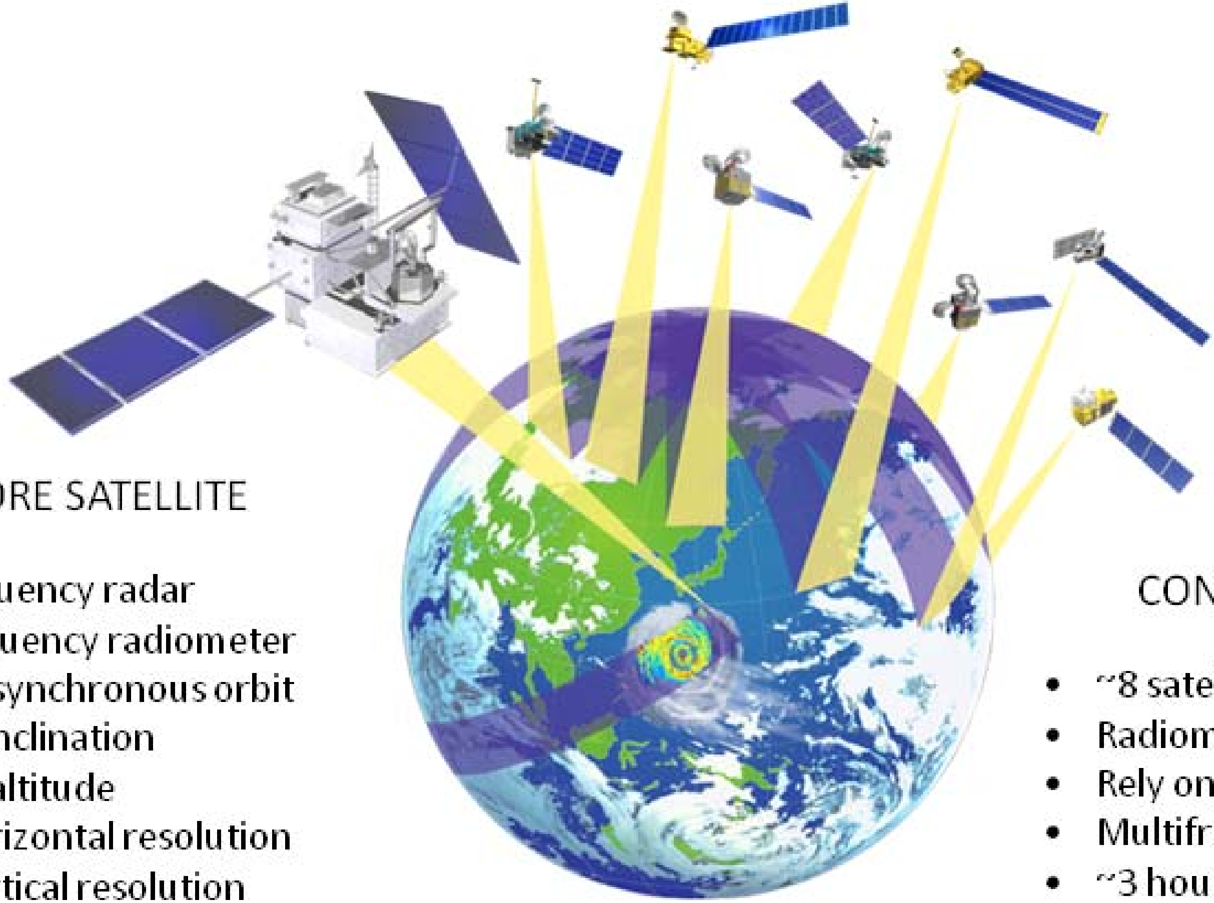
The Global Precipitation Mission



CORE SATELLITE

- Dual frequency radar
- Multifrequency radiometer
- Non-sun synchronous orbit
- ~70 deg inclination
- ~400km altitude
- ~4km horizontal resolution
- 250m vertical resolution

MISSION: Understand the horizontal and vertical structure of rainfall and its microphysical elements. Provide training for constellation radiometers

CONSTELLATION SATELLITES

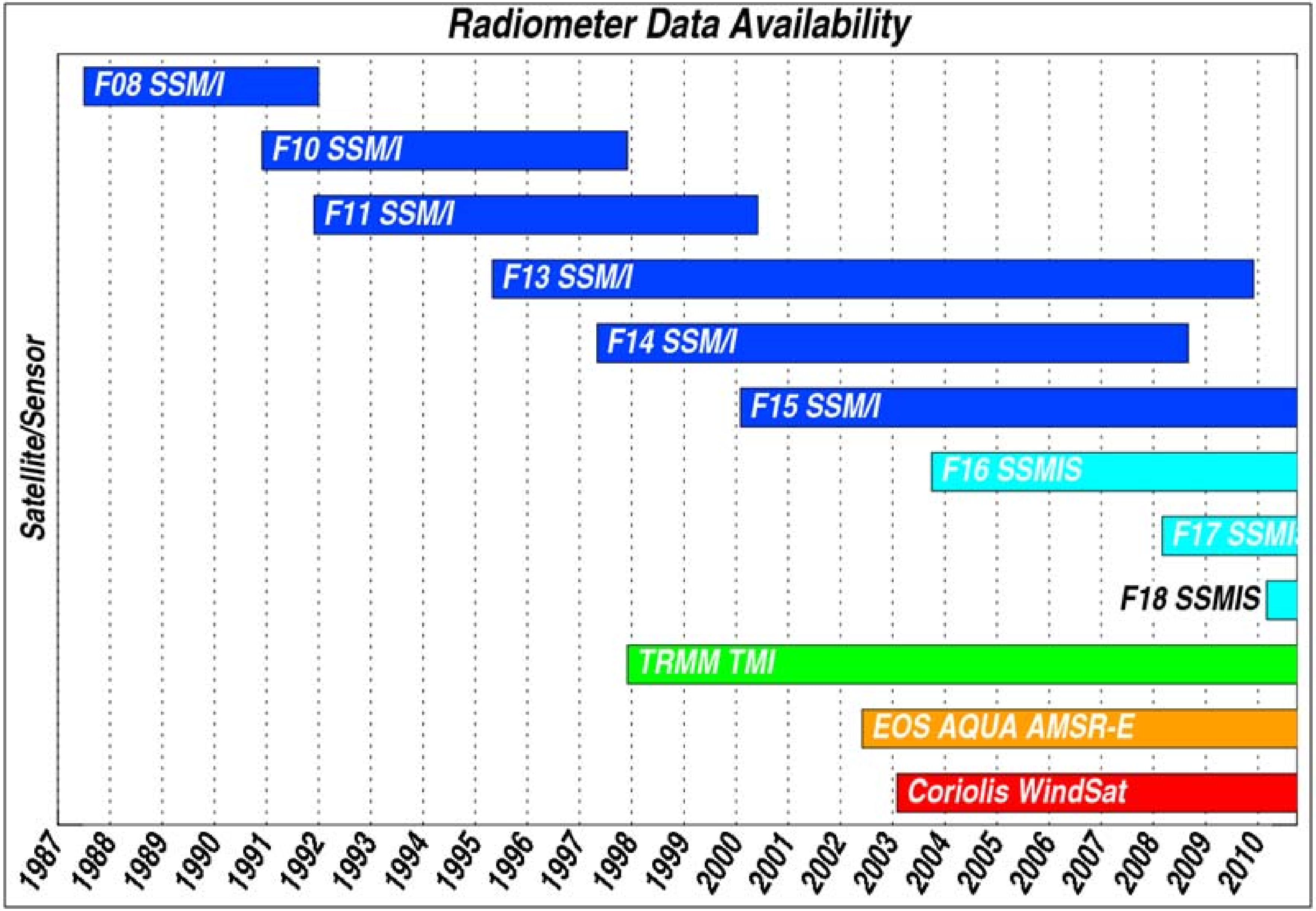
- ~8 satellites
- Radiometer only
- Rely on existing radiometers
- Multifrequency radiometer
- ~3 hour average revisit time

MISSION: Provide enough sampling to reduce uncertainty in short-term rainfall accumulations. Extend scientific and societal applications.

Outline

- Introduction
- Overview of NOAA SDS Project
- XCAL and other intercalibration activities
- Cross-track biases
- Ephemeris and geolocation errors
- Sun and incidence angles
- Diurnal variability
- Monitoring of changes in TBs over time
- Approaches to intercalibration
  - Simultaneous overpasses
  - TRMM crossovers
  - In-situ comparisons of geophysical parameters
  - Vicarious techniques
- Summary

Currently Available Radiometer Data



Differences in Sensor Characteristics

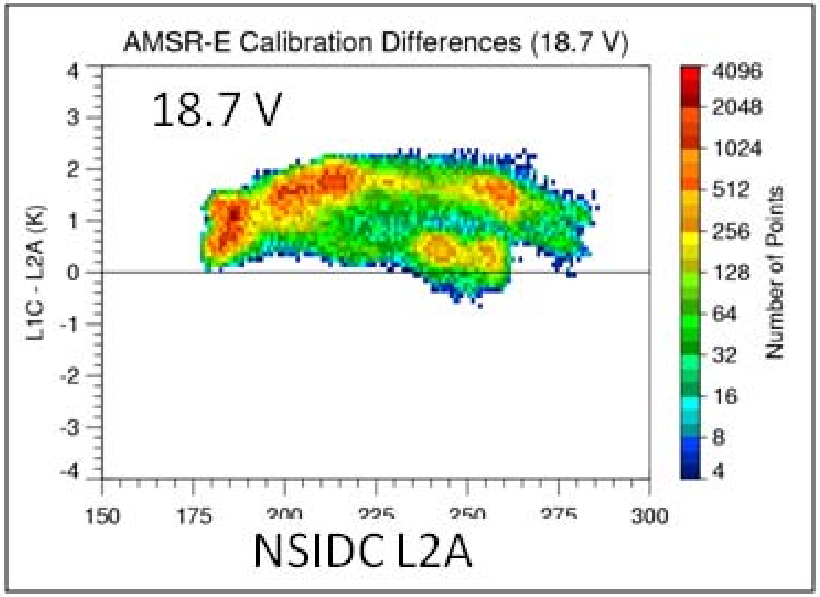
Sensors for GPM

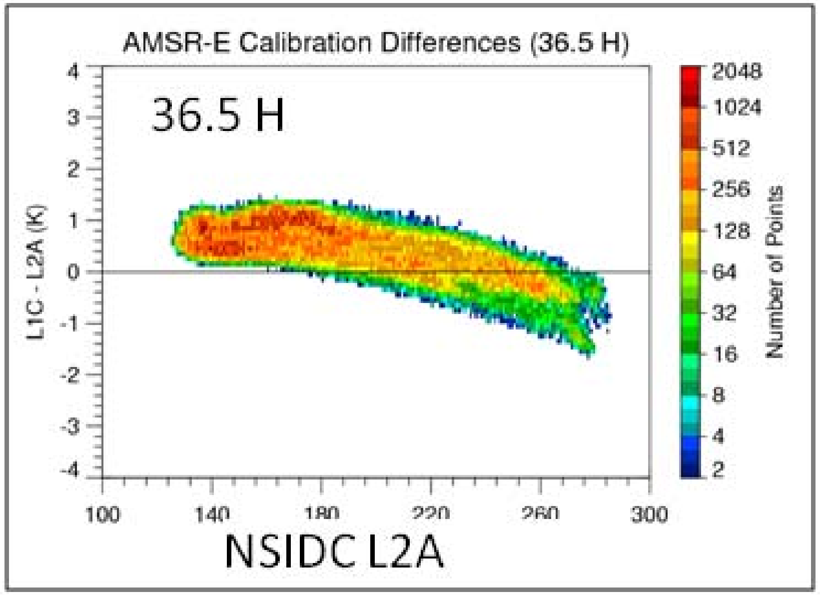
Sensor	Channel Frequency (GHz)								Inc Ang
TMI		10.7	19.4	21.3[a]	37	85.5			53.4°
AMSR-E	6.9	10.7	18.7	23.8	36.5	89			55.0°
SSM/I			19.4	22.2[a]	37	85.5			53.1°
SSMIS			19.4	22.2[a]	37	91.7	150[b]	183.3 ±1,3,7[b]	53.1°
WINDSAT	6.8	10.7[c]	18.7[c]	23.8	37[c]				49.9° - 55.3°

[a] V-Pol only; [b] H-Pol only; [c] V, H, +/45º, L, R

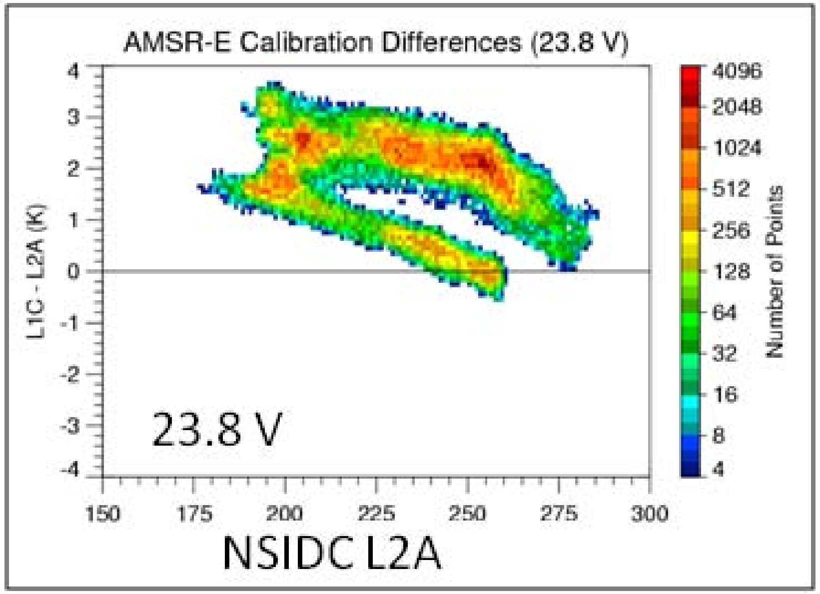
AMSR-E Calibration Differences

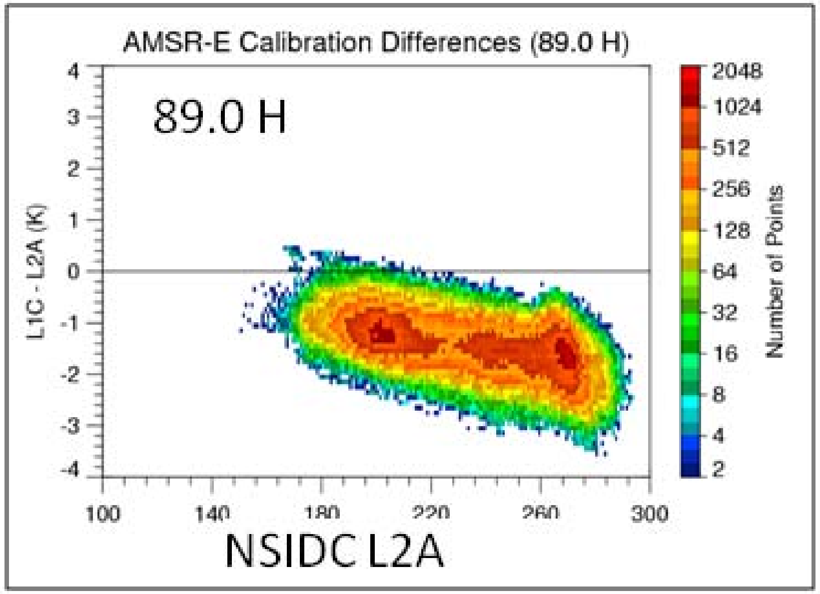
L1B – L2A



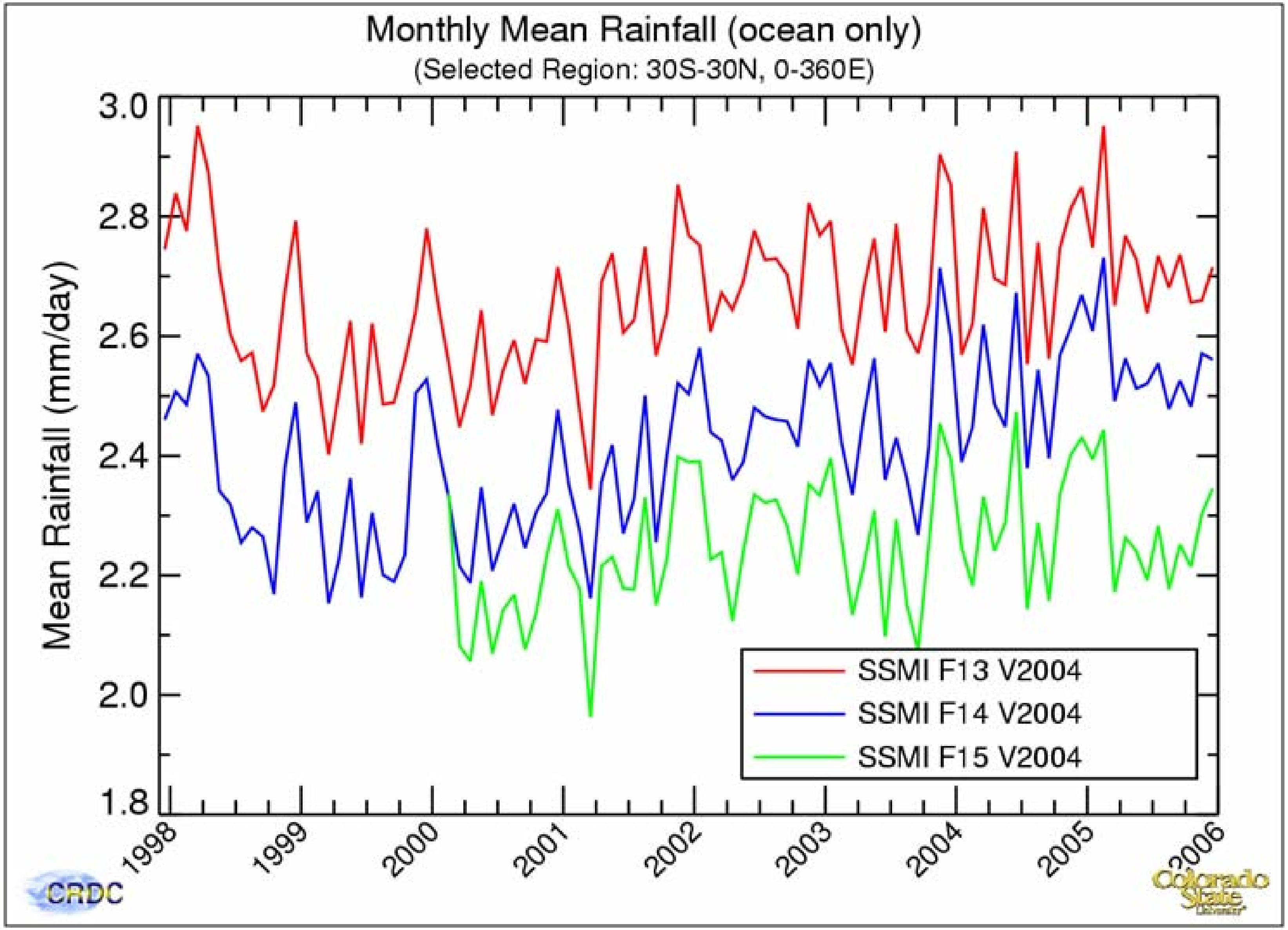


L1B – L2A





SSM/I Calibration



NOAA SDS Project

Create a Fundamental Climate Data Record (FCDR) of SSM/I and SSMIS

Goal

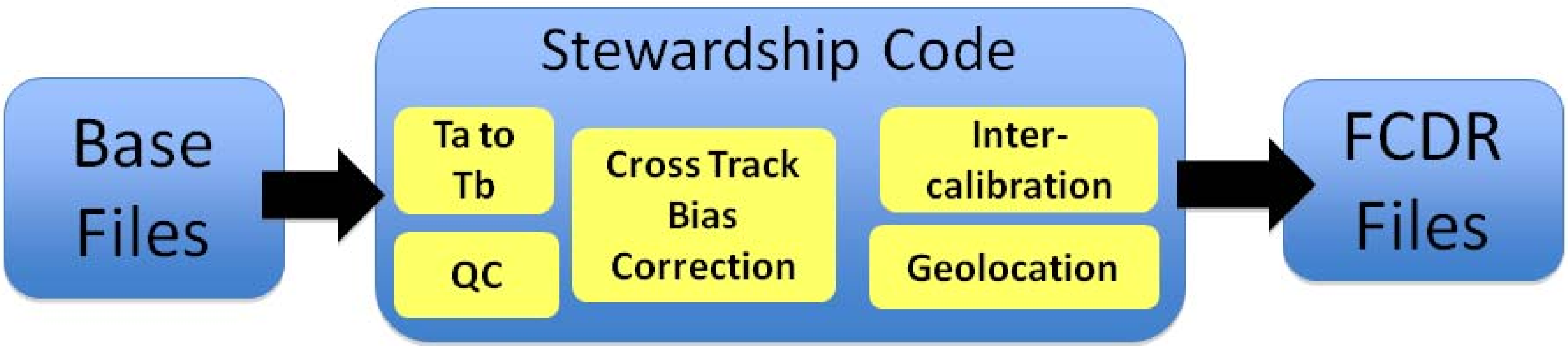
- Generate a transparent and documented Fundamental Climate Data Record (FCDR) of SSM/I and SSMIS brightness temperatures from 1987 - Present.
- Develop/implement multiple approaches for intercalibration and then identify and apply the best approach in the stewardship code to produce FCDR.

SSMI(S) FCDR Philosophy

- Science Data Stewardship must be an open and transparent process involving the broad science and user communities
- After an initial development period, we envision Science Data Stewardship to consist of a sustained level effort by the community that leads to occasional reprocessing of the data
- SDS is not a real time activity although some tools are being developed to monitor instrument stability. Because users will always press for faster release of products, it is important to plan for this from the onset of the activity.

SSMI(S) FCDR Approach

1. Reformat SSMI/SSMIS TDR files into NetCDF "Base files". These files contain all the original data and nothing is modified except to make orbit granules, add ephemeris and reformatted time, and reformat to NetCDF.
2. Create a well documented software package ("Stewardship code") that ingests the Base files, applies corrections (i.e QC, cross-track bias, TA-TB, geolocation, calibration) and outputs the final FCDR in NetCDF for use by the broader community.
3. Expert users can be given access to the Base files and the "stewardship code". This gives them access to the beta versions without confusing the general users.



SSMI(S) FCDR Intercalibration

- Sensor data must be physically consistent
  - Sensor still different due to differences in frequencies, view angles, resolution, observation time etc.
  - Geophysical retrieval algorithms must take into account sensor differences in order to create TCDR (eg: precipitation, wind, humidity, etc).
- Investigate calibration differences using multiple approaches [described later].
  - Consistency/inconsistency between approaches will provide insight into methods as well as estimate of the uncertainties.
- Goal is to understand any differences and use sensor information to select correct solution. If not possible, will select one method and use others to describe uncertainty in Version 1 of the FCDR.

Known issues/risks

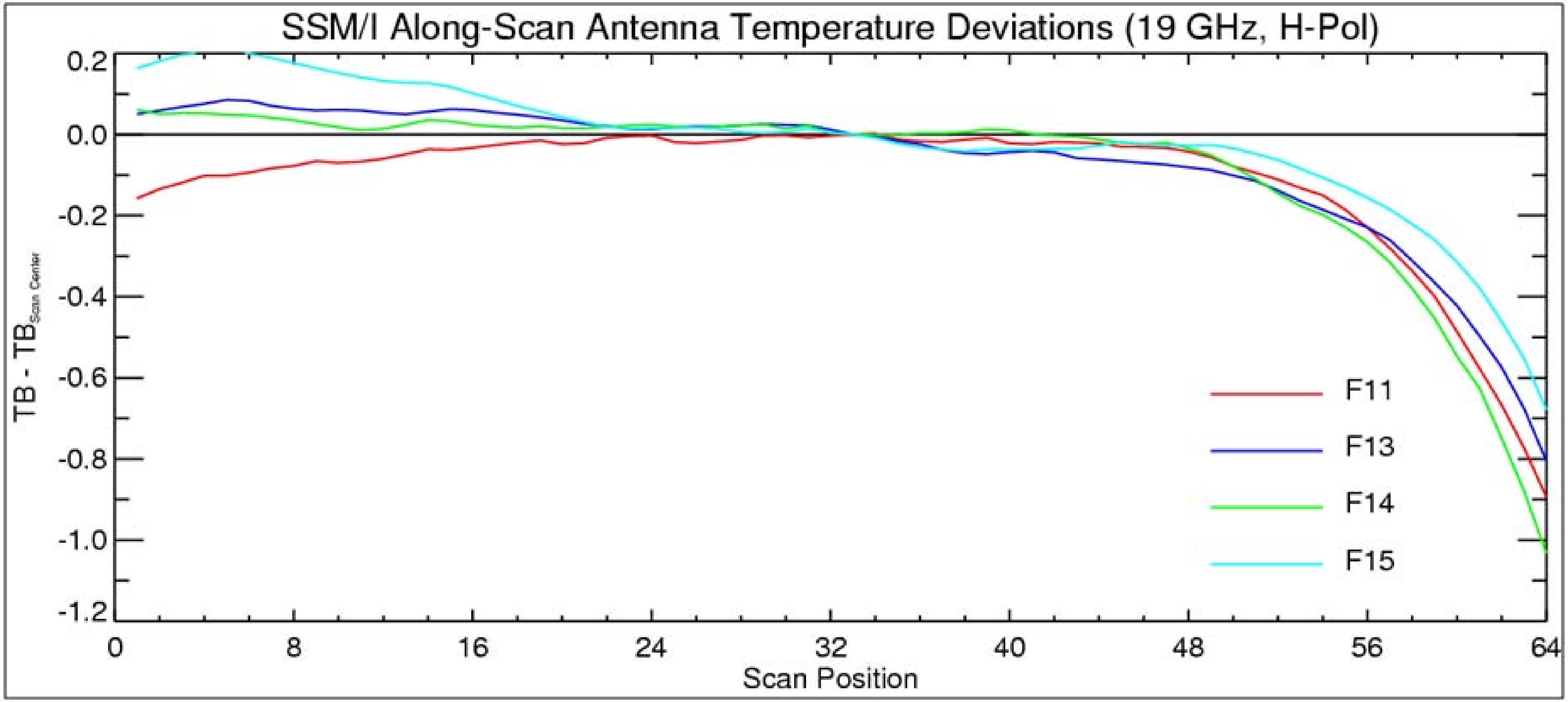
- Inconsistency between Calibration Methods
  - Using multiple approaches will help to identify problems and estimate uncertainties.
  - Ultimately stewardship must allow for future investigators to look into discrepancies and develop new/improved techniques/approaches.
- Geolocation Errors
  - Difficulty in separating effects of spacecraft orientation from other issues.
  - Limitations in determining spacecraft attitude
- Other sensor Issues
  - Warm versus cold end calibration, nonlinearities etc.
  - Unknown error sources that can be difficult/impossible to quantify/correct.

Xcal and other intercalibration activities

- XCAL is a working group of the NASA Precipitation Measurement Missions (PMM) project whose goal is to intercalibration available radiometers for GPM.
  - Meets ~2-3 times per year
  - Comprised of multiple institutions/groups who have developed different techniques for intercalibration.
  - Working group consists of experts in both engineering and science application aspects of radiometers
  - Responsible for developing intercalibration adjustments for Level 1C Data (Intercalibrated TB dataset for GPM).
- GSICS – Global Space-based Inter-Calibration System
  - Effort is focused on operational weather satellites and funded by operational agencies
  - http://www.wmo.int/pages/prog/sat/GSICS/

Cross Track Biases

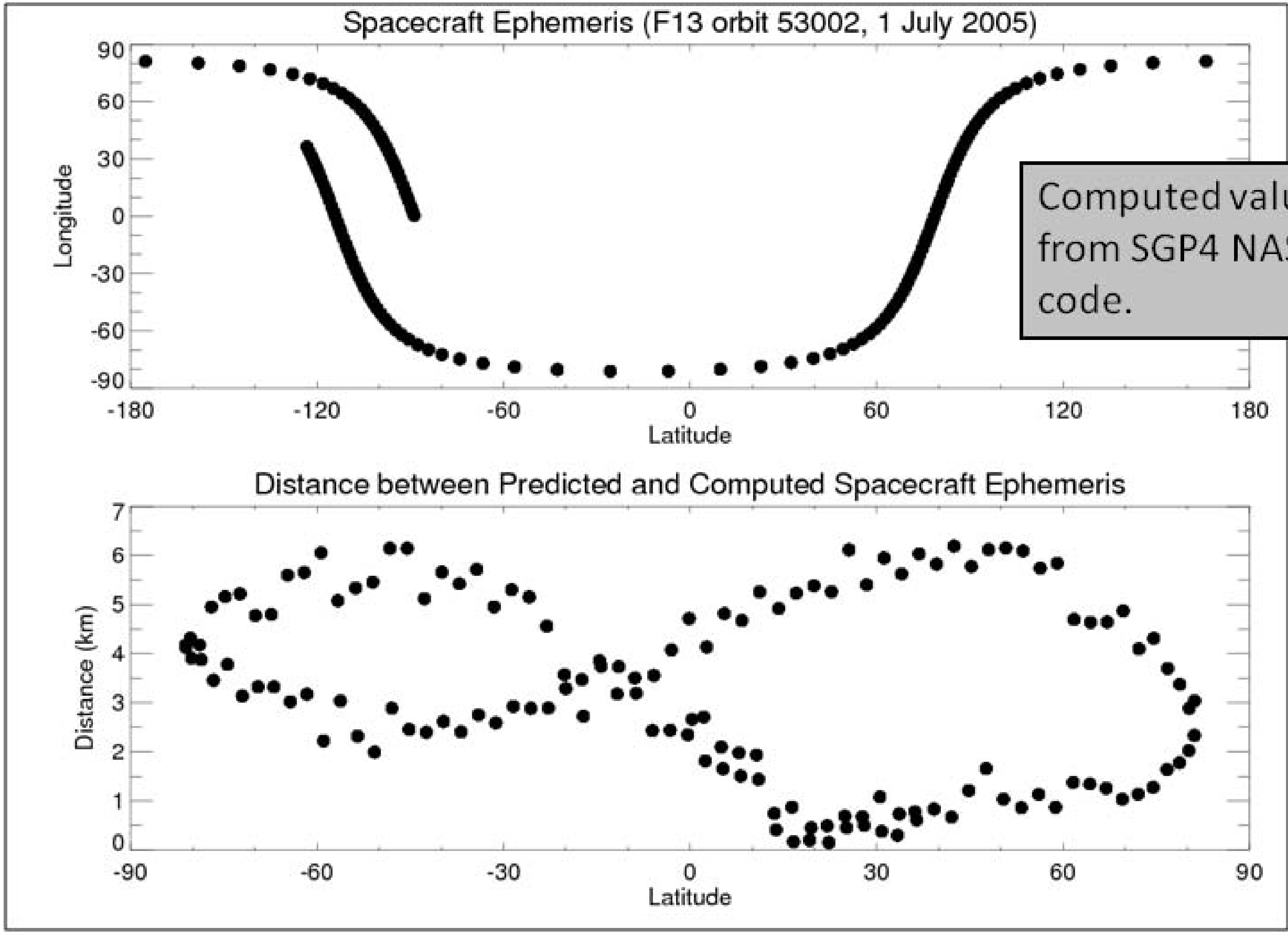
- Caused by partial beam blockage or other (unknown?) issues



Spacecraft ephemeris and pixel geolocation

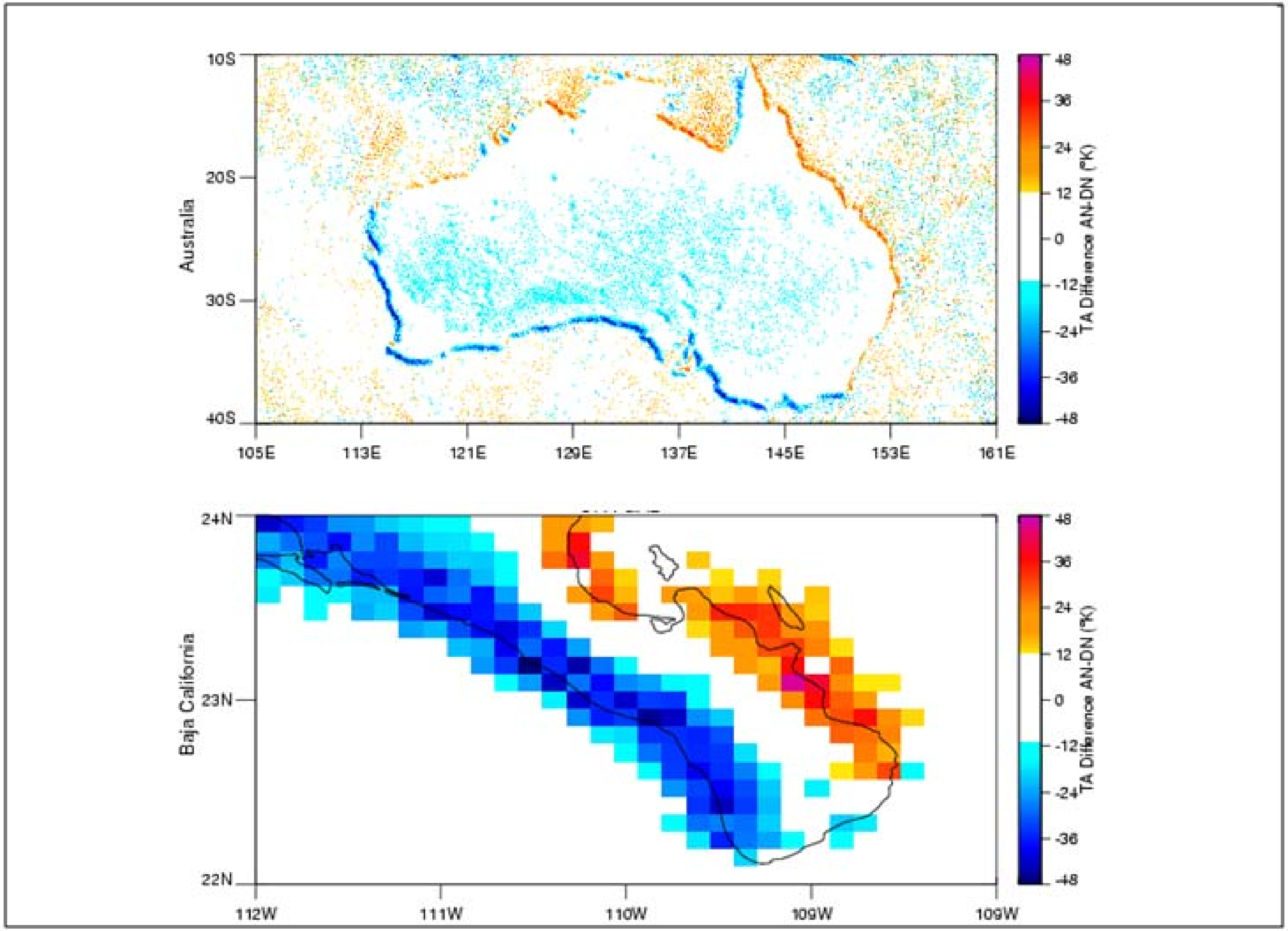
- Many operational satellites such as SSM/I on board the DMSP spacecraft use predicted ephemeris.
- Spacecraft ephemeris are recomputed using 2-line element data and SGDP4 code.
- Pixel geolocation depends on accurate spacecraft ephemeris and pointing information (spacecraft attitude and sensor alignment).
- Retrieval algorithms are often sensitive to the EIA or view angle of the sensor.

Predicted vs computed spacecraft ephemeris

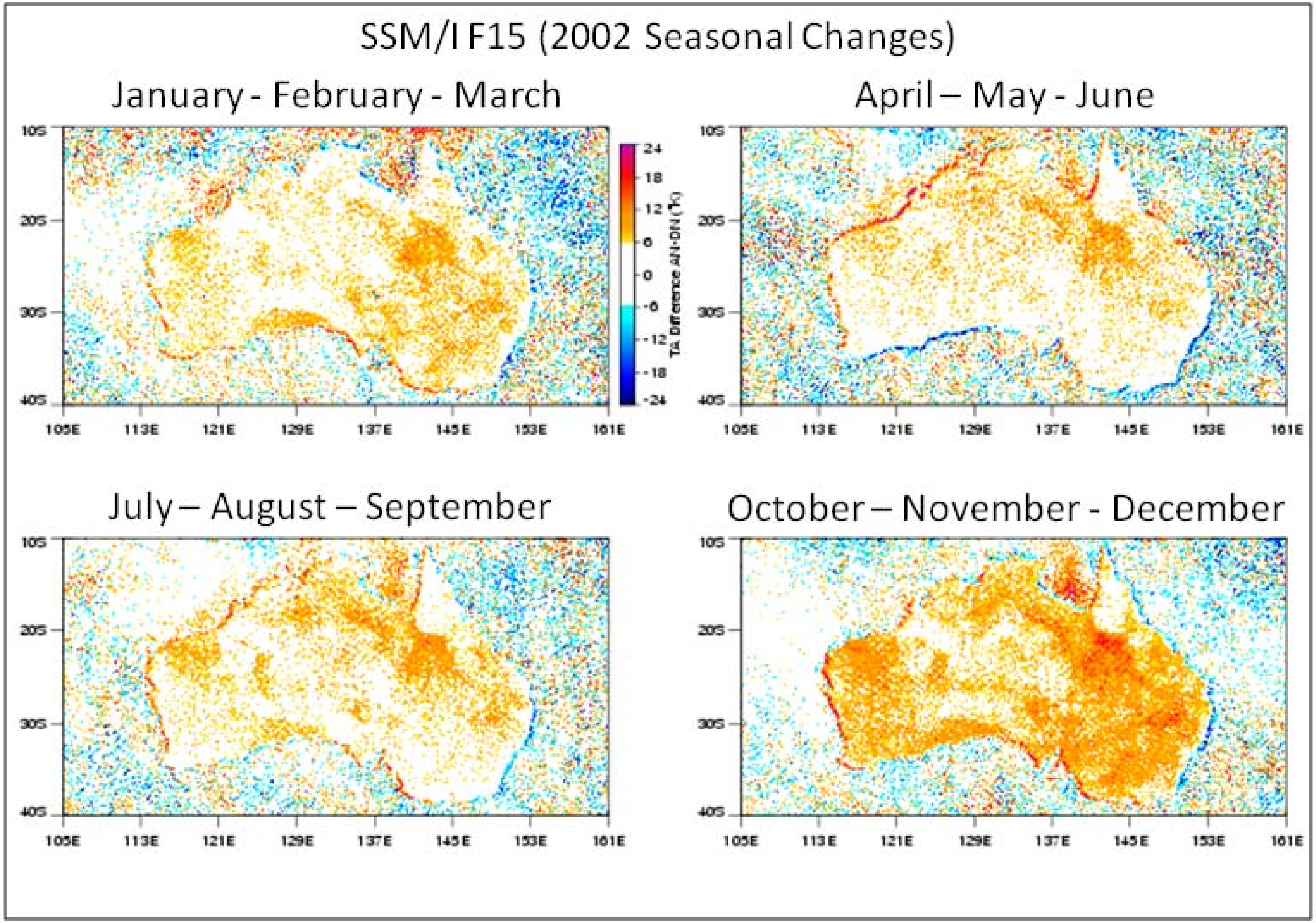


Computed values derived from SGP4 NASA/NORAD code.

Ascending/descending pixel geolocation differences

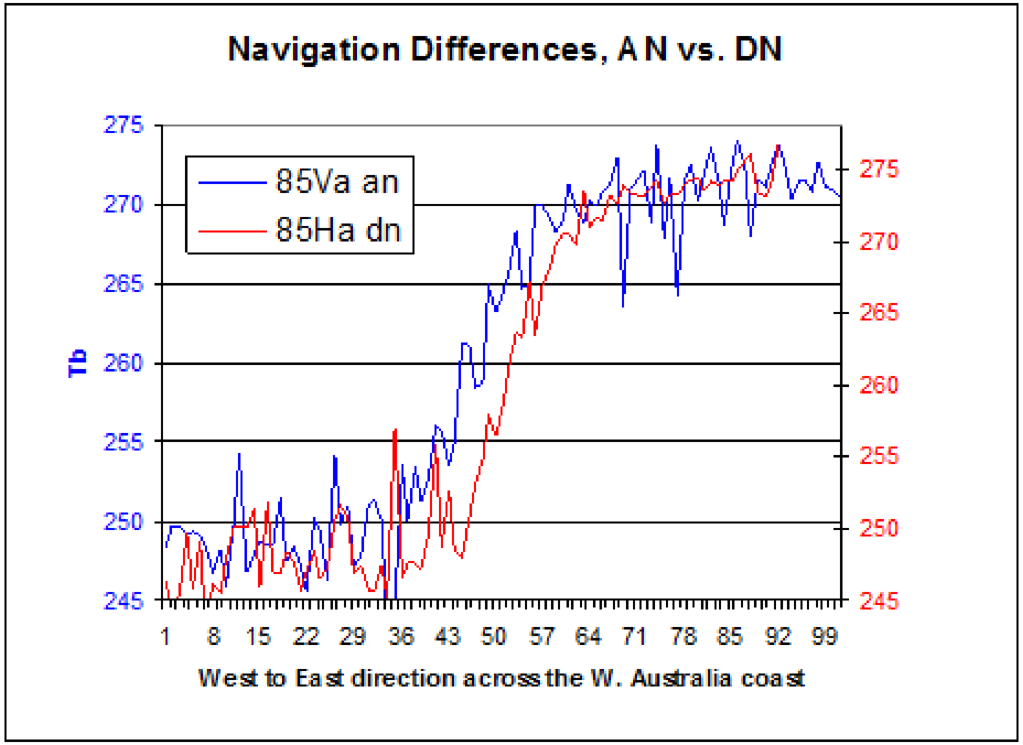


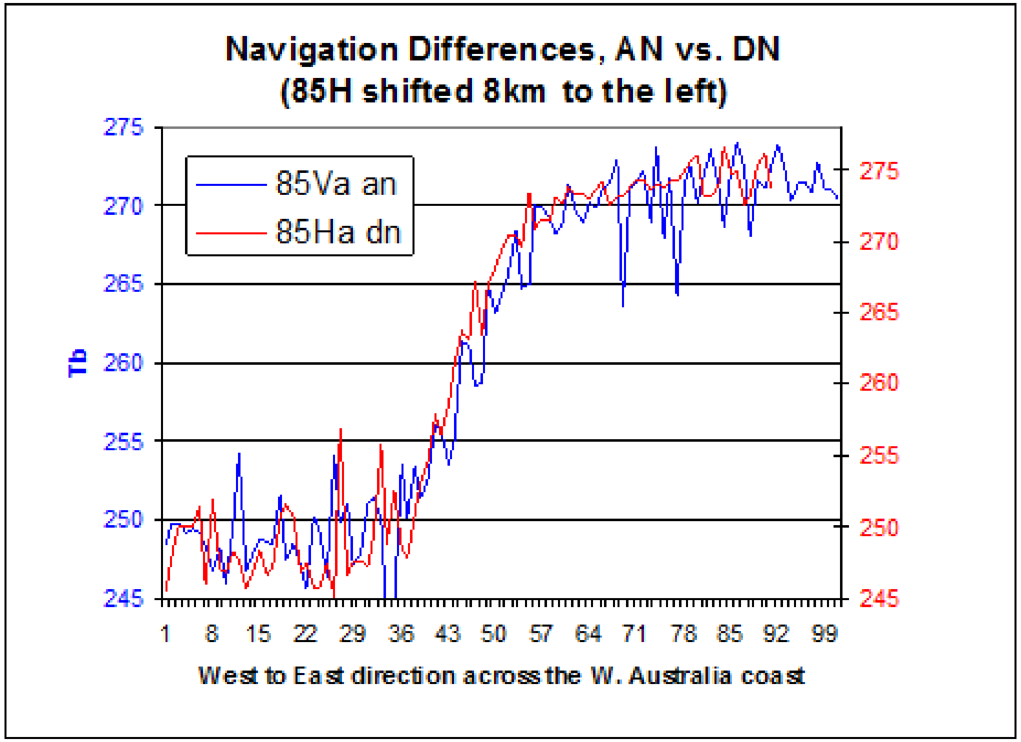
Ascending/descending pixel geolocation differences



Ascending/descending pixel geolocation differences

Example of differences in coast line location





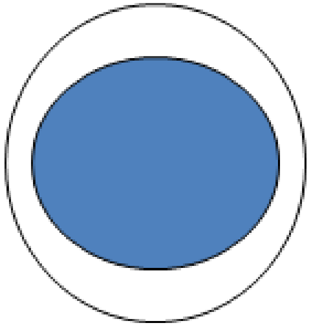
Sun and Incidence Angles

Notes for presentation at
GPM Intercalibration Working Group
August 3, 2008

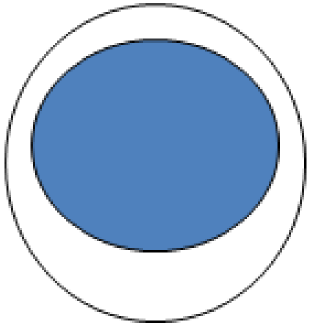
Steve Bilanow
Wyle Information Systems
SESDA II contract support for the
Precipitation Processing System (PPS)

Altitude Sensitivity

Even a perfectly circular orbit has some altitude variation due to Earth Oblateness. (Earth 23 km flatter at poles.) Additional variation results from orbit eccentricity.

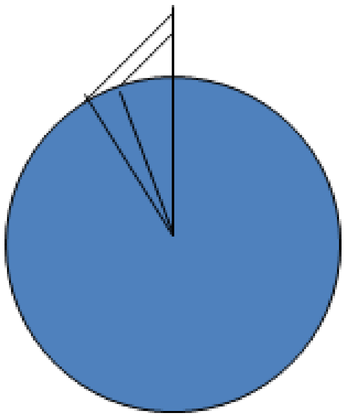


e.g roughly circular

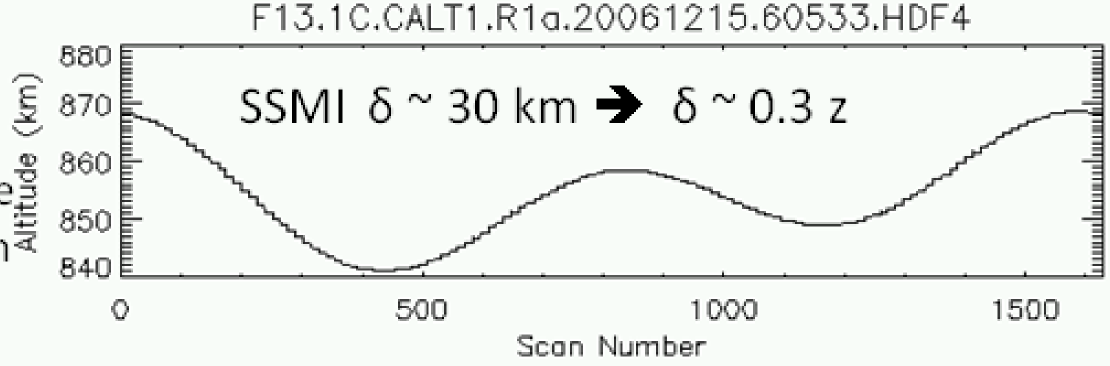


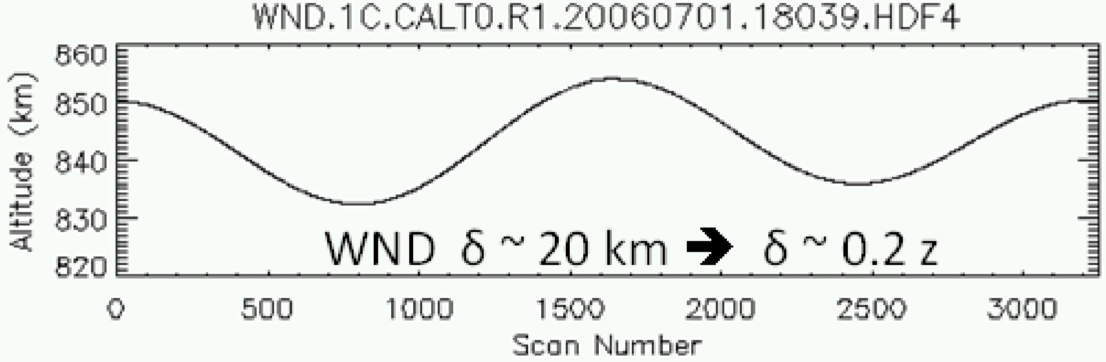
e.g eccentric, frozen

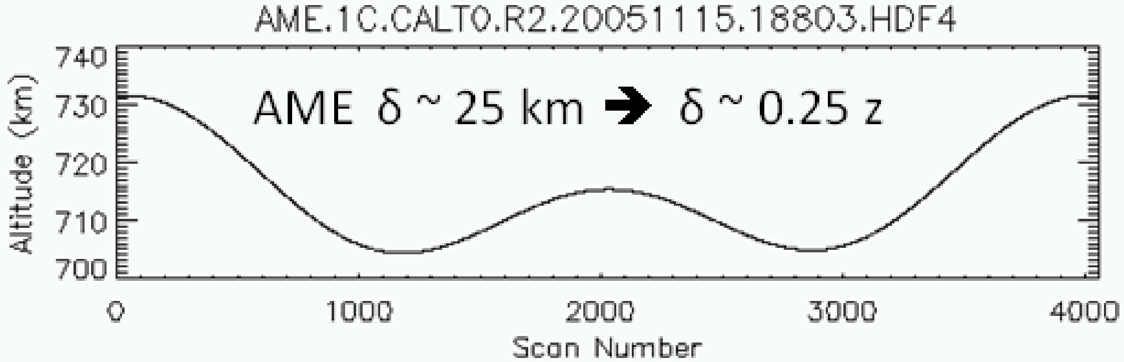
Altitude affects Earth Incidence Angle due to Earth's Curvature

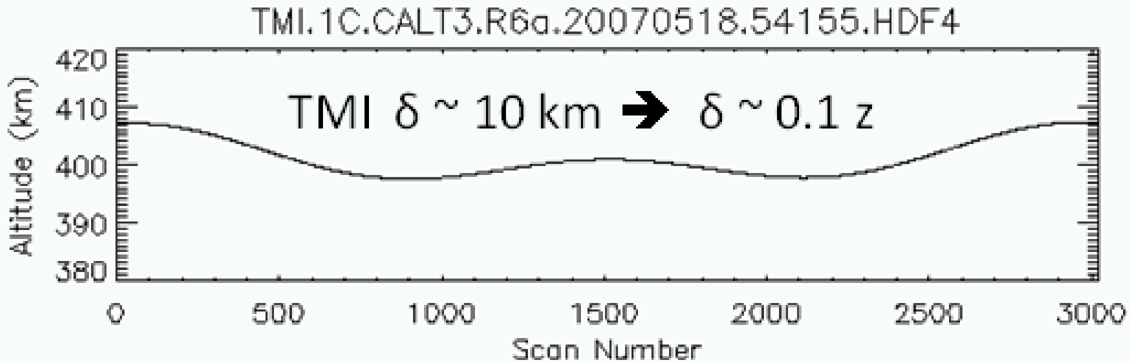


Roughly 0.1 degree per 10 km change.



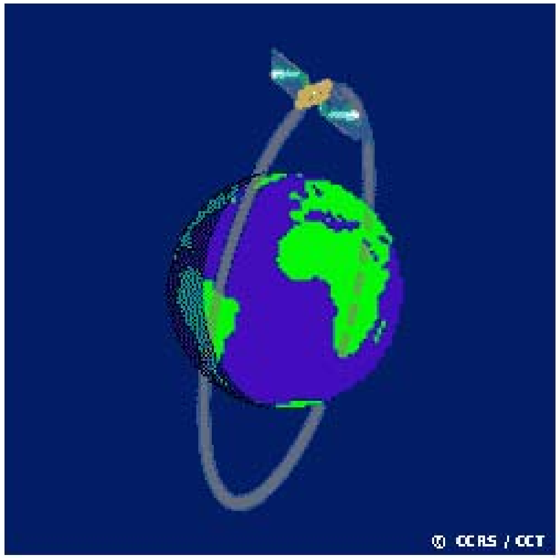


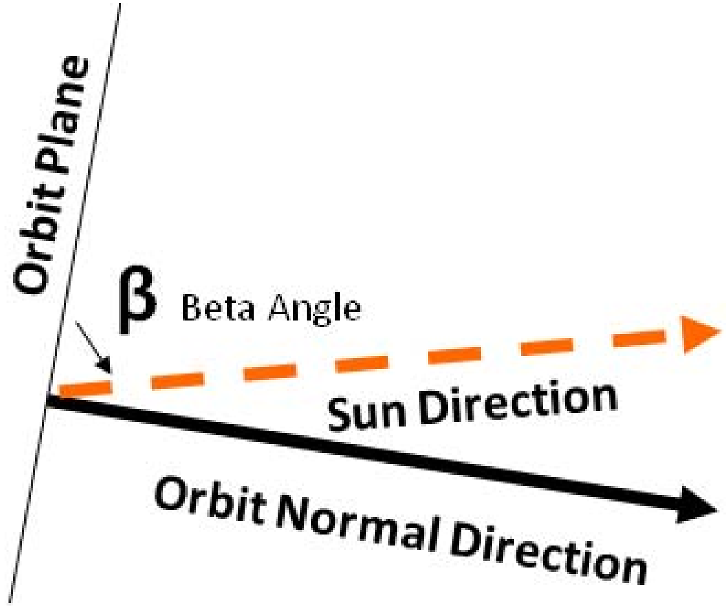




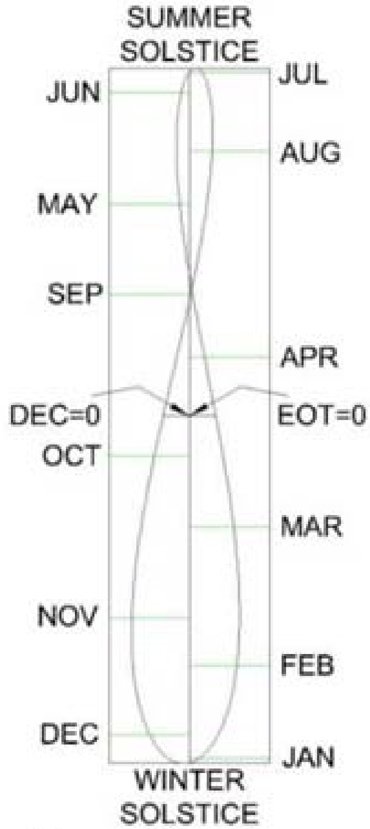
Solar Beta Angle

- **Beta Angle, β : the Sun elevation above the orbit plane (positive toward the positive-orbit-normal direction).**
- **Affects illumination and thermal environment.**





Orbit Illustration: Typical inclination for Sun Synchronous Orbit shown with Dusk Ascending Node on Earth's far side (similar to F13, F14, and Windsat orbit geometry).



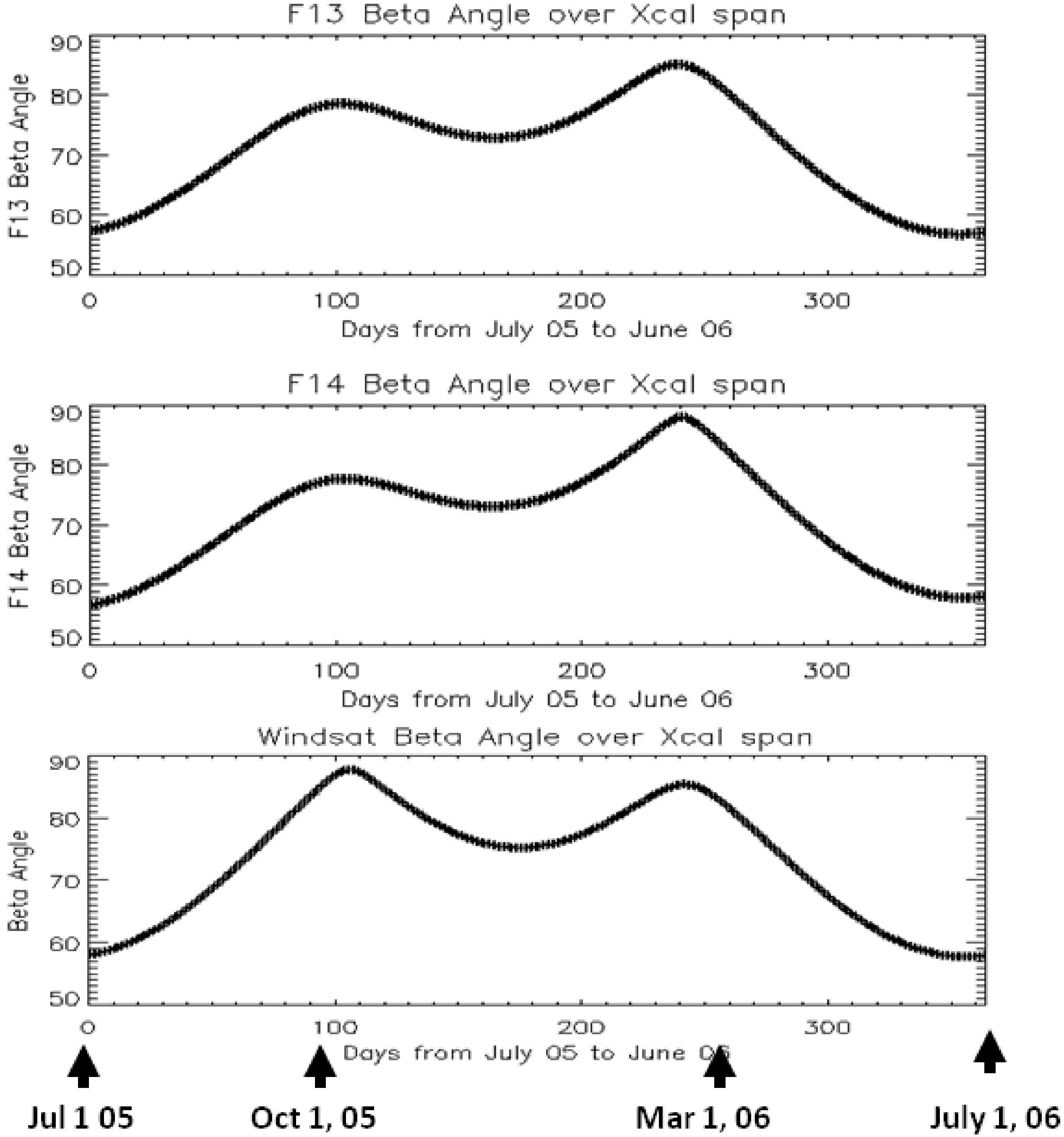
Analemma : Annual Path of Sun direction as seen at noon from Earth.

Solar Beta Angle History for Intercalibration Span

F13 SSMI

F14 SSMI

Windsat



TRMM V7 Correction and Angle Issues

Presentation material for GPM inter-calibration working group meeting, May 19, 2009

Sayak Biswas, Dr. Linwood Jones

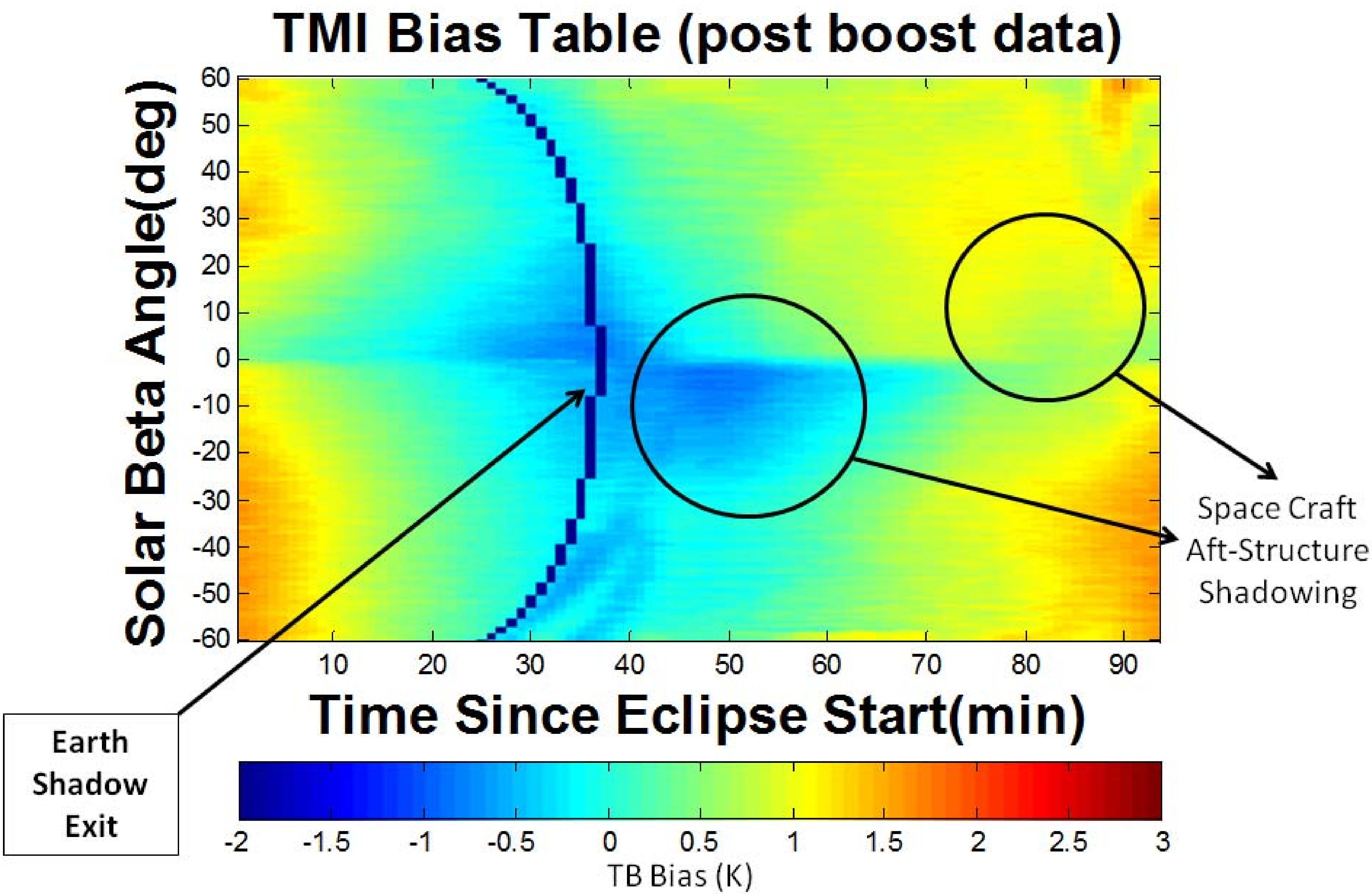
UCF, CFRSL

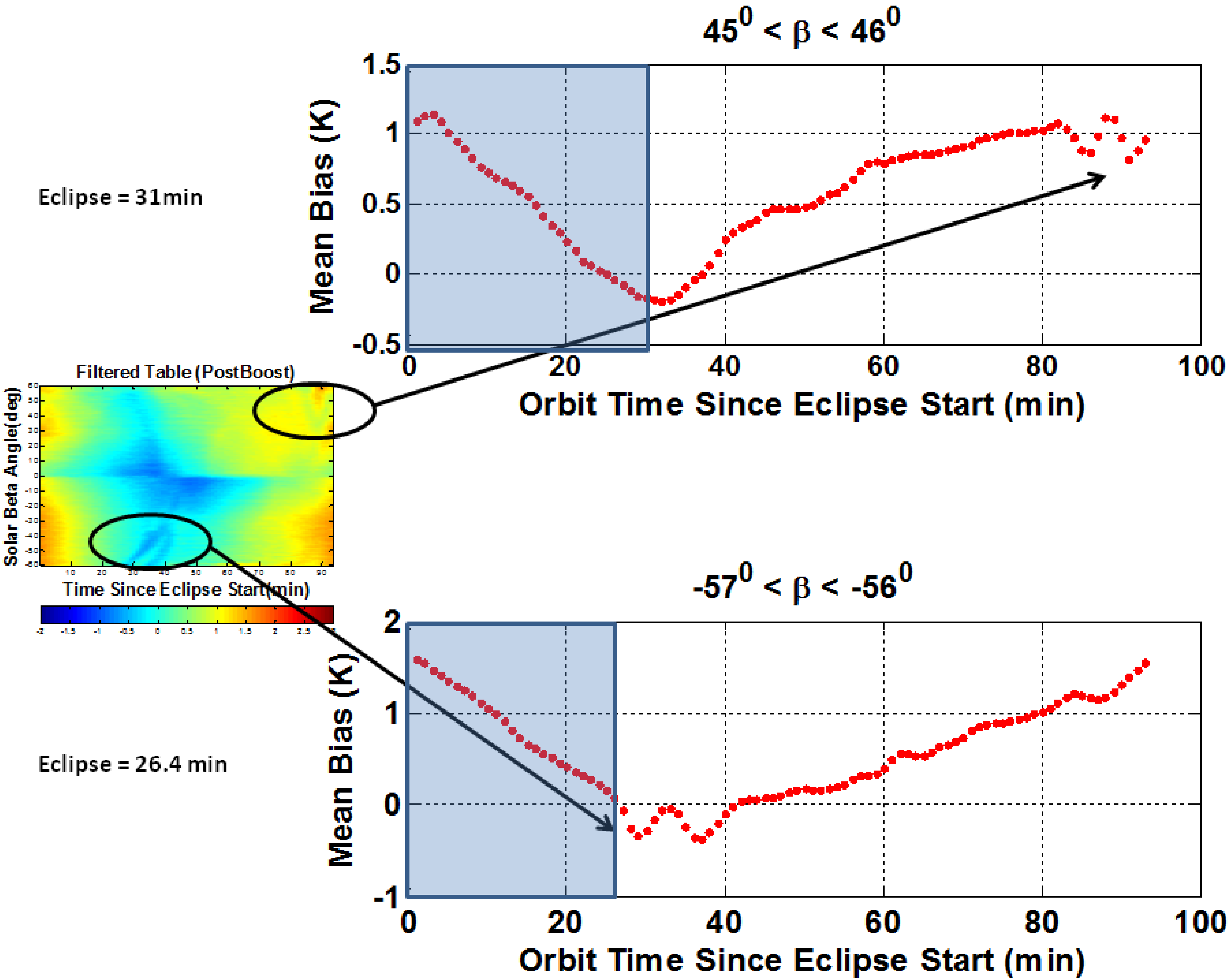
Dr. Kaushik Gopalan

UMD, ESSIC

Steve Bilanow

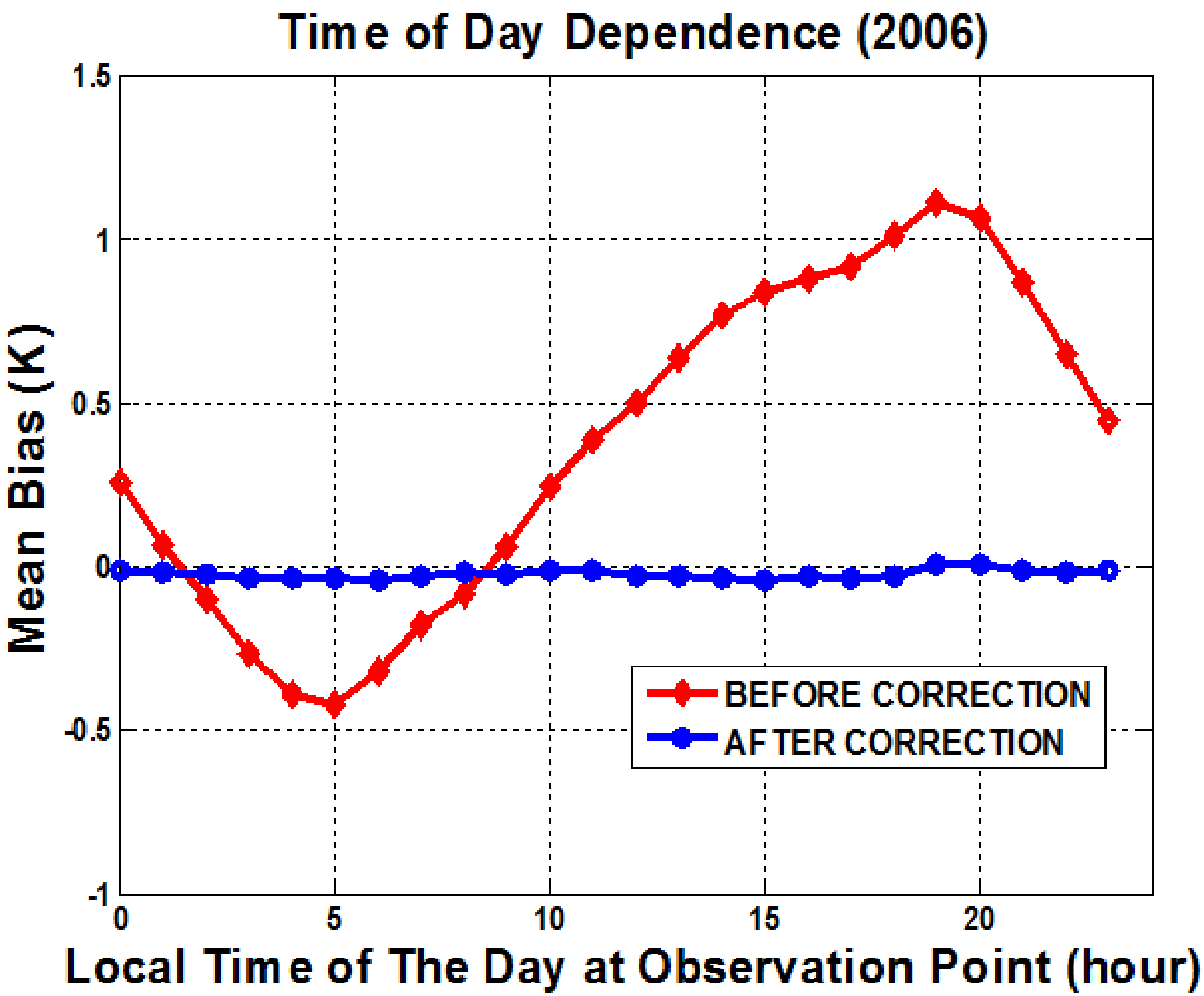
Wyle, PPS


TMI Bias Table (post boost data)
Solar Beta Angle(deg)
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
10
20
30
40
50
60
70
80
90
Time Since Eclipse Start(min)
Space Craft
Aft-Structure
Shadowing
Earth
Shadow
Exit
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
3
TB Bias (K)

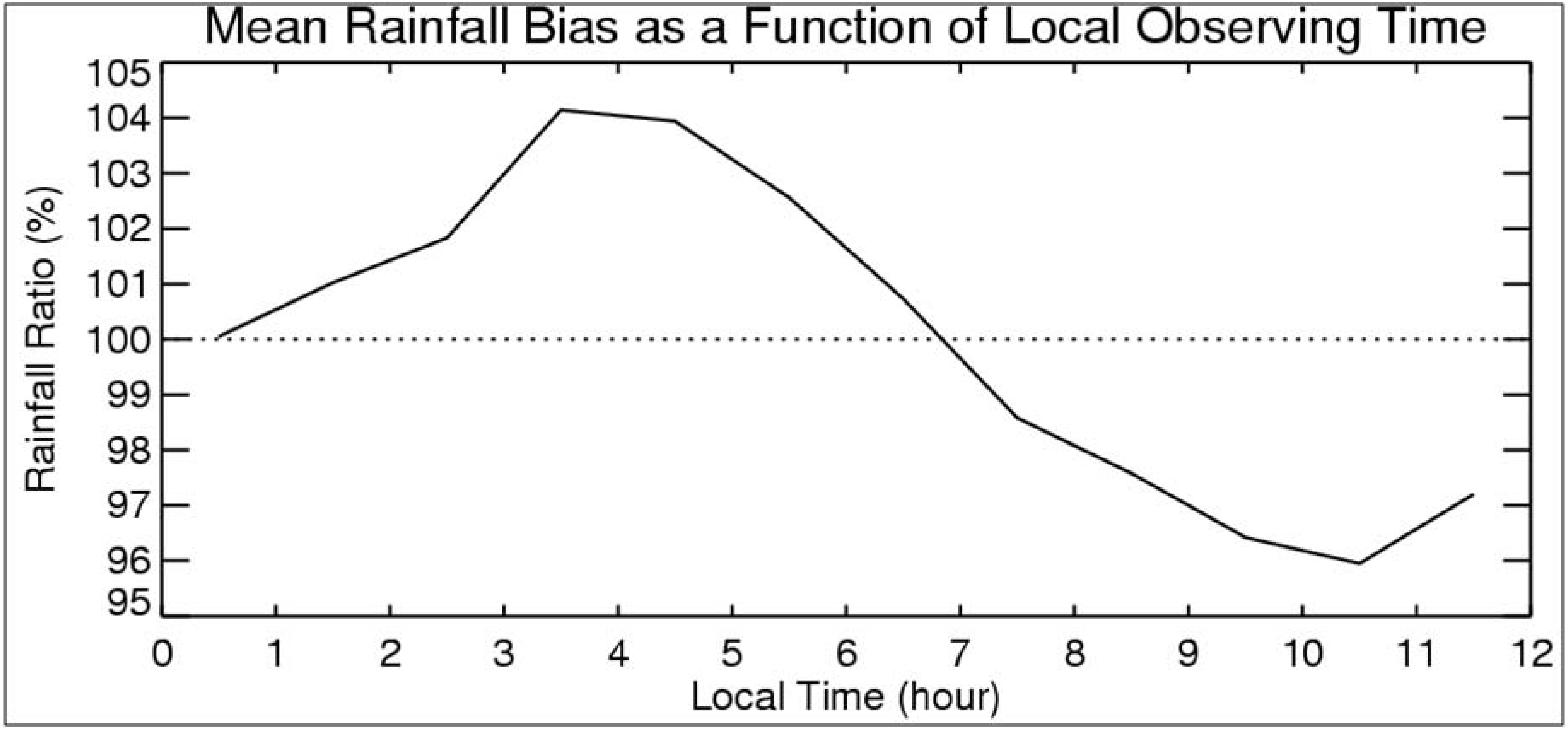


$45^0 < \beta < 46^0$
Mean Bias (K)
1.5
1
0.5
0
-0.5
0
20
40
60
80
100
Orbit Time Since Eclipse Start (min)
Eclipse = 31min
Filtered Table (PostBoost)
Solar Beta Angle(deg)
Time Since Eclipse Start(min)
$-57^0 < \beta < -56^0$
Mean Bias (K)
2
1
0
-1
0
20
40
60
80
100
Orbit Time Since Eclipse Start (min)
Eclipse = 26.4 min

Time of Day Dependence

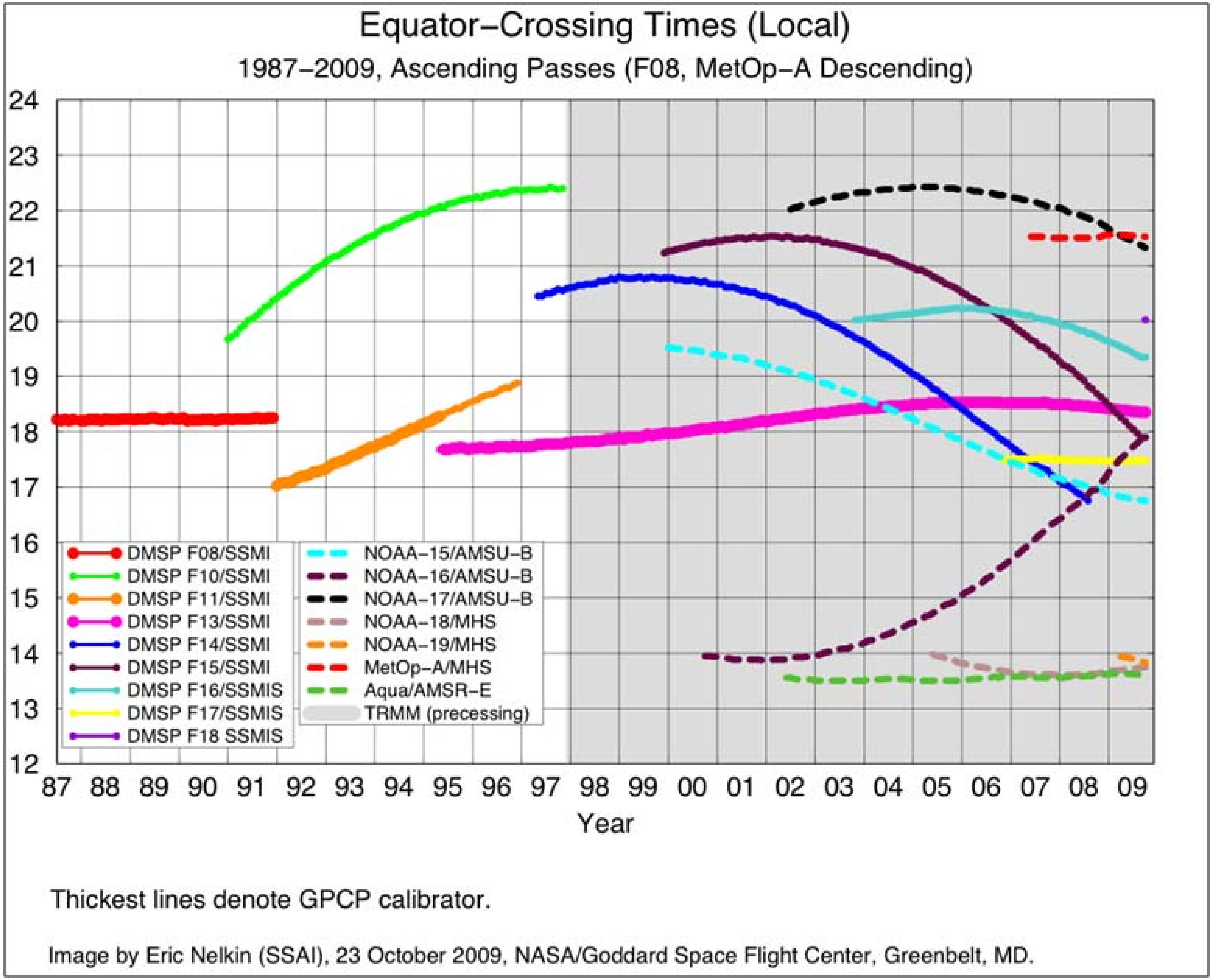


Diurnal Impacts



- It is important to properly account for these differences when comparing TBs from different satellites
- The intercalibrated brightness temperatures (i.e. FCDR) should retain these differences.

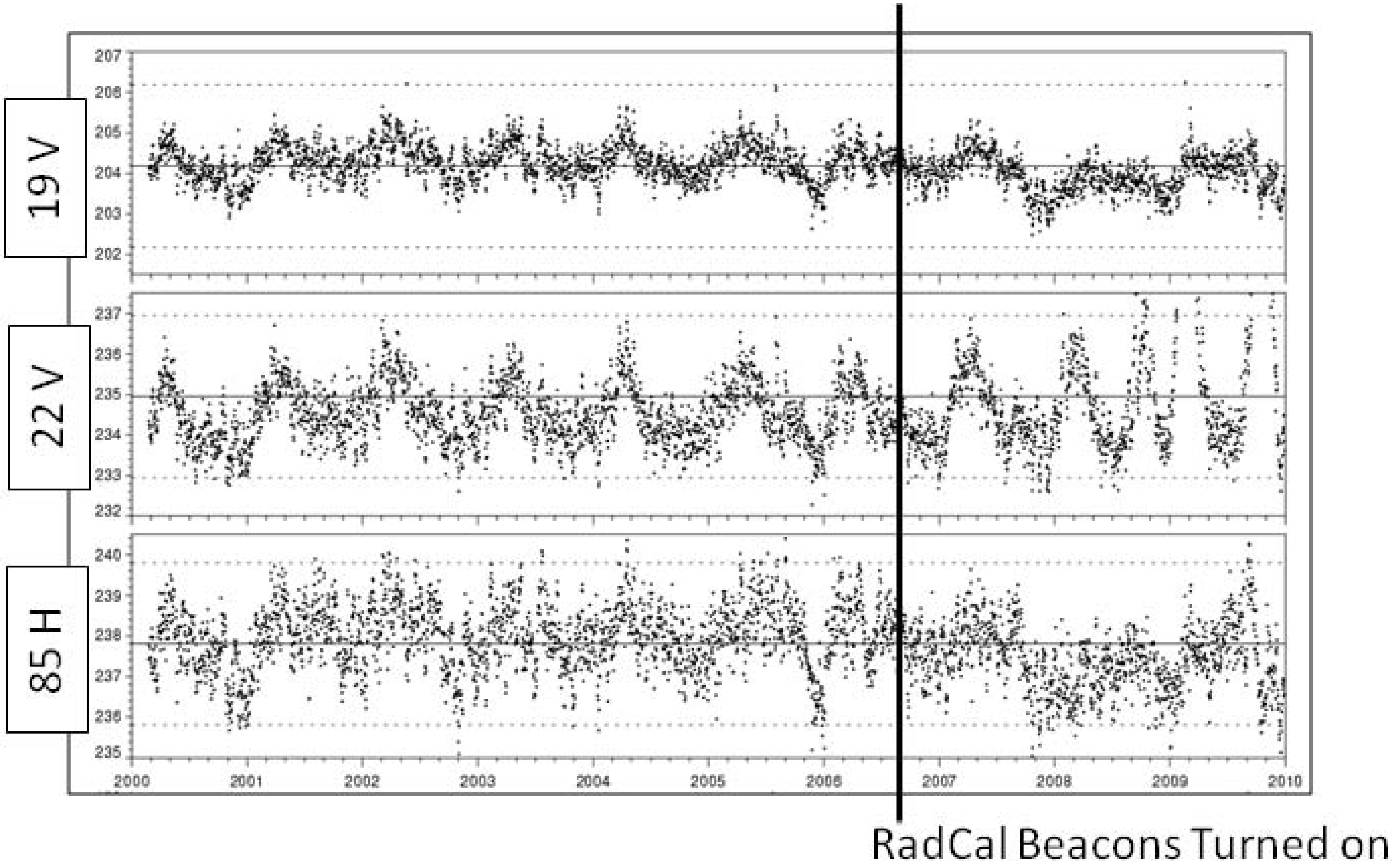
Window Channel Radiometer Record



Monitoring TBs

SSM/I F15 RADCAL issue: beacon was switched on in 2006, lead to severe interference

- Important to monitor satellites for calibration issues



Intercalibration

- Satellite providers deal with the *absolute calibration* of satellite observations
  - Errors can be large (1-2K)
  - Providers do not use same technique or standard so absolute cals differ
- Projects such as NOAA SDS and NASA GPM need consistent estimates from several satellites
  - Seek to intercalibrate the satellites to within ~.1-.2K
  - Goal is to estimate adjustments to TBs for each channel so as to make observations consistent with some *calibration standard*
  - Calibration standard choice not easy and might be arbitrary/political
  - Aim to make sensors physically consistent (not correct channel diffs, etc)
- Intercalibration often takes the form of simple offsets, although TB dependent adjustments may be more appropriate
  - How do we calculate TB-dependent adjustment? Need to use techniques that cover a large portion of TB space
  - Need at least 2 points: low and high TB

Intercalibration techniques

- Different satellites have different sampling characteristics, so intercalibration has to use a common target
  - May need to account for Incidence angle, channel differences
- The following is not an exhaustive list, but does encompass the techniques used by XCal and for the CSU SDS project

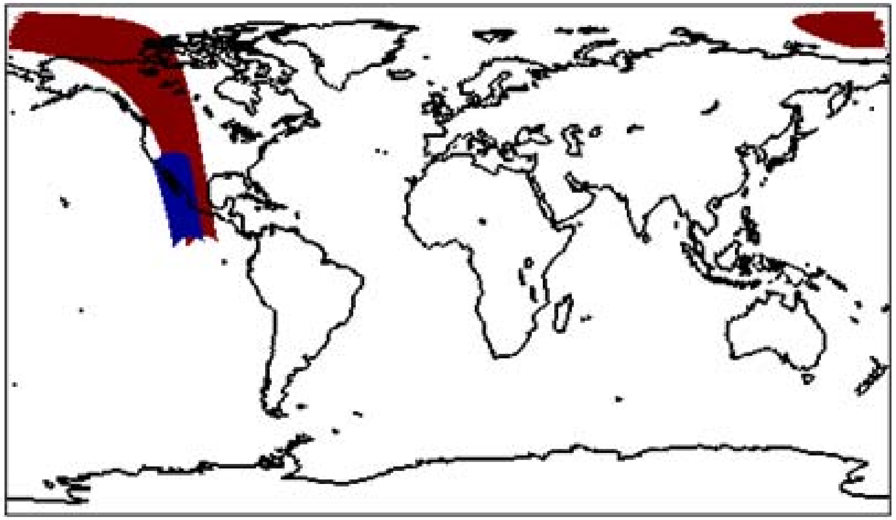
1. Direct comparison of satellites being intercompared
   - For polar orbiters, this takes the form of polar matchups
   - Matchups are available elsewhere if one of the satellites is not in a non-Sun-synchronous orbit (TRMM, GPM core)
2. Comparison of each satellite with a non-Sun synchronous satellite
3. Comparison with a fixed target
   - Target could be an in situ observation related to TBs by a geophysical retrieval
   - Target could be a strictly homogeneous area (not many of these exist)
4. Calculation of some fixed reference point with known properties
   - Only example of this is from Vicarious calibration

1. Polar Matchups

- This technique allows direct comparison of two polar orbiting satellites by finding instances where the paths of the satellites intersect at the poles
  - Note that a limited range of TBs may be observed at poles
- This technique has been primarily used in cases where the satellites are very similar and so direct comparison is acceptable
  - The main issue is incidence angle dependence although channel differences are also important
  - Note that EIA is fixed across the scan for conical scanners (such as SSM/I and SSMIS)
    - Sometimes called Simultaneous Conical Overpass (SCO)
  - EIA may not be stable (ie: not a conical scan; spacecraft attitude issues), so sometimes use only nadir pixels
    - This approach sometimes called Simultaneous Nadir Overpass (SNO)

1. Polar Matchups

- Animation shows ~30 minutes of F13 and F14 swath
- Overlaps at poles are relatively common within 30 min window
  - Such a window is probably OK, but shorter windows have been used

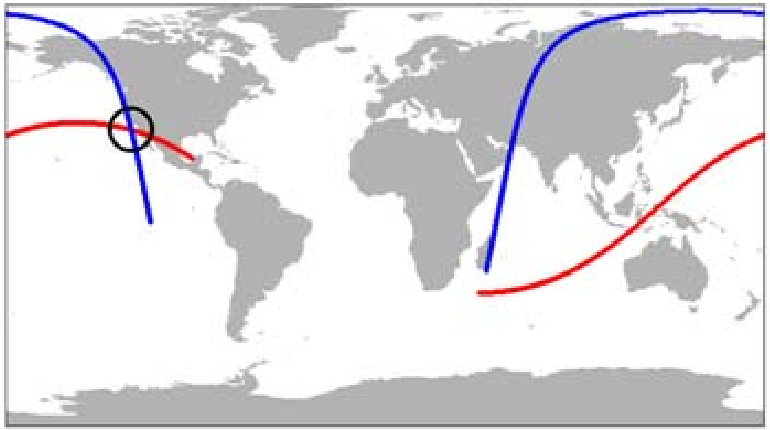


- Method:
  - Find matchups for each channel for the two satellites of interest
  - Calculate mean difference between the TBS for each of the satellites
  - This yields the calibration between the two sensors
- If direct comparison was not possible (eg: SSMI 85GHz and SSMIS 91GHz channels) then radiative transfer calculations could be used to simulate and compare (see next technique)

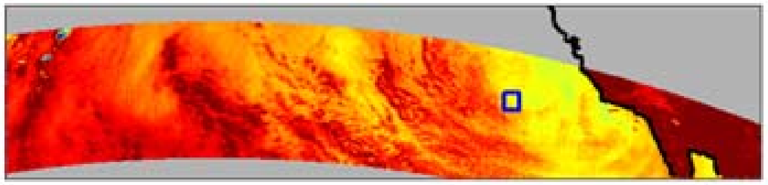
2. Comparison with TRMM TMI

- Get the matchups between SSMI and TMI
  - Obtain points where SSMI and TMI groundtracks cross within 30 minutes & 50km (exclude duplicates within 60 seconds of each other)
  - Calculate 1° average Brightness Temperature (Tb) for each sensor
  - Include only clear sky: require that SD(85GHz) < 5K
- Matchups between (eg) SSM/I and TMIare not directly comparable due to EIA differences and slight channel differences

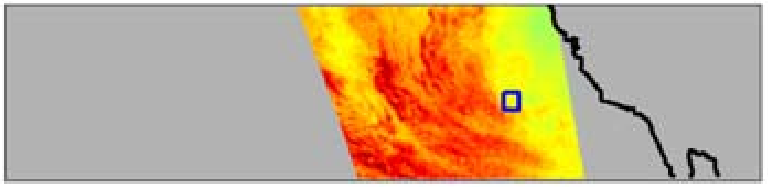
SSMI and TMI Ground tracks for 2-3am on 20 Nov 2004



TMI 85V

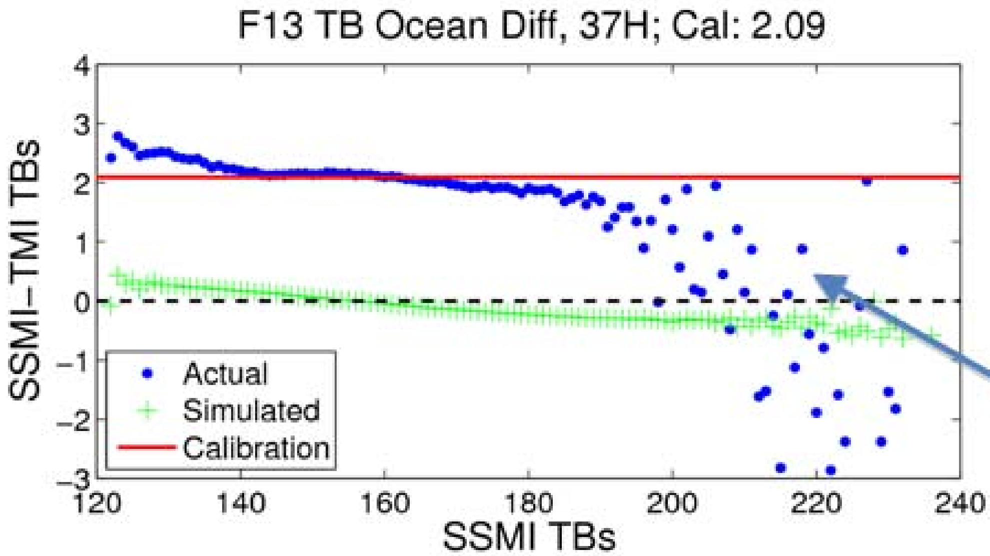


SSMI 85V



Removal of sensor dependent differences (CSU technique)

- Use Elsaesser and Kummerow (2008) Optimal Estimation (OE) approach to retrieve clear sky geophysical parameters (Wind, TPW, LWP) from TBs and SST (Reynolds)
  - Technique finds optimal geo parameters given TBs based on inversion of a Radiative Transfer (RT) model
- Use OE to get Geophysical parameters from TMI TBs
  - Use same RT model to simulate idealized TMI TBs from geo parameters
  - Use RT again to simulate SSMI TBs based on same geophysical parameters
- Compare difference between simulated TBs ($SSMI_{sim}$-TMI_{sim}) with difference between actual TBs (SSMI-TMI) to get calibration offsets
  - Note limited range of TBs for which this is valid



Green crosses show what SSMI-TMI should be if IA was the only difference

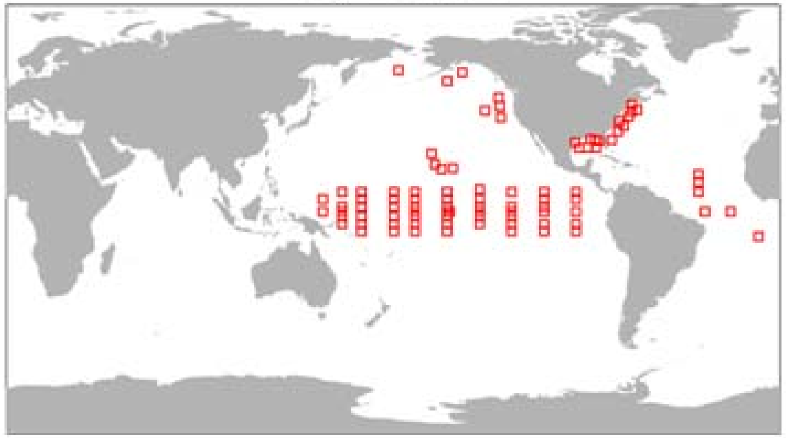
Blue circles show differences due to IA plus other factors (which we want to remove)

Raining portion – not used

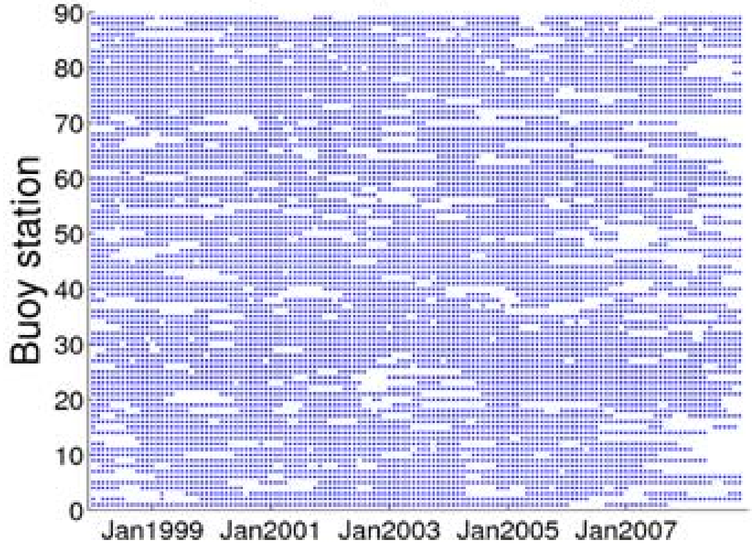
3. Comparison of retrievals with in situ

- **Concept: calculate wind from SSM/I using multiple wind algorithms and compare with matching hourly buoy wind speed observations to get relative bias**
- In this example, hourly buoy wind speed from NOAA National Buoy Data Center and TAO/TRITON buoys was obtained
  - Used SSM/I data within ½ hour of buoy observation time; made 1° average centered on station location
  - Excluded observations where 3-hrly wind speed Standard Deviation was not low
- Buoy measurements are made at heights of 3.5, 4, 5 or 10m (most are at 4m); BUT: most wind speed algorithms retrieve for 19.5m
  - Assumed log wind profile to adjust observations to 19.5m

Buoy Locations

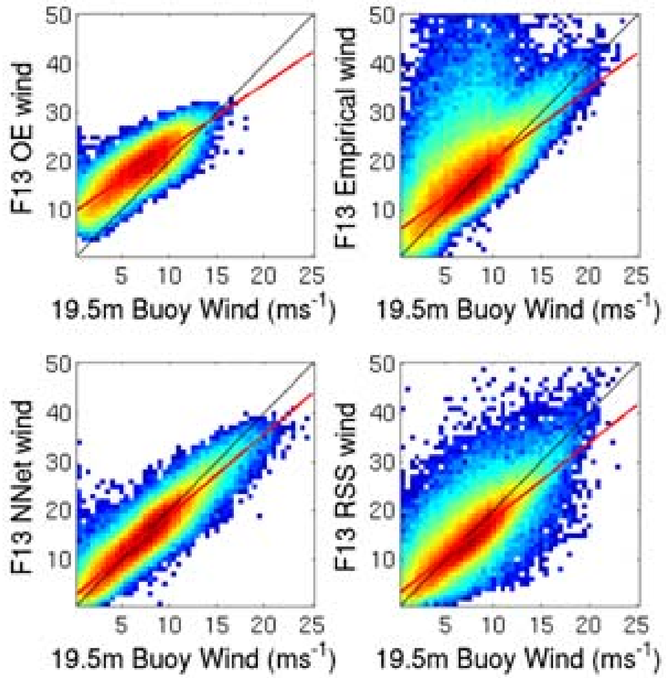


Buoy Temporal Coverage



Wind algorithms

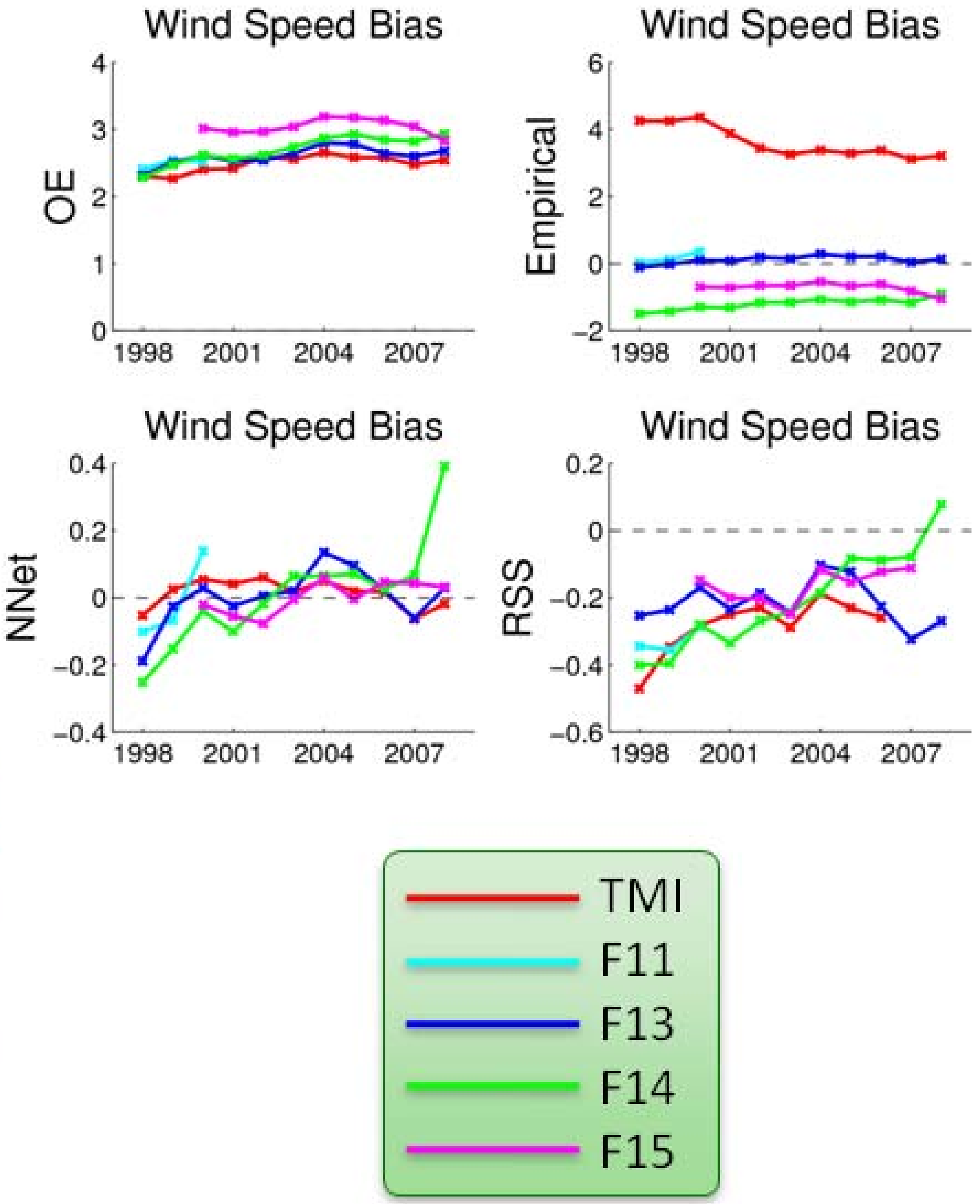
- Applied several different approaches and combinations of channels (applied to SSMI and TMI): focus three main types of approaches today
  - Optimal Estimation, Empirical and Neural Network
  - Also included RSS estimate of wind (u37) from nearest gridbox to buoy



Algorithm	Bias	RMS	Corr	Slope
OE	-2.53	2.9	0.83	0.66
Empirical	-0.92	2.79	0.66	0.74
NNet	0	1.21	0.91	0.83
RSS	0.21	1.82	0.8	0.78

Wind Speed Bias – preliminary results

- Can use this analysis to get multiple realizations of WSB
  - How do we convert this to Tb offsets?
- Algorithm skill varies: how to assign value to each algorithm?
- Algorithm sensitivity also varies. Example: F14 in 2008



Wind	TMI	F11	F13	F14	F15
OE	2.5	2.5	2.6	2.7	3.0
Empirical	3.6	0.2	0.1	-1.2	-0.7
NNet	0.0	0.0	0.0	0.0	0.0
RSS	-0.3	-0.3	-0.2	-0.2	-0.2

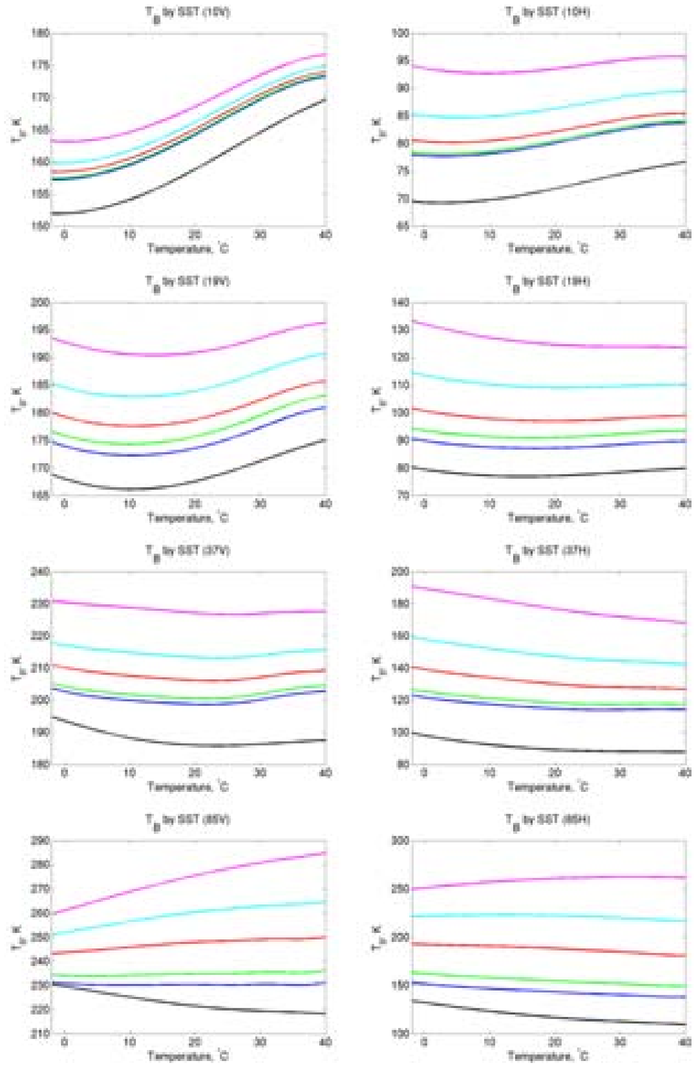
Mean Wind Speed Bias (ms^{-1})

Issues with this approach

- How to convert WSB into TB
  - Not enough information in wind speed to get back to 7 (4) channels (could use multiple parameters)
- This is an area of active research

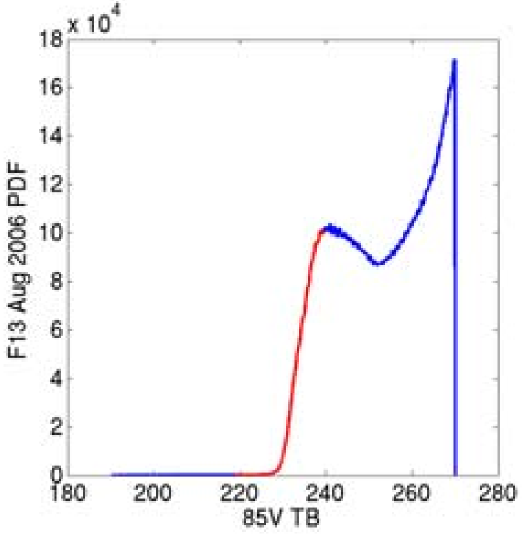
4. Vicarious Calibration

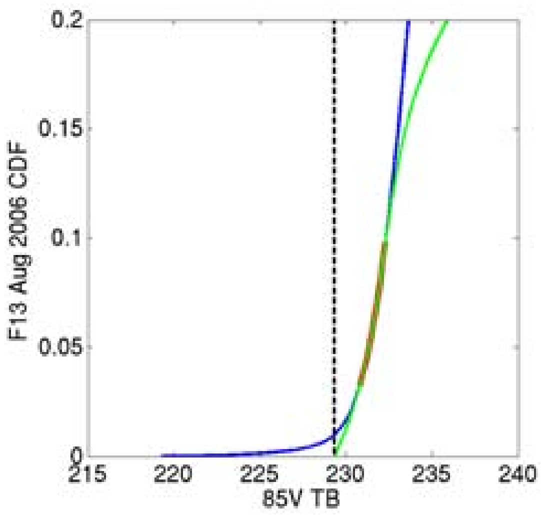
- Technique relies on finding minimum TB over ocean for cloud free, low humidity days
- Min TB for a specific channel/polarization is different from the min SST observed
  - Plot shows TBs for given SSTs from radiative transfer calcs
  - Black line has no atmosphere; colors have atmosphere with progressively more humidity
- The minimum TB is termed the *Vicarious Cold Calibration Point* and is "fixed" for a given channel
  - Only works for some channels; min TB can occur outside observed Earth SSTs

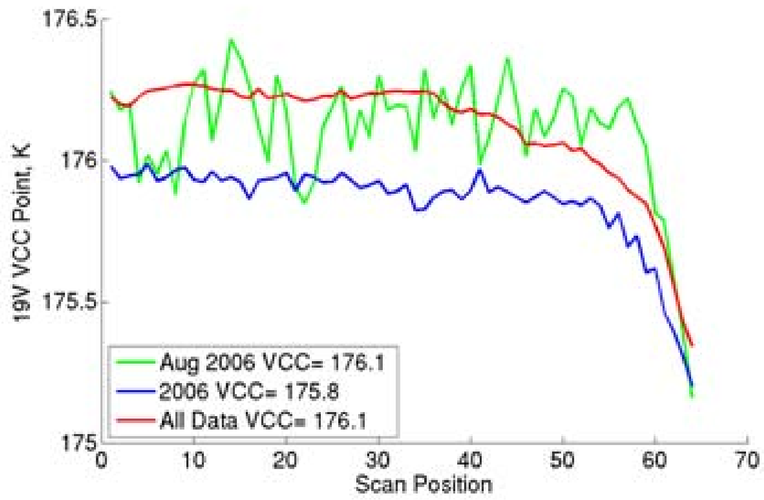


Obtaining the Vicarious Cold Calibration Point

- Screen out all pixels with high humidity, land or cloud/rain/ice
- Create histogram for each scan position for each channel
- Restrict to lowest part of histogram and estimate VCC from some statistical model fit to CDF
- Use this to obtain VCC for each scan angle and over all scan angles
  - Sampling can be an issue, so best to use lots of data to get better defined VCC values







Issues and extensions of Vic Cal

- U Michigan group (Prof. C. Ruff) that developed this technique also have a Warm calibration technique
  - Based on stable target at warm end (over the Amazon)
  - Useful as that technique gives points in an area of the TB range that is not well covered by other techniques
- Trends in humidity can affect VC
  - VCC would work perfectly if there was no atmosphere (this is why the fit to the CDF is used)
  - Estimates are based on low humidity, so if that increases with climate change it might effect VCC
- VCC point is not observed for some channels or sensors
  - Eg: TMI has limited range and does not observe cold SSTs that include the 19V
  - Technique still works, but may be less reliable

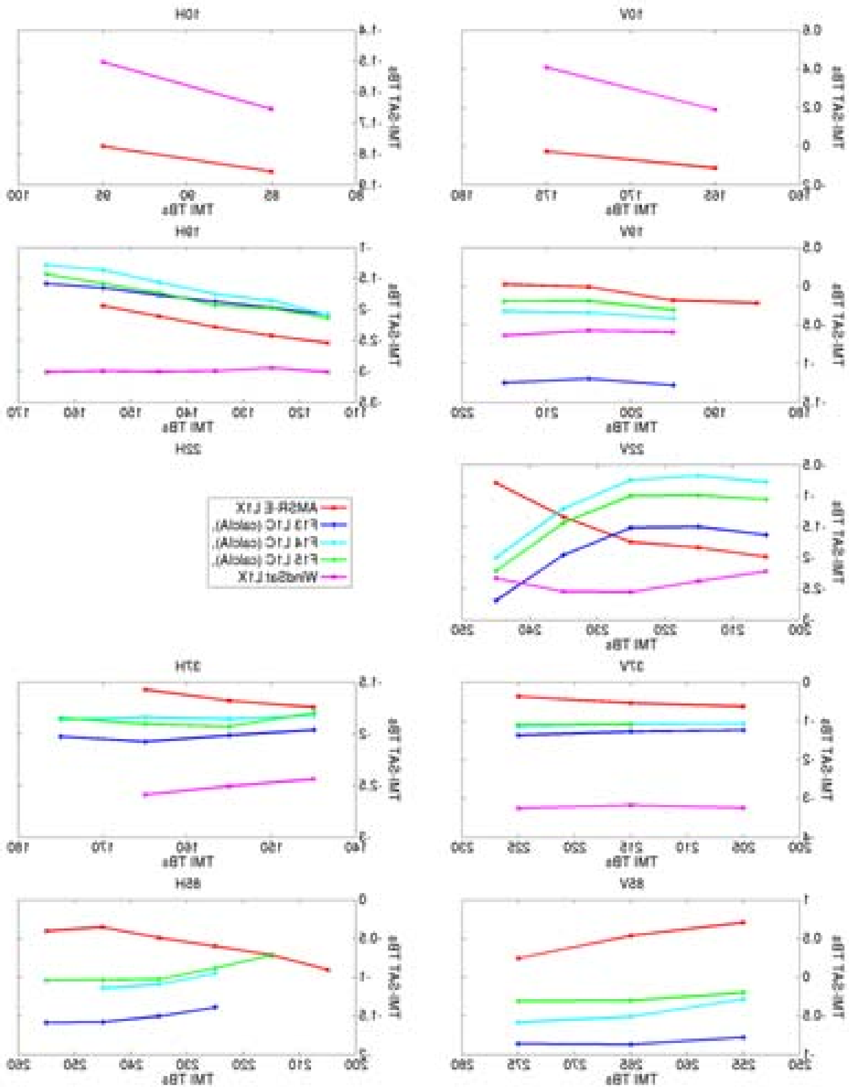
How well do these techniques compare?

- Table shows calibration offsets for F13 vs F14 from Vicarious Calibration, TMI comparison and Polar matchups (S. Yang, NOAA/STAR)
  - VCC and polar matchups did not attempt to account for EIA differences
  - TMI matchup technique used OE to account for such differences but known issues exist with the EIA values for SSMI (these versions used an adjusted nominal EIA)
- VCC and Polar are in excellent agreement
- Less agreement with TMI, but more work needed here

Method	19V	19H	22V	37V	37H	85V	85H
VCC	-0.29	0.35	-0.20	-0.81	0.29	-0.18	0.12
TMI Comparison	-0.86	-0.18	-0.73	-0.15	-0.05	-0.31	-0.28
Polar matchups	-0.43	0.32	-0.32	-0.81	0.21	-0.32	0.32

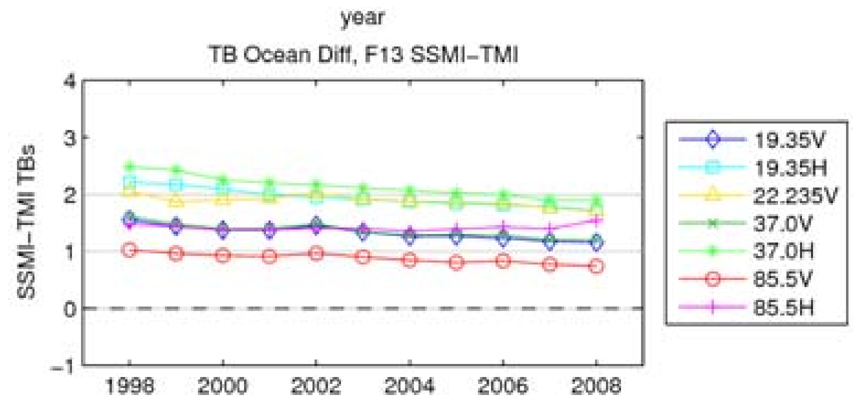
Using intercalibrations

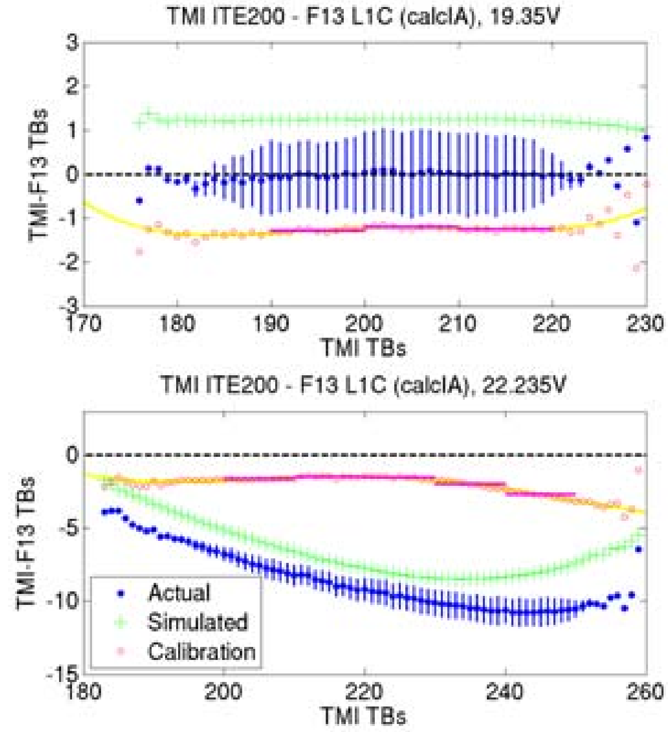
- Comparison of several satellites with TRMM TMI using OE technique
- Could use these numbers to intercalibrate all satellites to match TMI



Intercalibration Issues

- Non-physical trends can exist in satellite estimates
  - Can be difficult to quantify these given sampling requirements of some techniques
- No techniques calibrate in rainy part of TB spectrum
  - Difficult to get idea of how calibration should change with TB
  - Vicarious warm calibration helps here, but the middle of the spectrum is not sampled





Summary of key issues

- A number of specific calibration-related issues need to be addressed before sensors can be effectively intercalibrated (cross-track biases, geolocation and pointing errors etc.)
- Although conical-scanning radiometers designed to have same view angle across the scan, differences of as little as 0.1 degrees can impact calibration as well as geophysical retrievals, particularly over oceans.
- Calibration needs to be ongoing as sensors change/degrade, orbits drift, and new sensors are launched
- As demonstrated by biases in TMI due to heating of the antenna (Jones et al.), calibration errors often change over time (as with spacecraft heating) and can mimic real physical signals (i.e. diurnal cycle).
- Using multiple approaches to intercalibration helps to confirm results, identify issues, and determine residual errors.
- As a result, calibration should be considered an ongoing, continually evolving endeavor that involves collaboration by multiple groups with expertise in both the engineering and scientific aspects of the sensors.