A Time-varying Radiometric Bias Correction for the TRMM Microwave Imager

Kaushik Gopalan

Thesis defense : Oct 29, 2008

CFRSL

Outline

- Dissertation Objective
- Initial research
  - Introduction to GPM and ICWG
  - Inter-satellite radiometric calibration
- Current research
  - TMI time-varying bias correction
- Conclusions and Future work

CFRSL

Dissertation Objective

- Original Objective
  - To develop inter-calibration techniques for a constellation of satellite radiometers over ocean, Amazon and polar regions
- Current Work
  - Detection of systematic errors using inter-calibration and development of correction techniques that eliminate systematic errors detected in TMI

Motivation

- GPM contains a constellation of similar, but not identical, radiometers
  - Satellites of opportunity
- Inter-calibration is required in order to obtain self-consistent retrievals from all the radiometers in the constellation
- Separating long term environmental change from instrument errors due to aging

CFRSL

Calibration for GPM constellation

- GPM observatory : Non sun-synchronous tropical orbit
- Constellation satellites : Sun-synchronous polar orbits

CFRSL

Image Courtesy : NASA

ICWG Objectives

- Common Dataset
  - TMI as proxy for GMI
  - WindSat and SSMI on F13, F14 are the polar orbiting radiometers
- Verify the accuracy of TMI as the transfer standard
- Using the “gold standard” radiometer to calibrate polar orbiting radiometers
- Generation of a standard, repeatable protocol for use in GPM

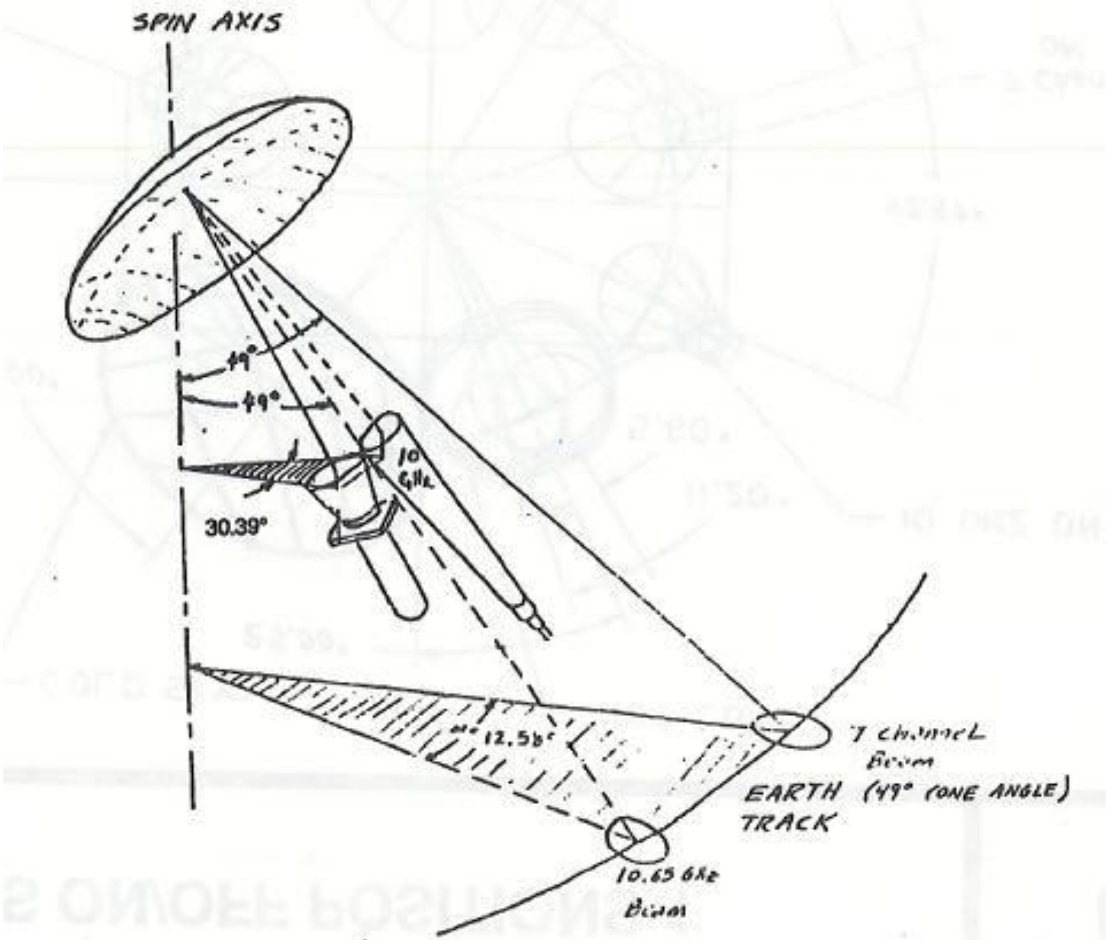
CFRSL

ICWG Methodology

- Four teams using independent techniques
  - BESS : Tom Wilheit
  - CSU : Chris Kummerow and Wes Berg
  - Michigan : Chris Ruf
  - UCF : Linwood Jones
- Common radiative transfer model
- Common dataset : July 2005 – June 2006
- Contributions by Fuzhong Weng and others…

CFRSL

TMI Scan geometry

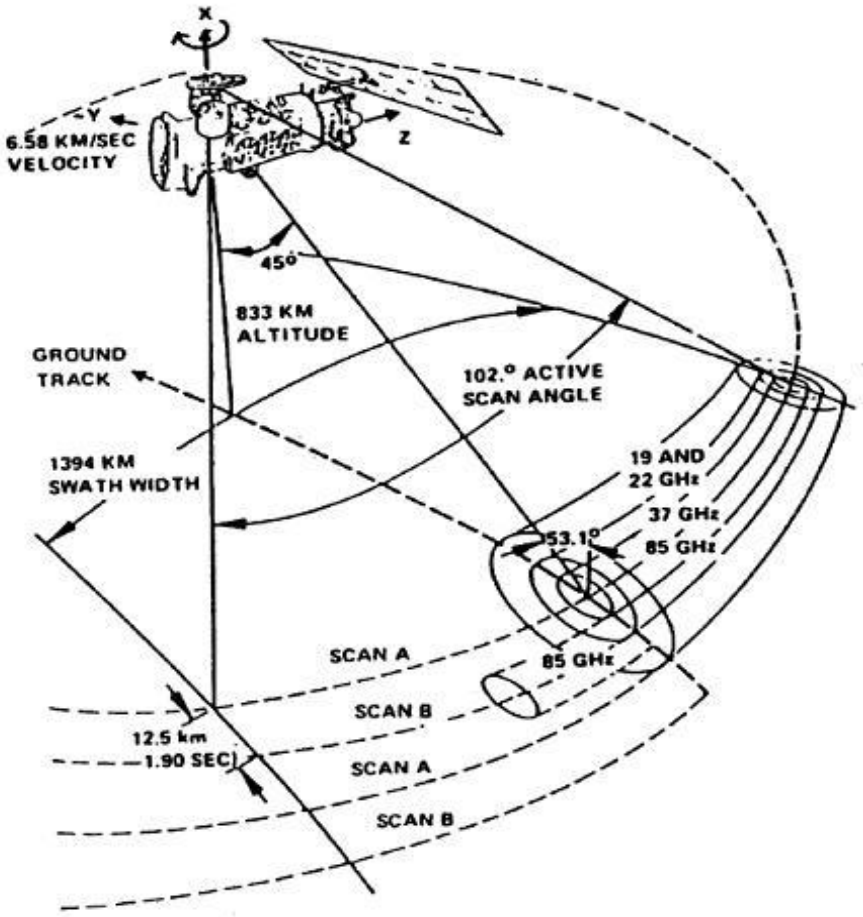


TMI channels

Freq GHz	Channels	EIA, deg	BW, MHz
10.65	V,H	52.3	100
19.35	V,H	52.3	200
21.3	V	52.3	500
37.0	V,H	52.3	2000
85.5	V,H	52.3	3000

CFRSL

SSMI scan geometry



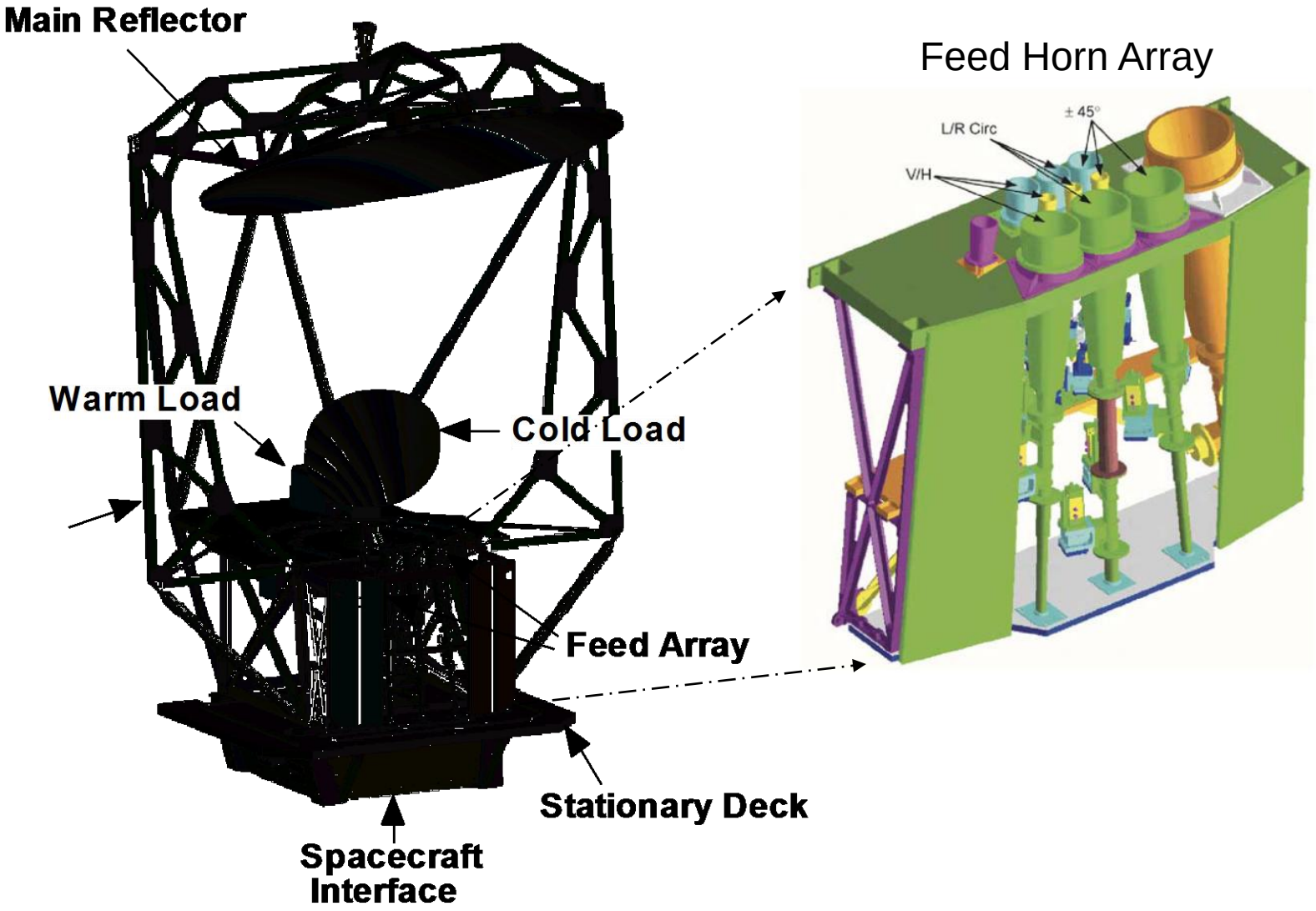
CFRSL

SSMI channels

Freq GHz	Channels	EIA, deg	BW, MHz
19.35	V,H	53.4	250
22.3	V	53.4	250
37.0	V,H	53.4	1000
85.5	V,H	53.4	1500

CFRSL

WindSat Sensor Assembly

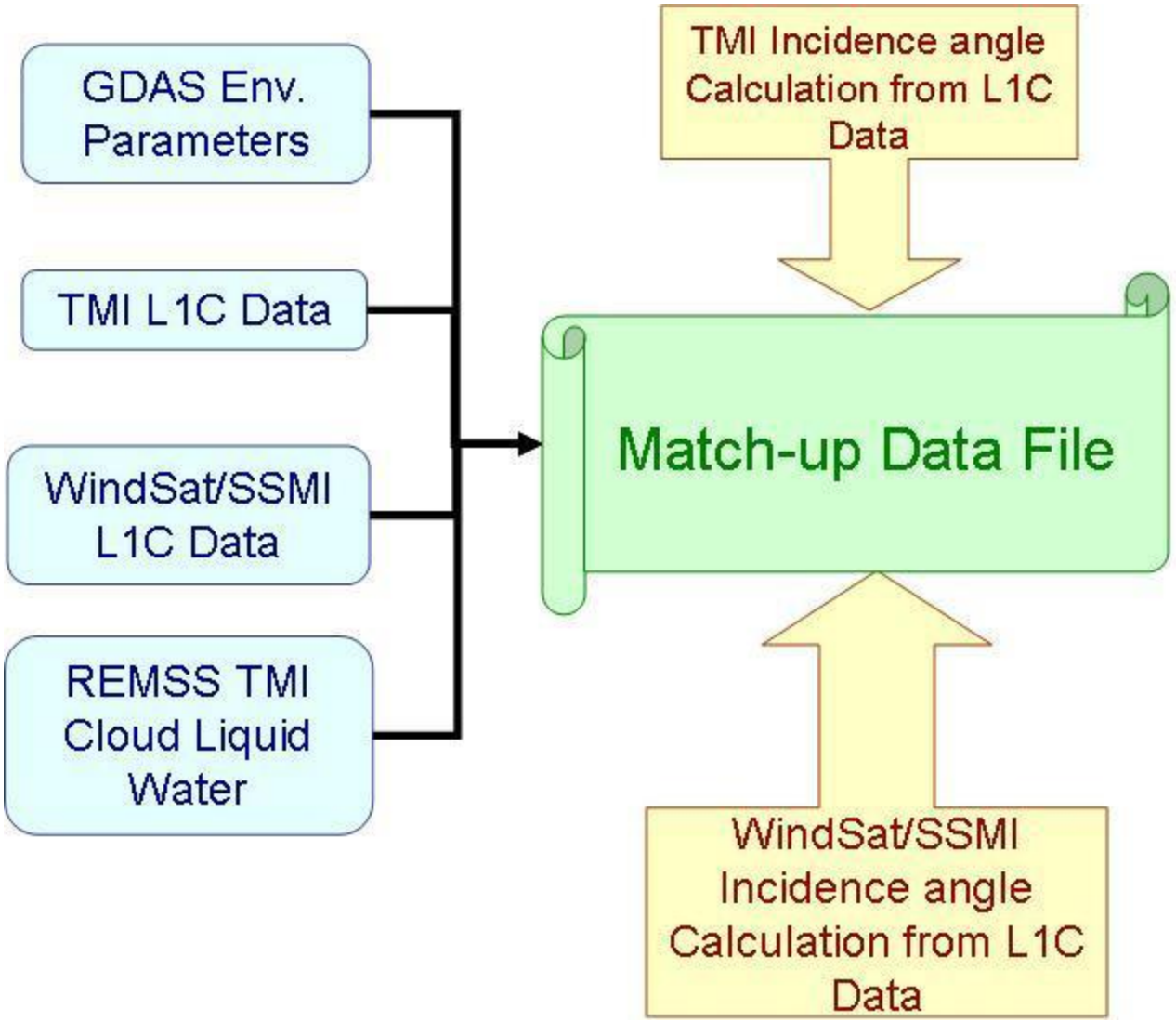


WindSat channels

Freq GHz	Channels	EIA, deg	BW, MHz
6.8	V,H	53.5	125
10.7	V,H,±45,lc,rc	49.9	300
18.7	V,H,±45,lc,rc	55.3	750
23.8	V,H	53.0	500
37.0	V,H,±45,lc,rc	53.0	2000

CFRSL

Match-up Data Sets



CFRSL

Match-up Data Sets

- ASCII files containing Tb meas, incidence and azimuth angles, & envir parameters
- Match-ups with temporal tolerance of ±1 hour and spatial quantization of 1º Lat x 1° Lng
- Three collocation files generated per day
  - TMI-WSat, TMI-SSMI-F13 & TMI-SSMI-F-14
- Match-up file formats available via SSH to the research community

CFRSL

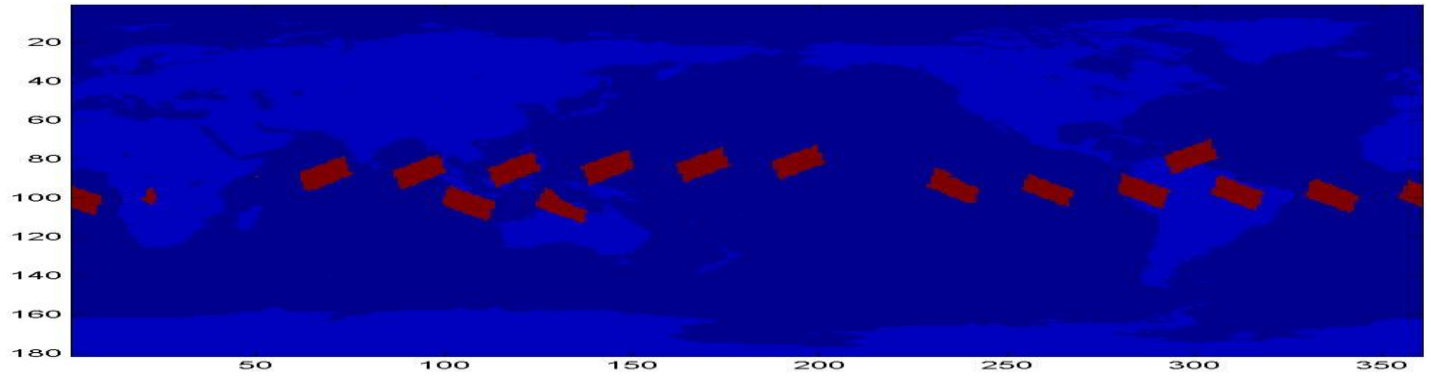
Match-up Environmental Data Sets

- Atmospheric parameter profiles from GDAS
  - Pressure, temperature, water vapor
  - @ 21 atmos pressure layers
  - Global @ 1° lat/lon grid, every 6 hours
- Oceanic surface parameters from GDAS
  - Sea surface temperature, wind speed & direction
- Ocean salinity from NOAA climatology
- Columnar cloud liquid water from TMI retrievals
  - Remote Sensing Systems

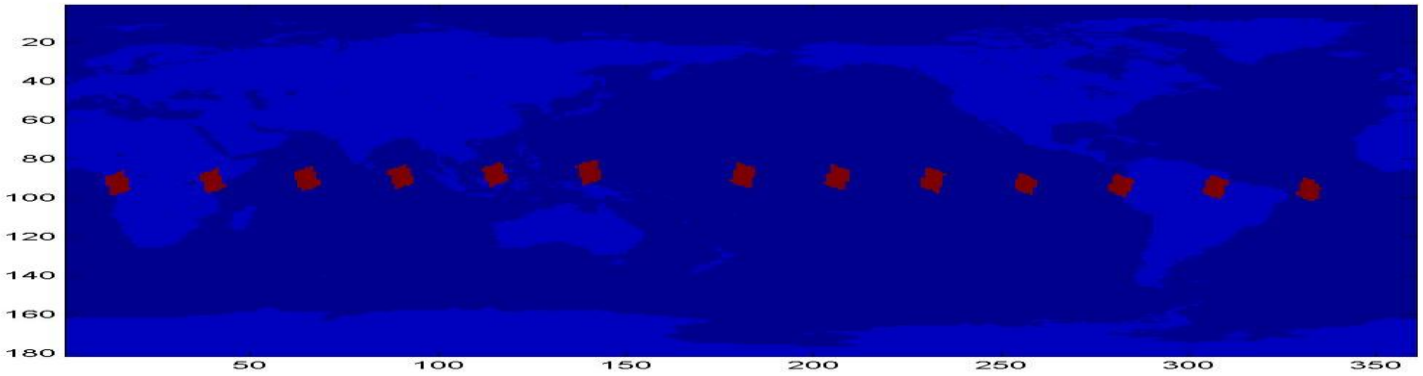
CFRSL

Match-up locations

SSMI F-13



WindSat



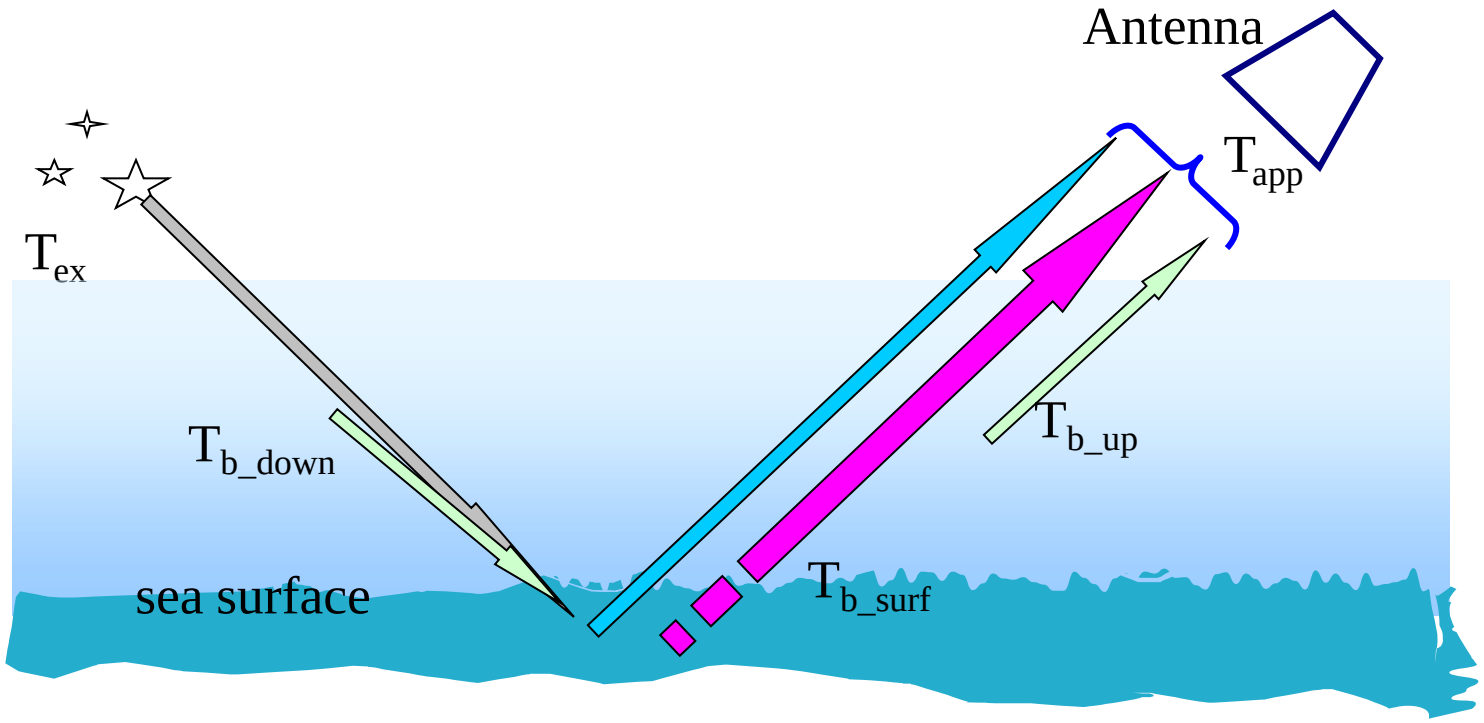
CFRSL

Match-up Data Sets : Tb Filtering

- Filtering of match-up Tb samples to remove non-homogeneous environmental scenes & bogus outliers
  - In each 1° lat/lon bin, std dev of:
    - V-pol ≤ 2K, H-pol ≤ 3K Upper limits of Tb's applied to remove rainy and land pixels
    - TMI: 10V (185K), 10H (115K), 19V (230K), 19H (200K), 21V (260K), 37V (240K), 37H (210K)
    - WindSat: 6V (200K), 6H (120K), 10V (200K), 10H(150K), 18V (250K), 18H (200K), 23V (260K), 23H (230K), 37V (250K), 37H (200K)
  - Conservative "Land Mask" applied

CFRSL

Radiative Transfer Theory



$$T_{refl} = (1-\varepsilon)(\tau T_{ex} + T_{b\_down})$$

$$T_{app} = T_{b\_up} + \tau(T_{b\_surf} + T_{refl})$$

Image courtesy : Liang Hong

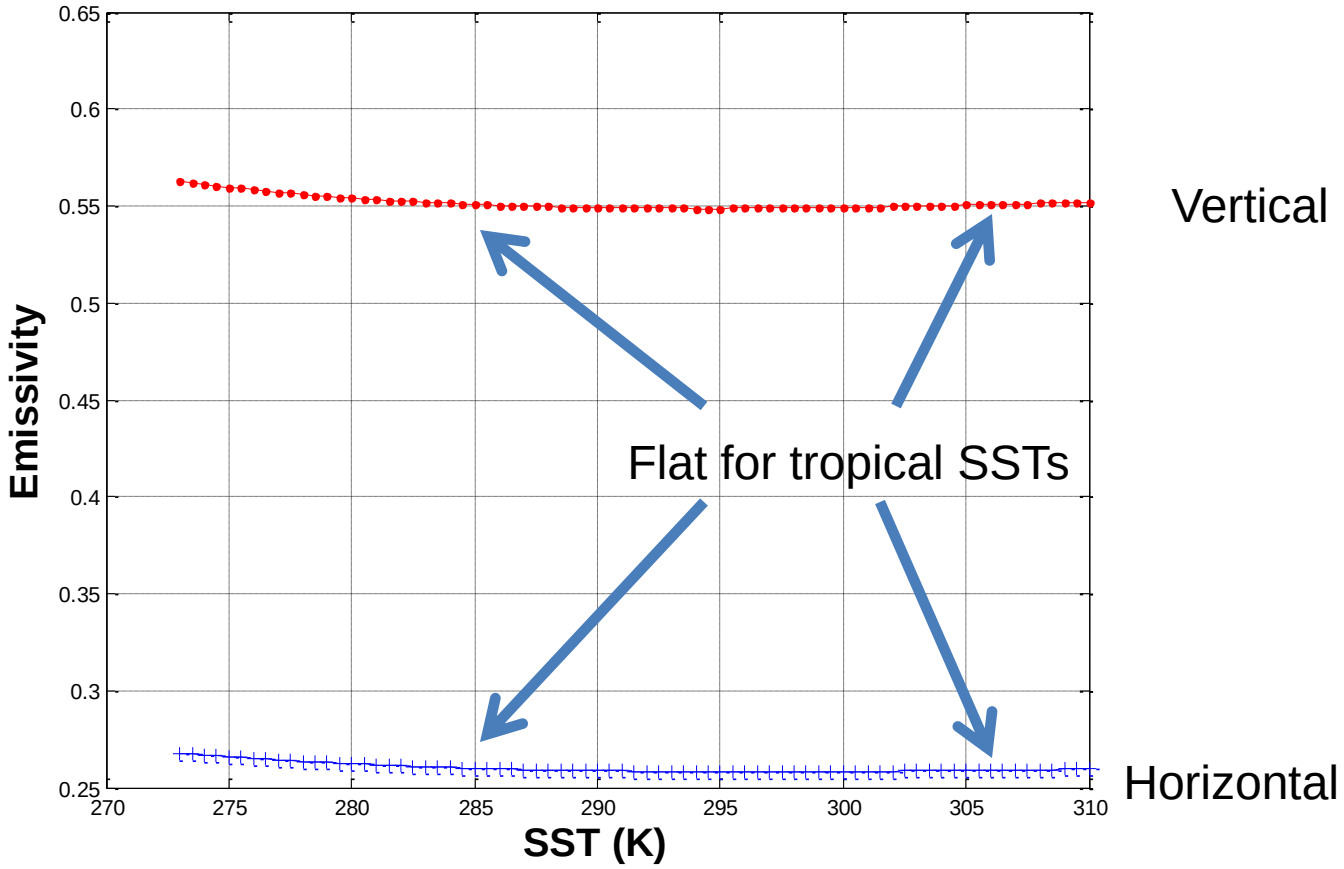
CFRSL

Radiative Transfer Model - ICWG Subroutines

- 100 atmos layers, each of thickness 200m
- Elsaesser model for ocean isotropic emissivity
- Weng model for ocean directional emissivity
  - Anisotropic with relative direction
  - Calc from GDAS wind dir & Tb observation azimuth
- Rosenkranz model for WV, CLW, O2 and N2 absorption
- Implemented in MATLAB and C

CFRSL

SST dependence of 10.7 GHz emissivity



CFRSL

TMI/WindSat Radiometric Biases

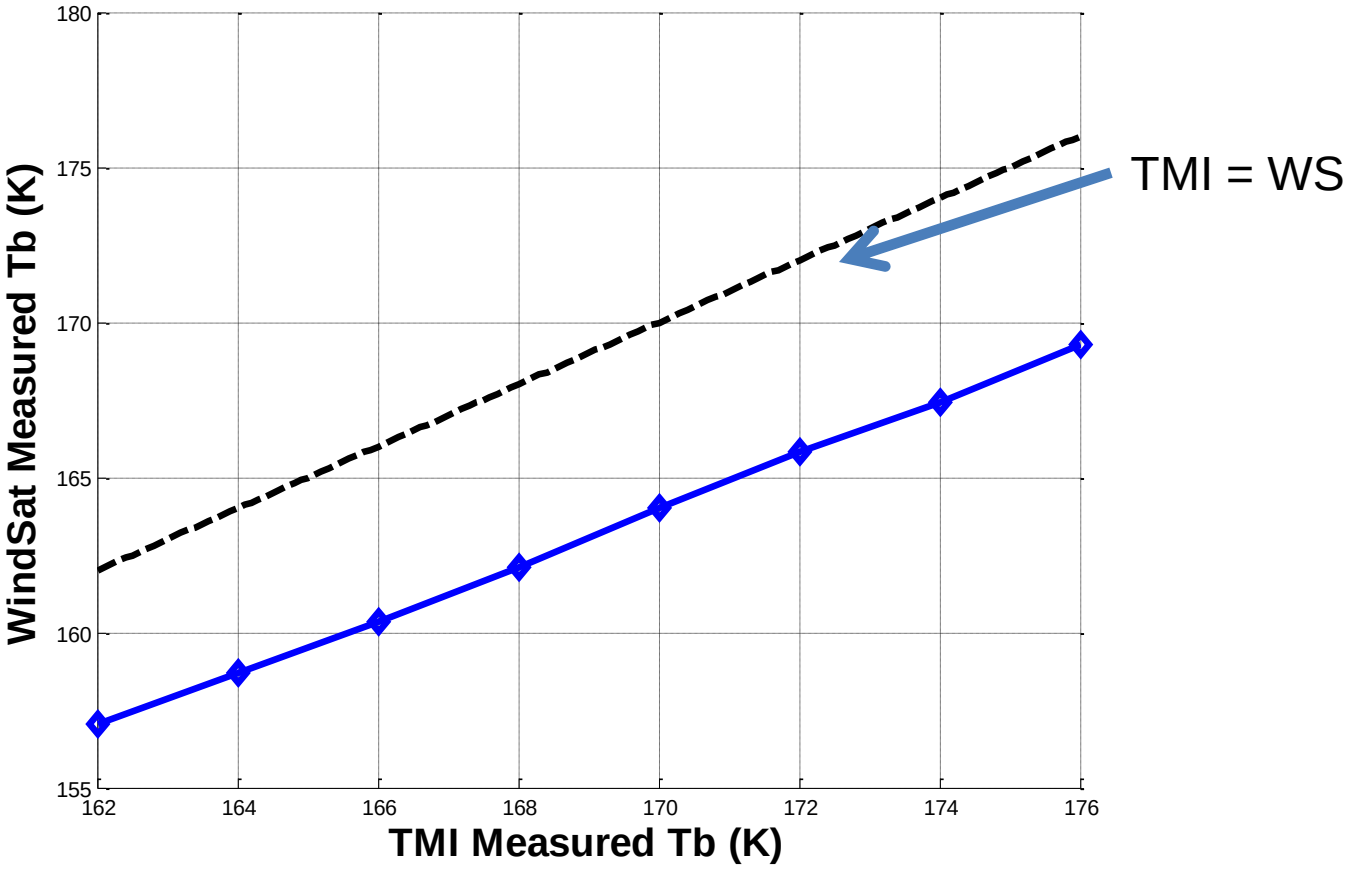
$$Tb\_SS_{norm} = Tb\_SS_{obs} + Tb\_TMI_{pred} - Tb\_SS_{pred}$$

$$Tb\_diff = Tb\_TMI_{obs} - Tb\_SS_{norm}$$

- Tb_SSnorm : WindSat/SSMI Tb normalized to TMI freq. and angle
- Tb_diff : Unexplained radiometric bias between TMI and WindSat/SSMI

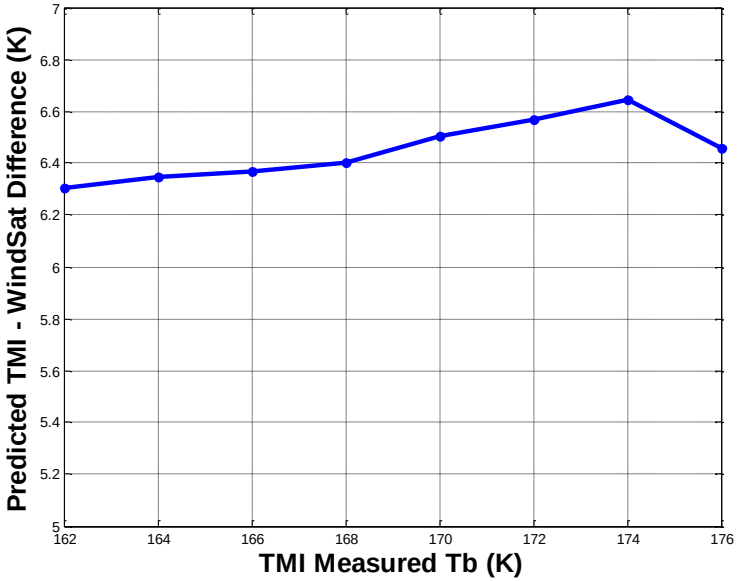
CFRSL

Example : 10V

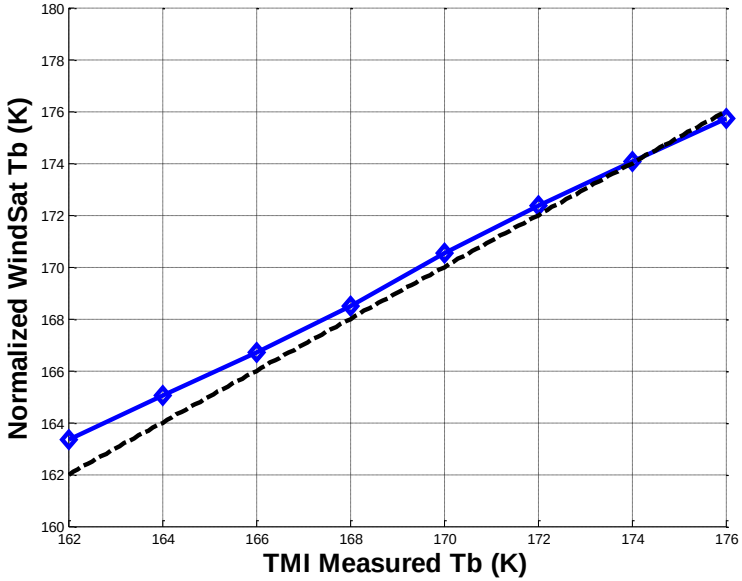

180
175
170
165
160
155
162
164
166
168
170
172
174
176
WindSat Measured Tb (K)
TMI Measured Tb (K)
TMI = WS

Example : 10V

Predicted Tb difference



Normalized Tb

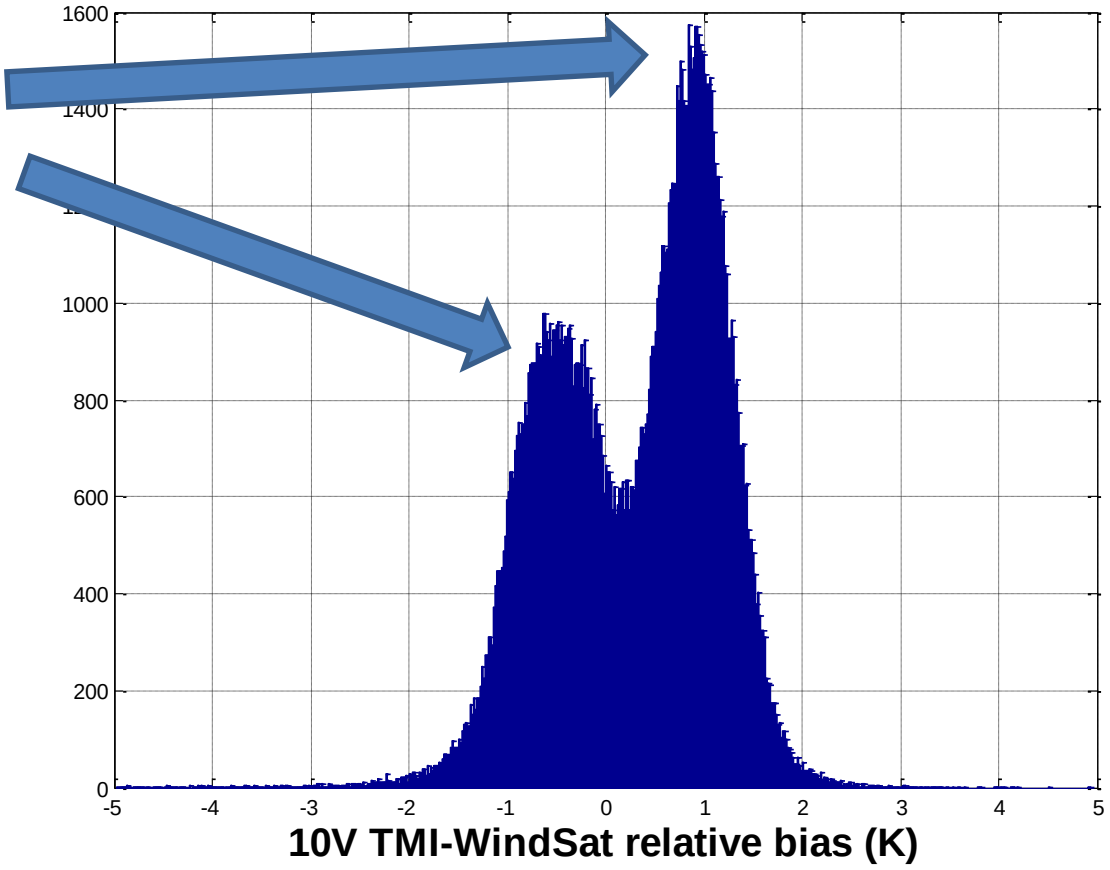


Inter-Sat Tb Comparison Results

- Relative Biases for TMI and WindSat analyzed for 1 year (ICWG period)
- The radiometric bias between TMI and WSat radiometers **must be** independent of envir parameters
- Anomaly:
  - Results indicate apparent correlation between the bias and SST.

Inter-Sat Tb Comparison Results

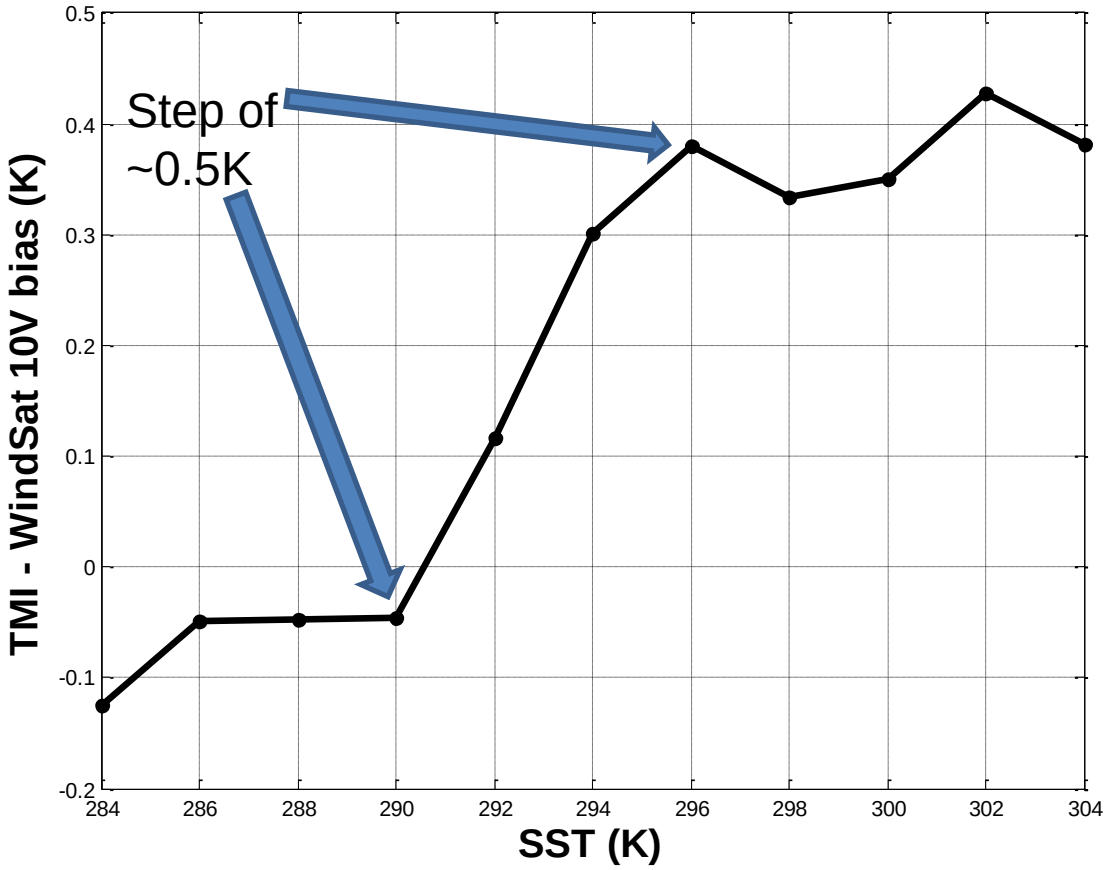
Two distinct random error sources?



CFRSL

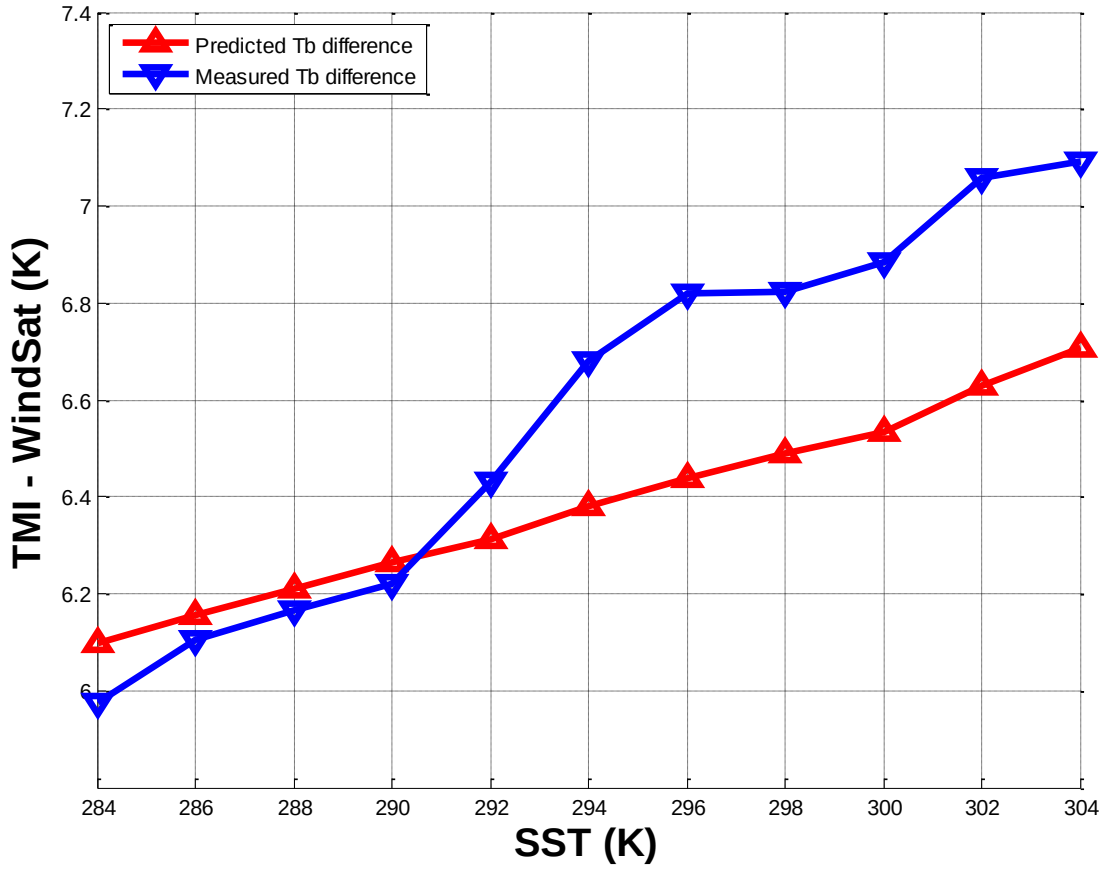
10V Bias between WindSat & TMI

Concern: bias is *f(envir pars) ???*



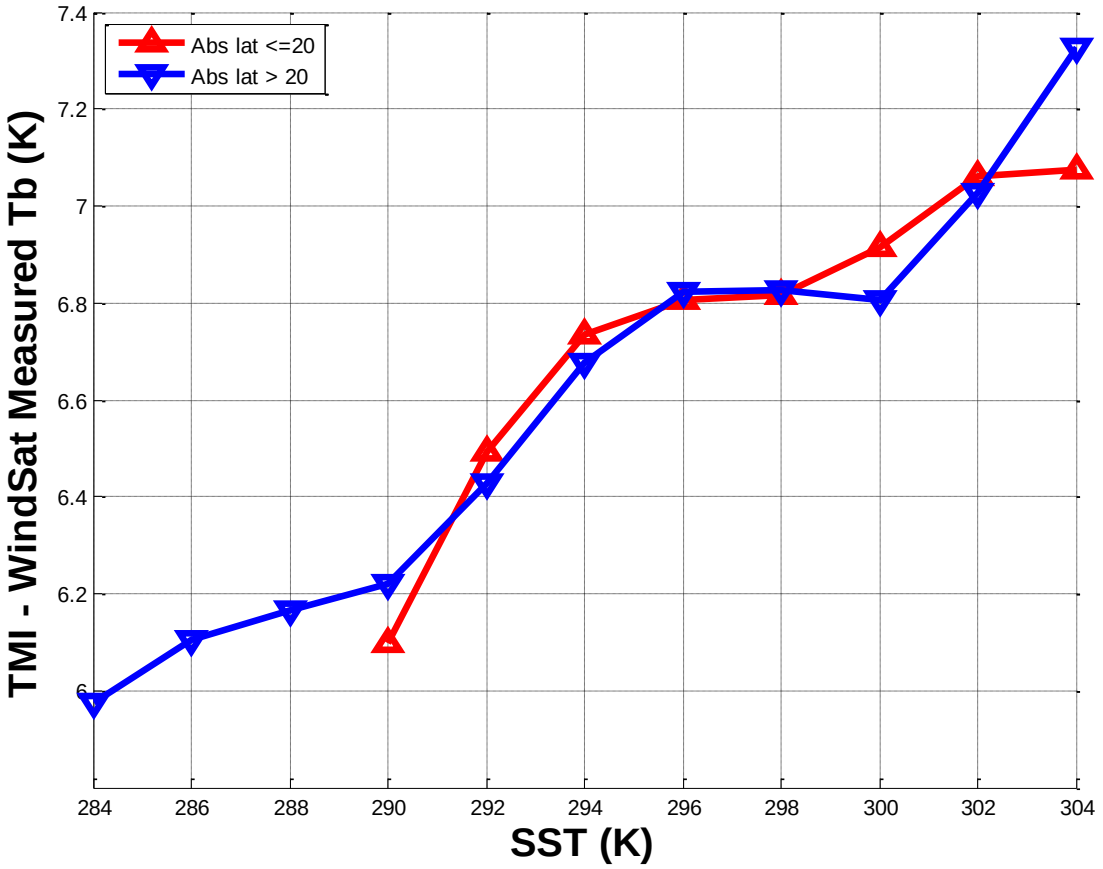
CFRSL

Predicted and measured differences



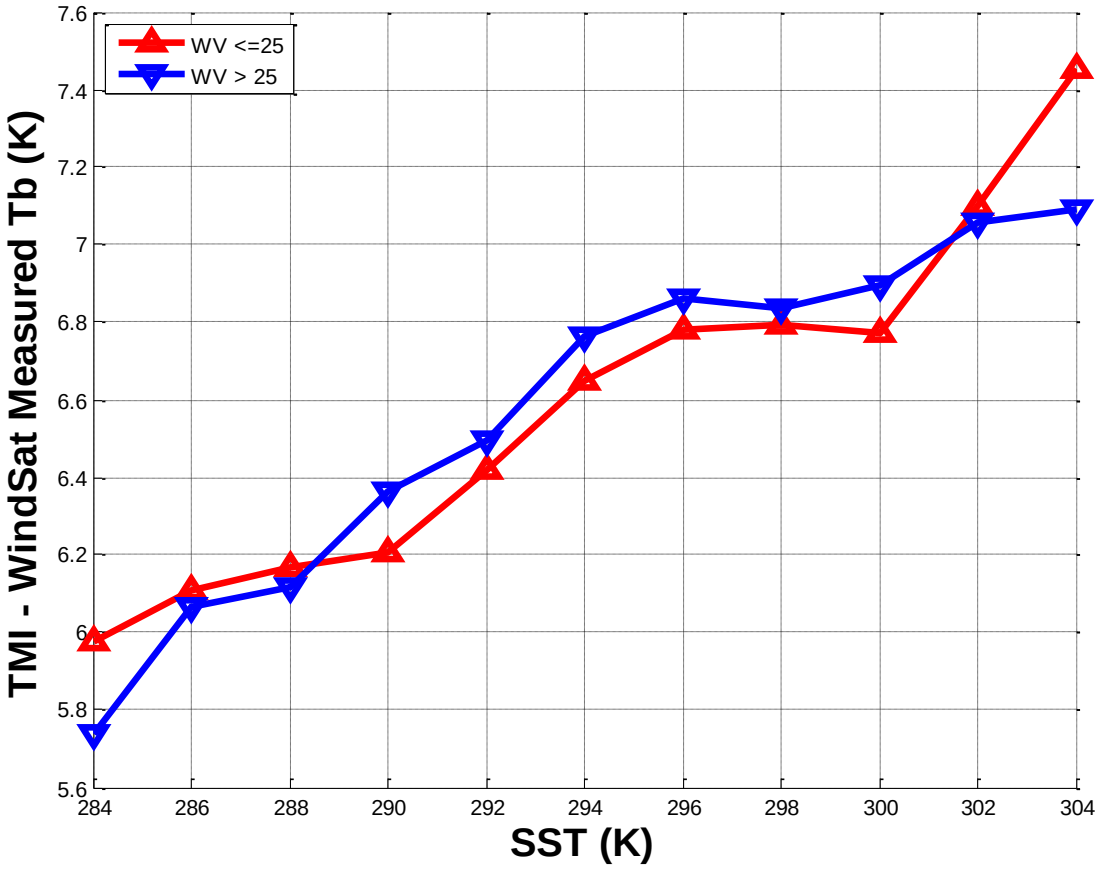
CFRSL

Latitude dependence of measured Tb differences



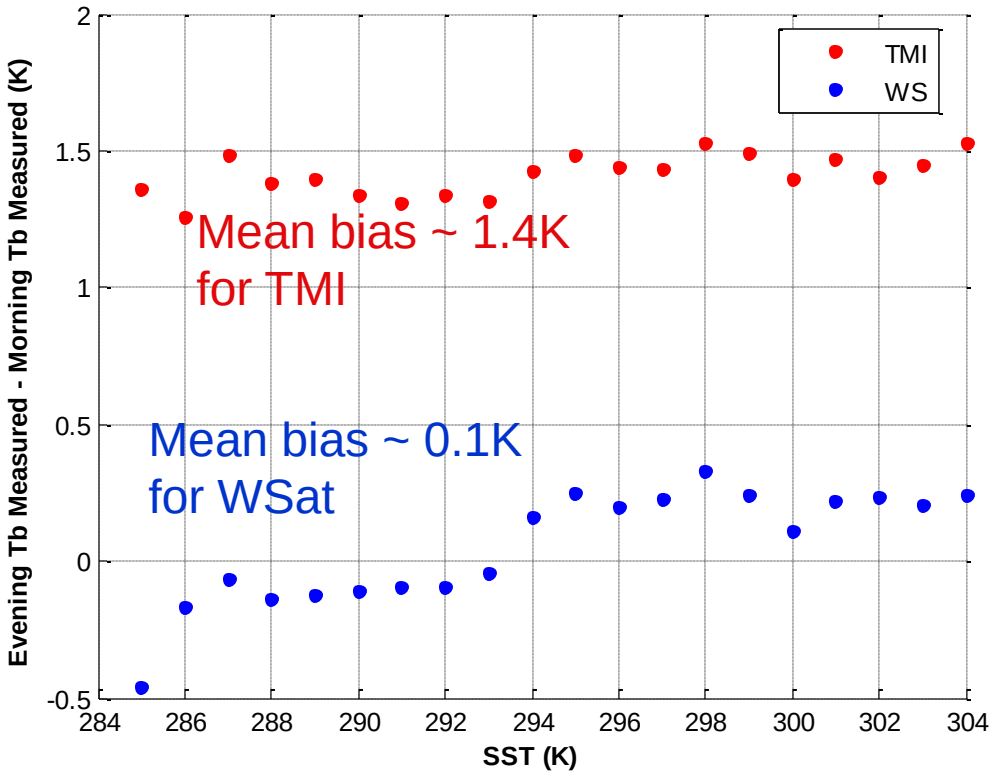
CFRSL

WV dependence of measured Tb differences



CFRSL

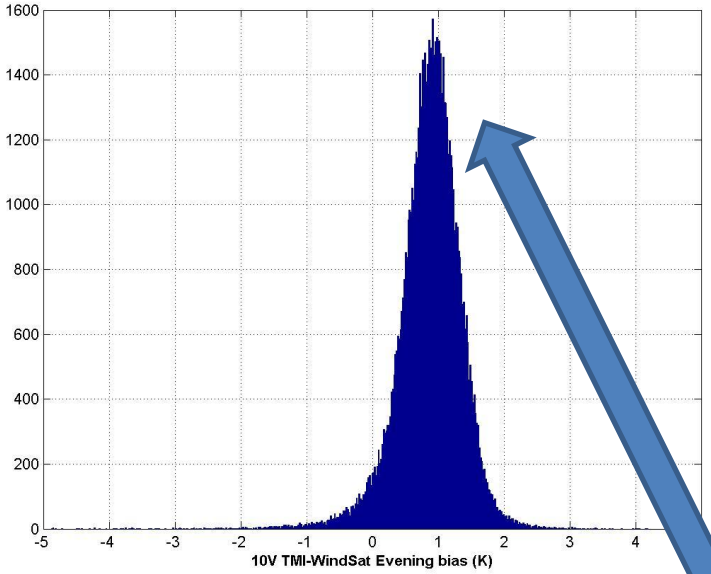
(Evening – Morning) measured Tb diff.



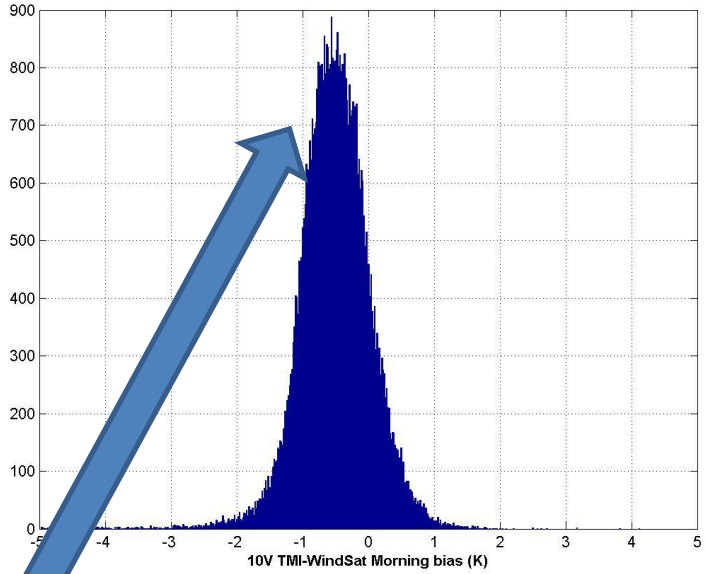
CFRSL

Evening/Morning separation

Evening



Morning



Unimodal

TMI Time of Day bias variation

- TMI reflector has been estimated to have a reflectivity of about 96% [Wentz et. al. 2001]
  - Bias varies with reflector physical temperature, which has a diurnal cycle
- Challenge : WindSat, F13 and F14 have very similar equator crossing times
  - TMI daily bias variation cannot be estimated from the match-up dataset
- Solution : Compare TMI meas. with RTM model

CFRSL

Wentz Correction (Implemented in V5 TMI data product)

$$T_{ant} = \Gamma T_{sc} + (1-\Gamma) T_{phy}$$

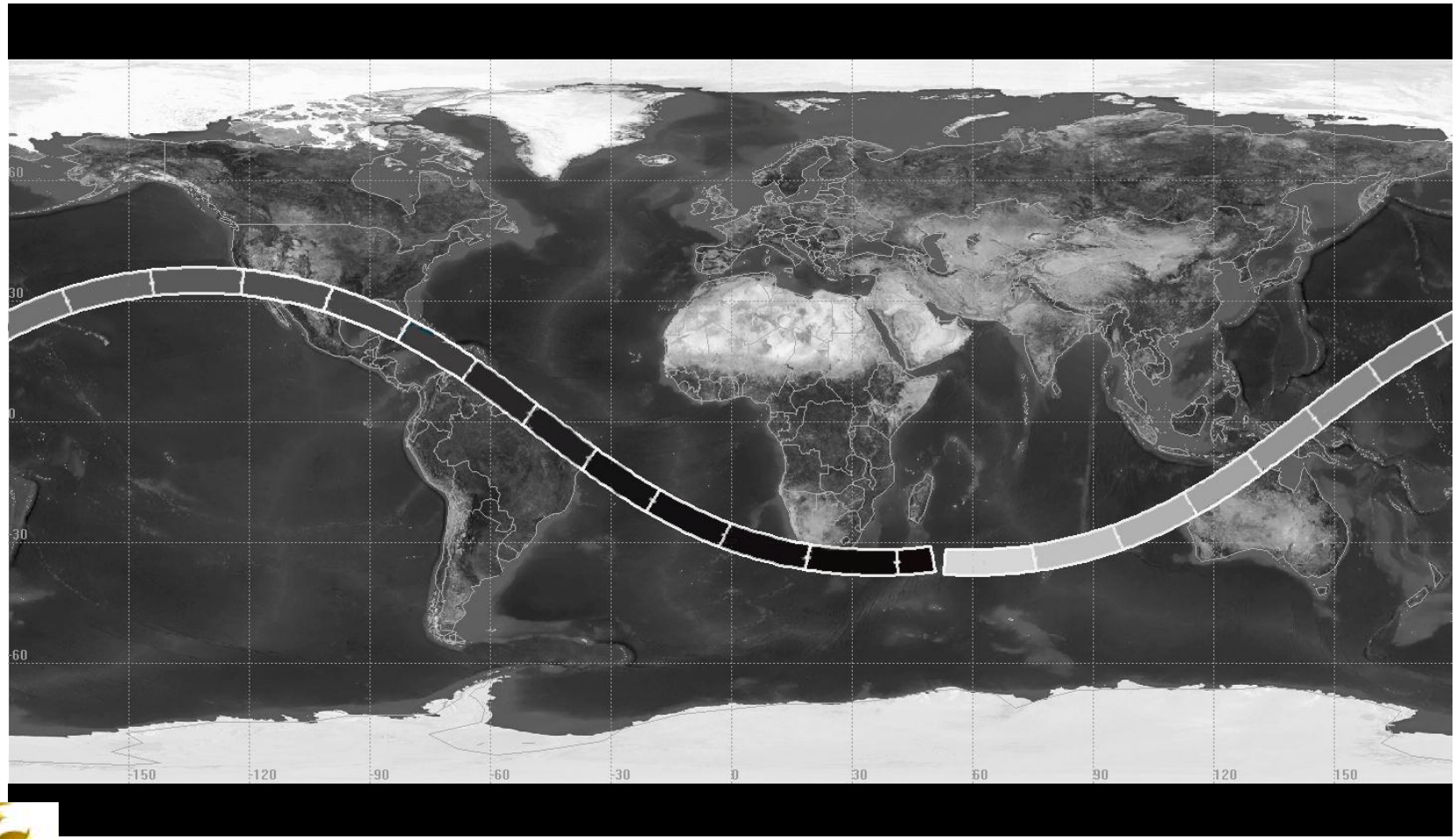
Constant

PARAMETERS RELATING TO THE MODEL FOR THE TMI WARM BIAS. THE EMISSIVITY ε AND TEMPERATURE T_0 OF THE UNKNOWN EMITTER ARE GIVEN ALONG WITH THE PREDICTED AND OBSERVED WARM BIAS AT $T_A = 2.7$ K

Channel	ε	T_0 (K)	$\Delta T_{A,\,pred}$ (K)	$\Delta T_{A,\,obs}$ (K)
19V	0.0370	302.3	11.1	12.4
19H	0.0284	290.4	8.2	12.3
21V	0.0377	294.6	11.0	13.5
37V	0.0375	296.1	11.0	13.2
37H	0.0274	294.7	8.0	12.2
85V	0.0396	279.6	11.0	13.7
85H	0.0277	239.6	6.6	13.0

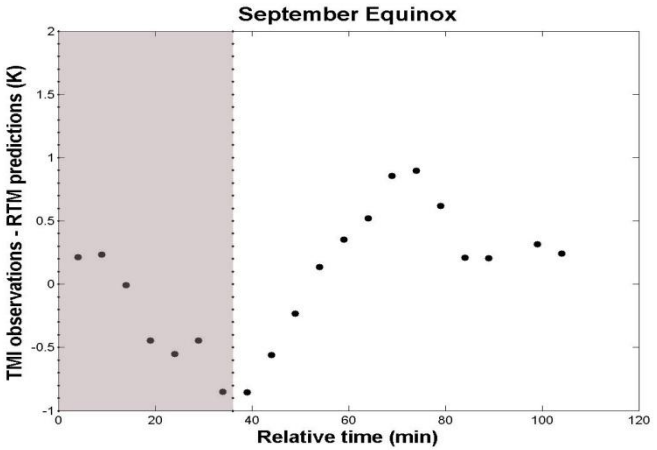
CFRSL

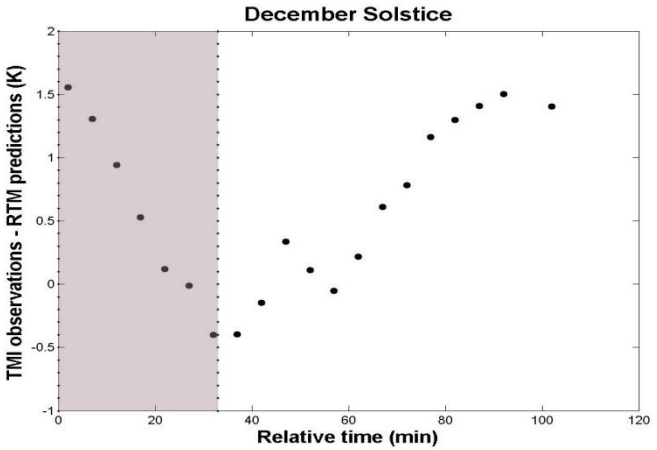
5 minute averaging over TMI orbit

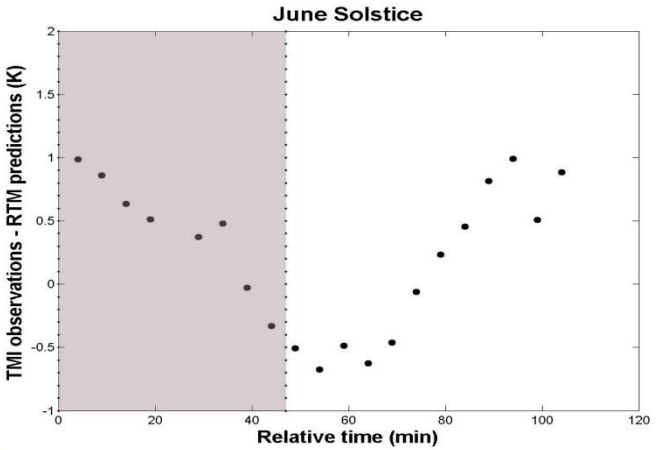


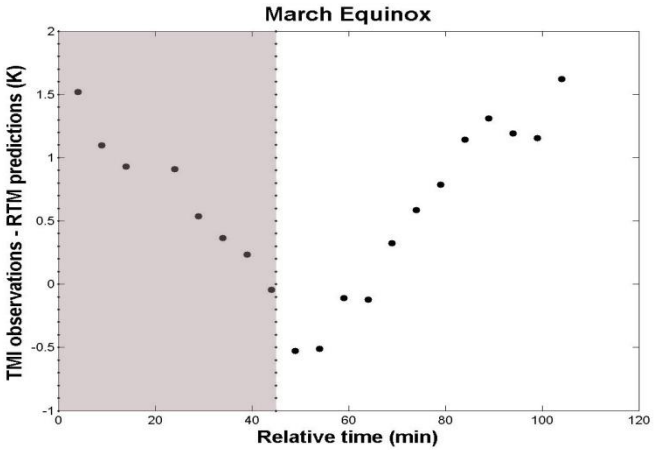
CFRSL

TMI bias variation with orbit time





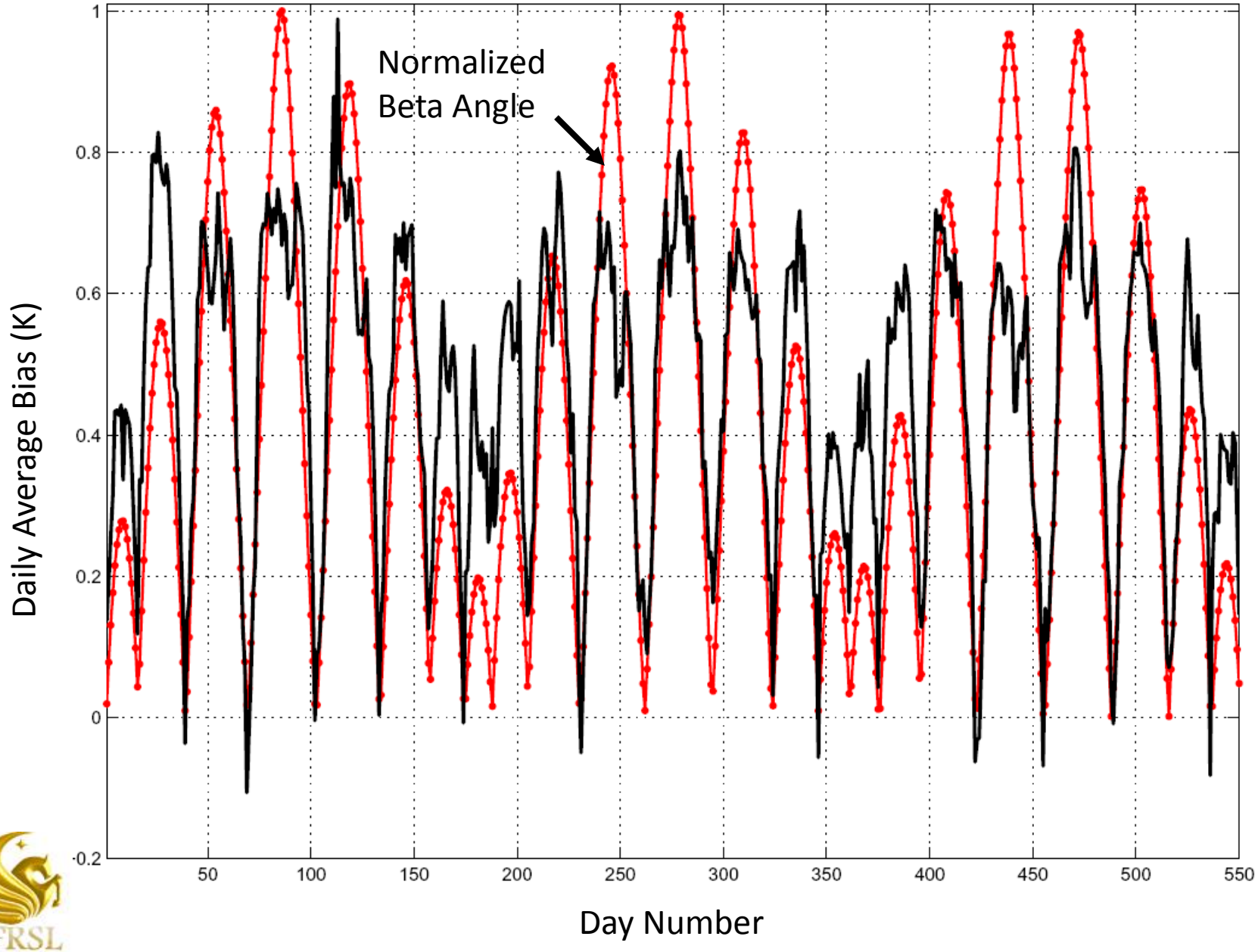




CFRSL

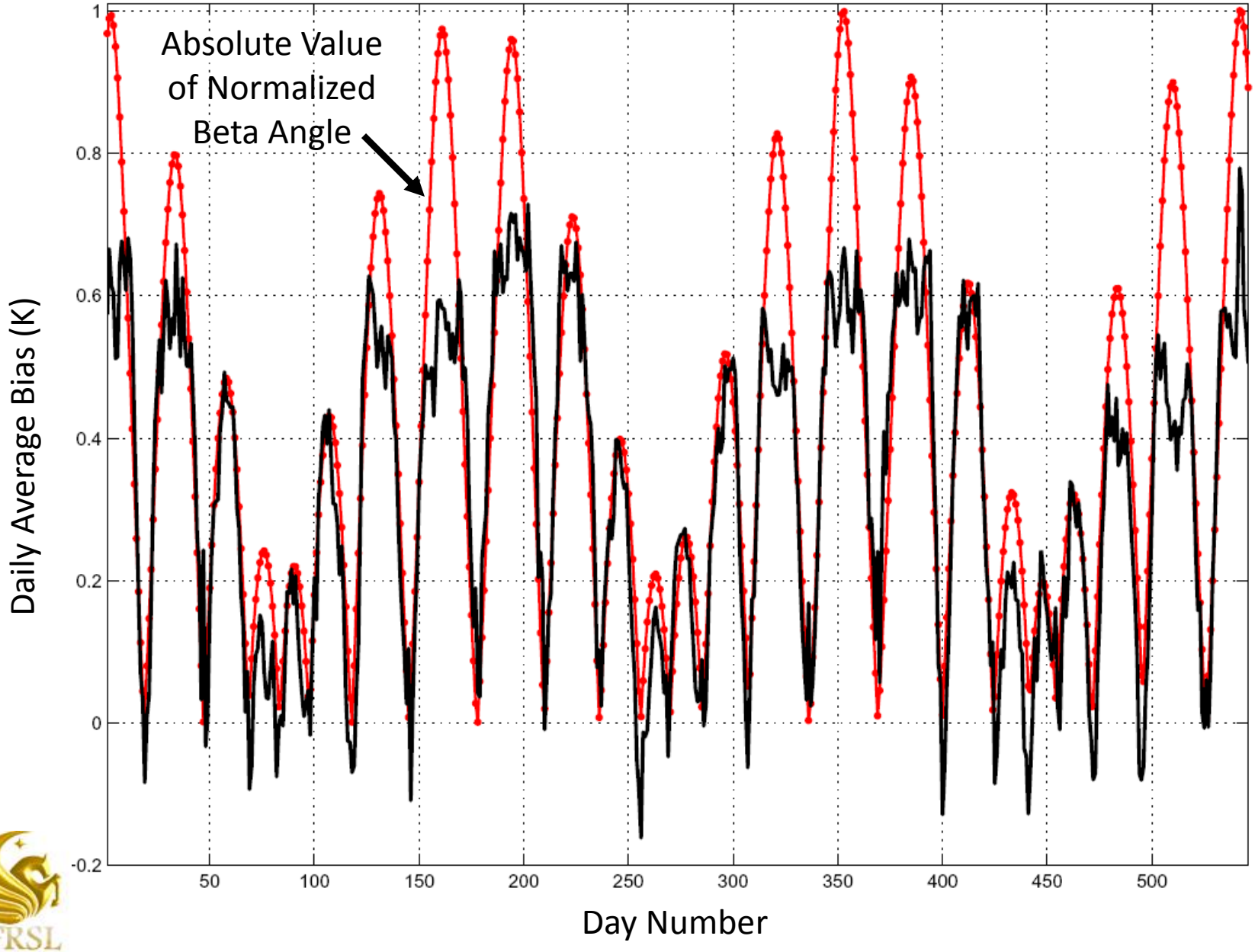
Bias variation with Solar Beta angle

TMI Daily Average Bias Plot For Positive Beta Angles [2004-2006]



CFRSL

TMI Daily Average Bias Plot For Negative Beta Angles [2004-2006]

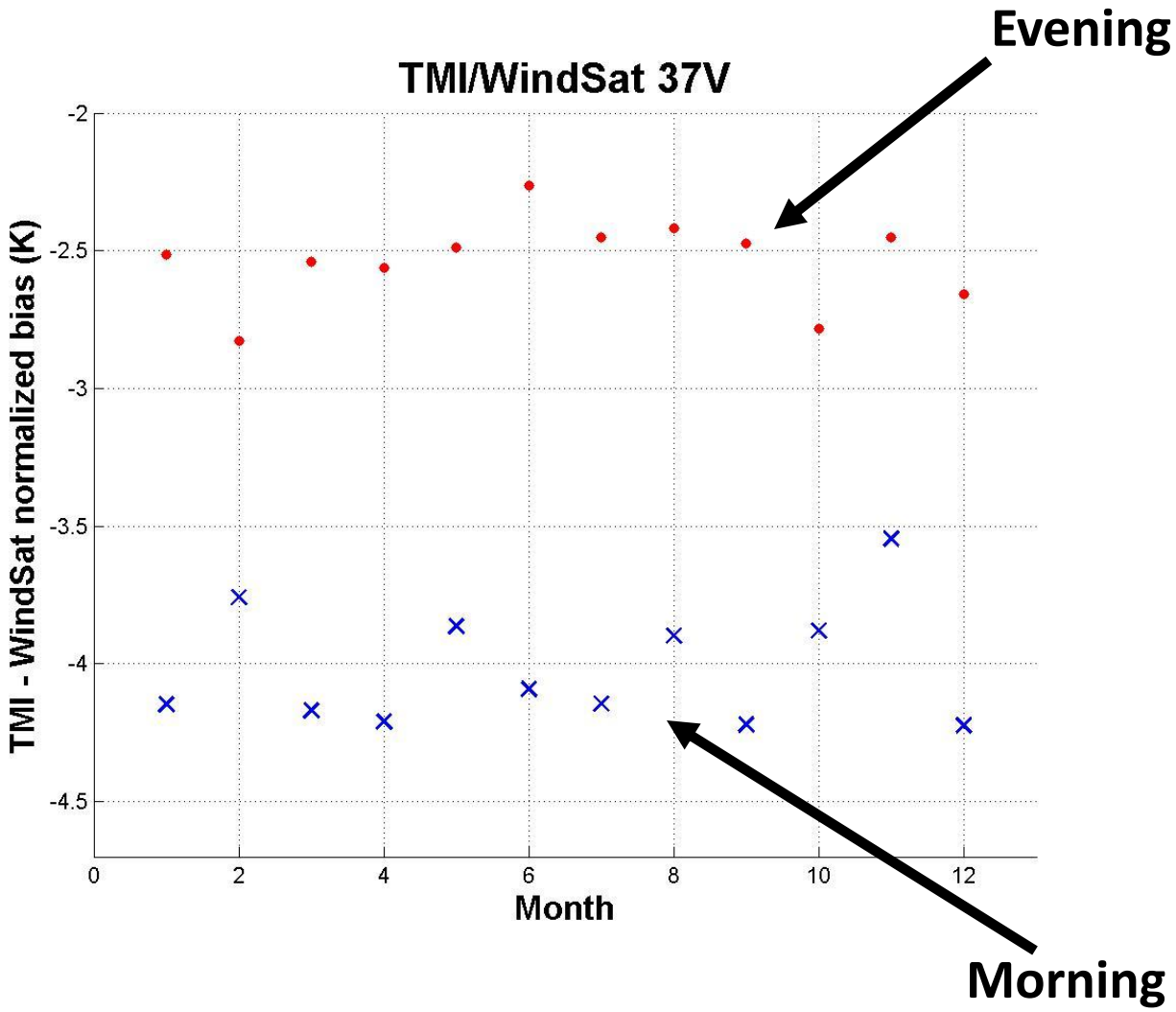


CFRSL

Effect of TMI time-varying bias correction on Inter-Cal results

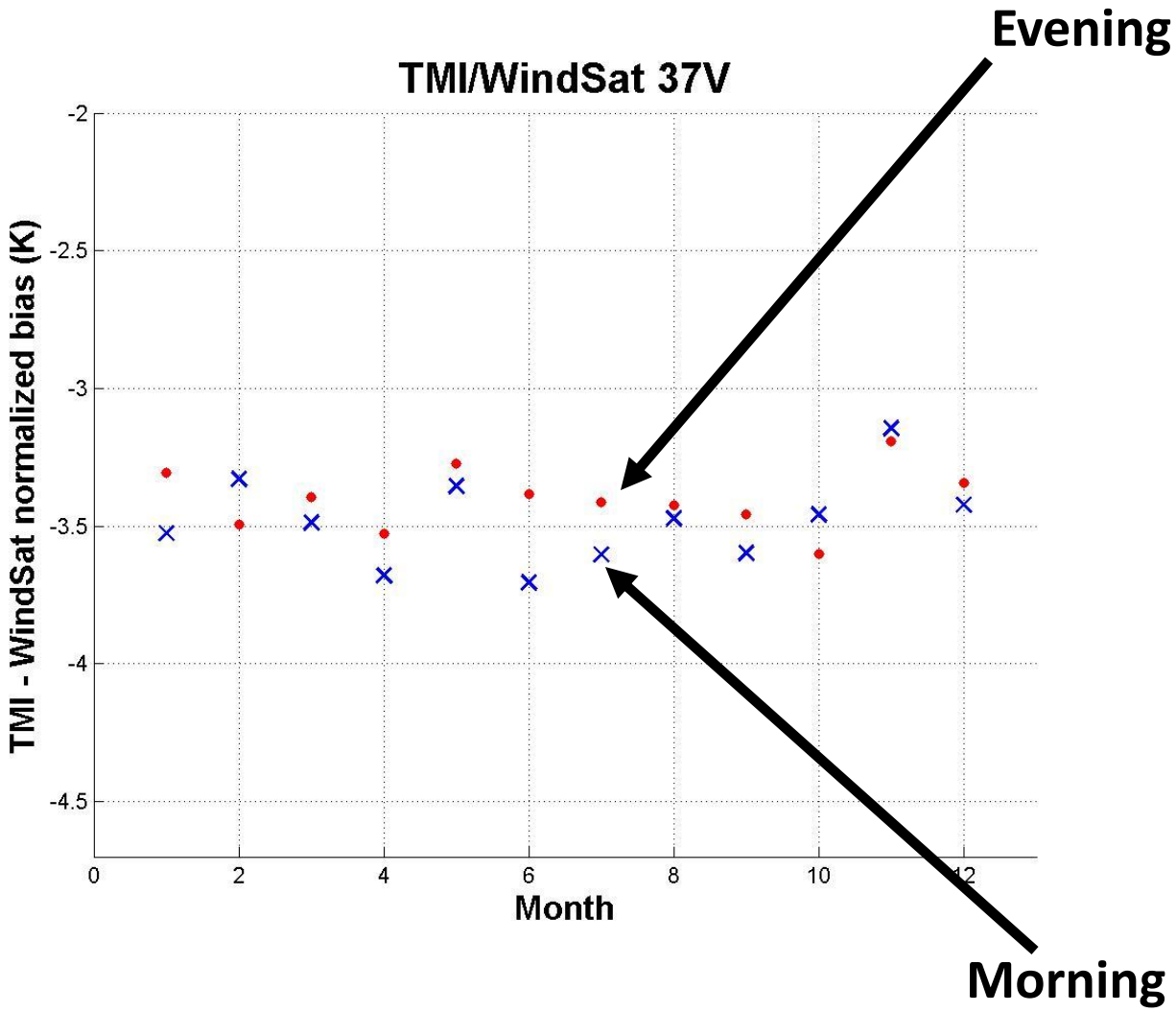
CFRSL

WindSat Uncorrected



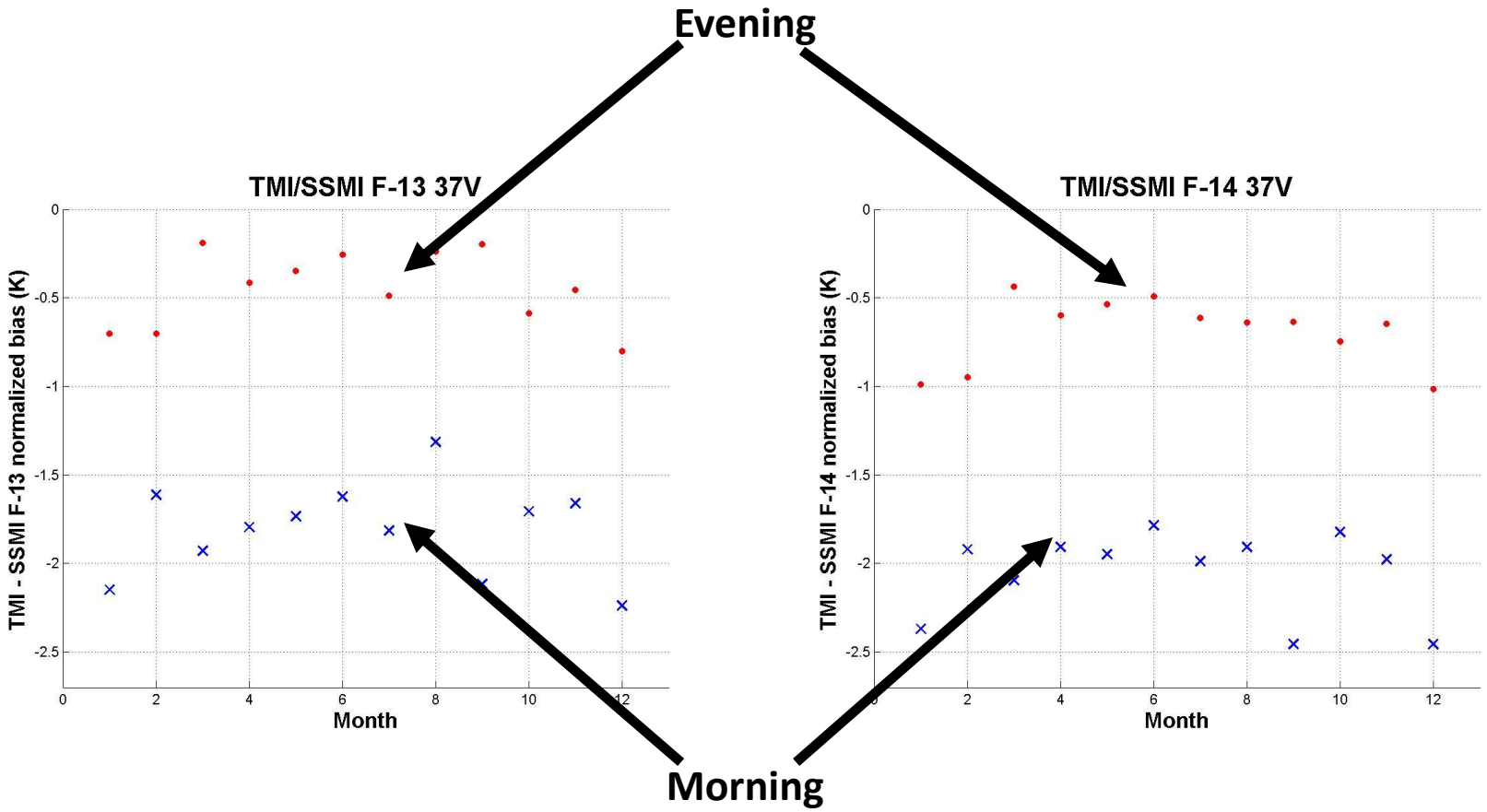
CFRSL

WindSat Corrected

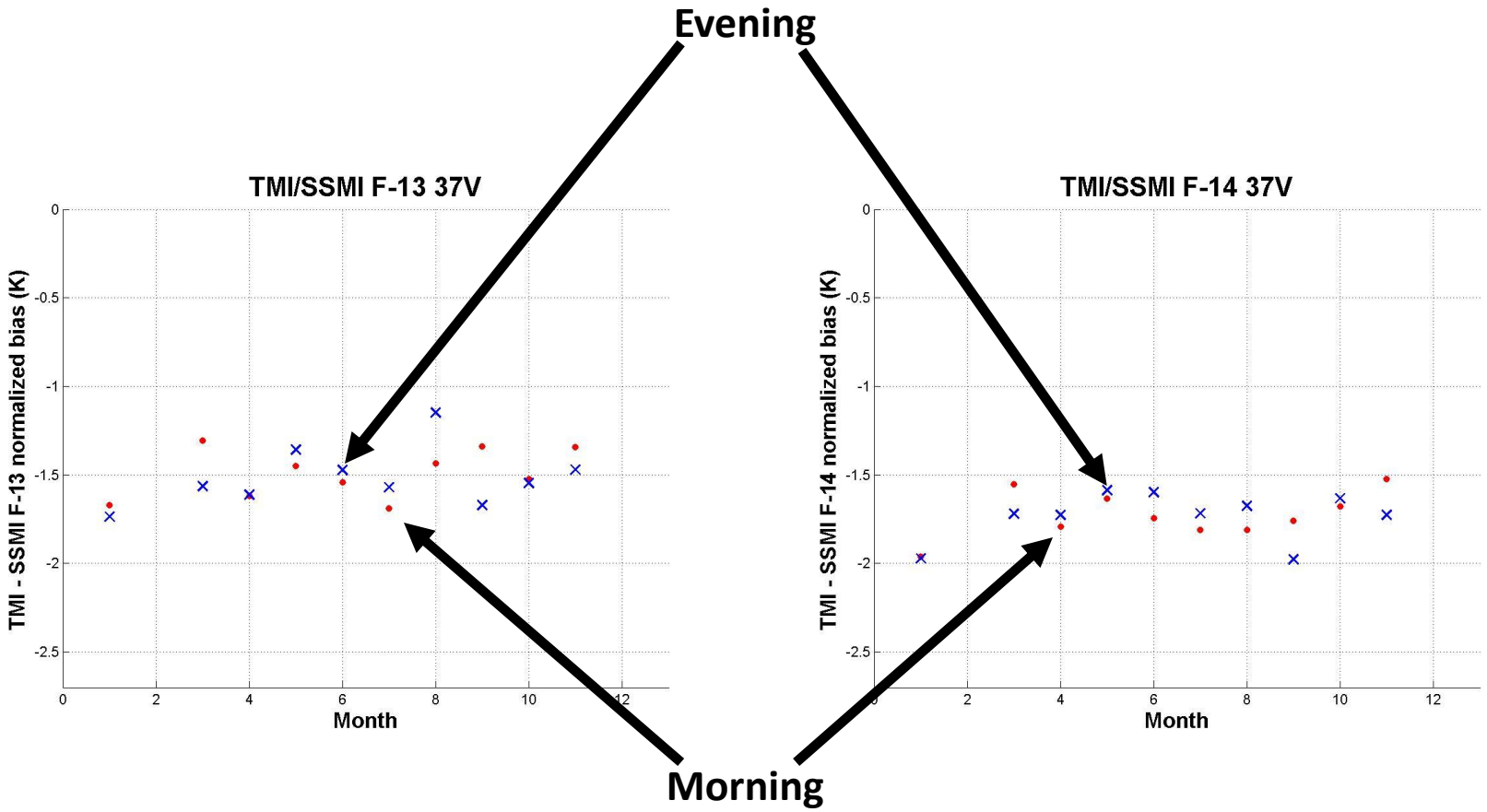


CFRSL

SSMI Uncorrected



SSMI Corrected



CFRSL

SSMI V-pol biases (Uncorrected)

Tb bias	F-13		F-14	
	Evening	Morning	Evening	Morning
19V	-0.44	-1.86	-0.07	-1.43
21V	-1.61	-2.99	-1.23	-2.62
37V	-0.44	-1.82	-0.68	-2.06

CFRSL

SSMI V-pol biases (Corrected)

Tb bias	F-13		F-14	
	Evening	Morning	Evening	Morning
19V	-1.50	-1.58	-1.12	-1.13
21V	-2.67	-2.71	-2.28	-2.32
37V	-1.50	-1.54	-1.73	-1.76

CFRSL

TMI-WindSat V-pol biases

Tb bias	Uncorrected		Corrected	
	Evening	Morning	Evening	Morning
10V	0.87	-0.54	0.00	-0.01
19V	0.16	-1.38	-0.71	-0.85
21V	-0.95	-2.58	-1.82	-2.05
37V	-2.53	-4.01	-3.40	-3.49

CFRSL

V7 Radiometric Bias

- Estimated bias applied in the form of look-up table based on orbit time after eclipse and beta angle
- Beta angle : 1 degree (or finer) quantization
- Orbit time : 1 minute quantization
- Separate look-up tables for pre-boost and post-boost periods

V7 Radiometric Bias

- Post-boost bias estimate table to be created by averaging estimated bias for all 1 degree pixels from 2004-2007 for every beta/orbit time bin
- Pre-boost bias estimate table to be created by averaging estimated bias for all available 1 degree pixels for every beta/orbit time bin
- Smoothing applied to table for both beta and time

Summary

- Radiometric Inter-calibration performed for ICWG dataset
- Time-varying TMI bias discovered, and corrected using an empirical method based on comparing TMI observations to RTM
- TMI error estimated as function of orbit time after eclipse and sun angle
- Correction will be applied to TRMM 1B11 v7, scheduled for release in 2010

CFRSL

Publications

- K. Gopalan, L. Jones, T. Wilheit, and T. Kasparis, “Inter-Satellite Radiometer Calibration of Windsat, TMI AND SSMI”, *IGARSS 2008.*
- K. Gopalan, L. Jones, S. Biswas, S. Bilanow T. Wilheit, and T. Kasparis, “A Time-Varying Radiometric Bias Correction for the TRMM Microwave Imager”, submitted to TGARSS (accpted by GRSL)

CFRSL

Future work

- Analysis of TMI bias for pre-boost period
- Direct comparisons between WindSat and SSMI in polar regions
- Comparison of WindSat and RTM
- Detection of possible TMI pointing errors through comparison with RTM

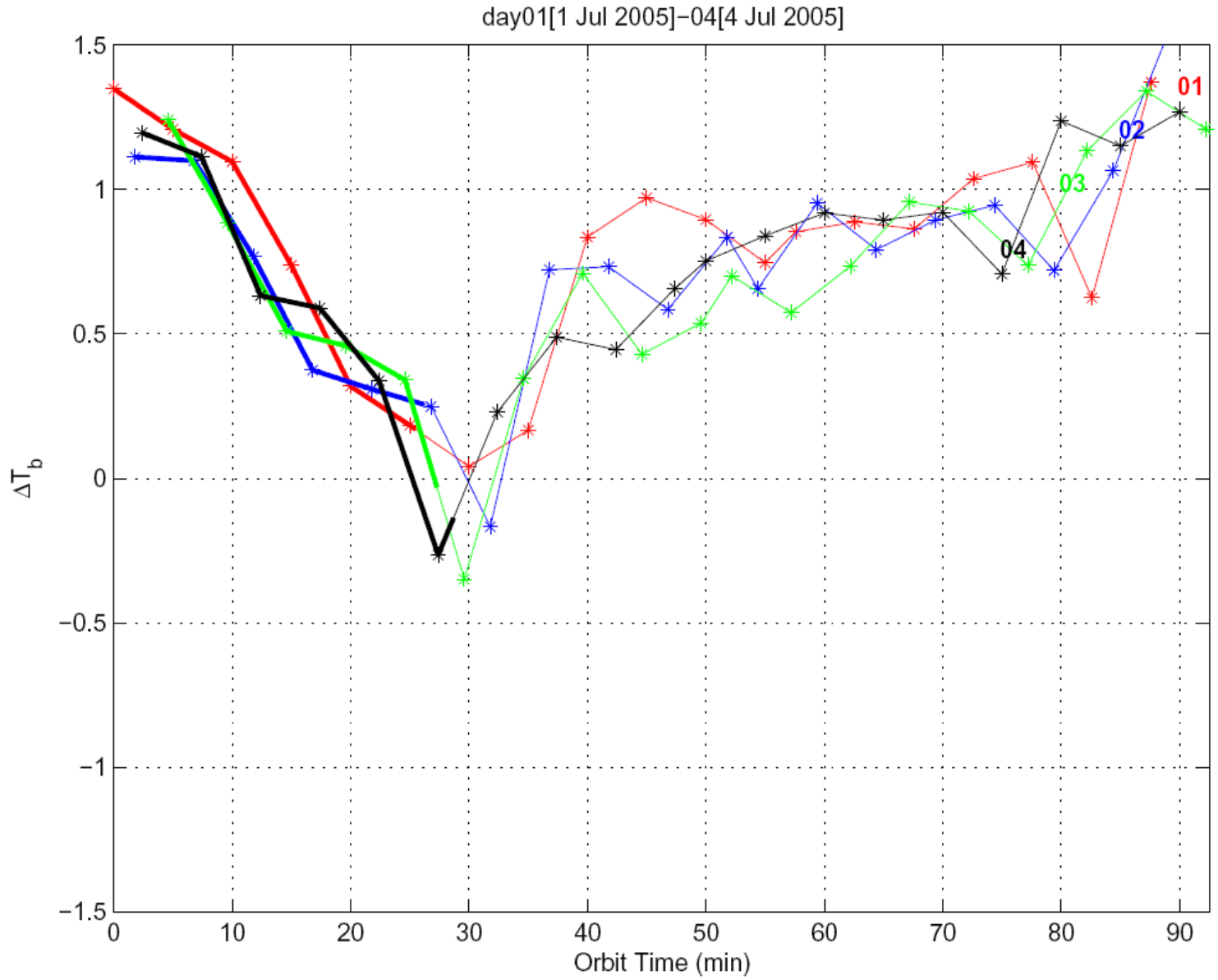
CFRSL

Back-up slides

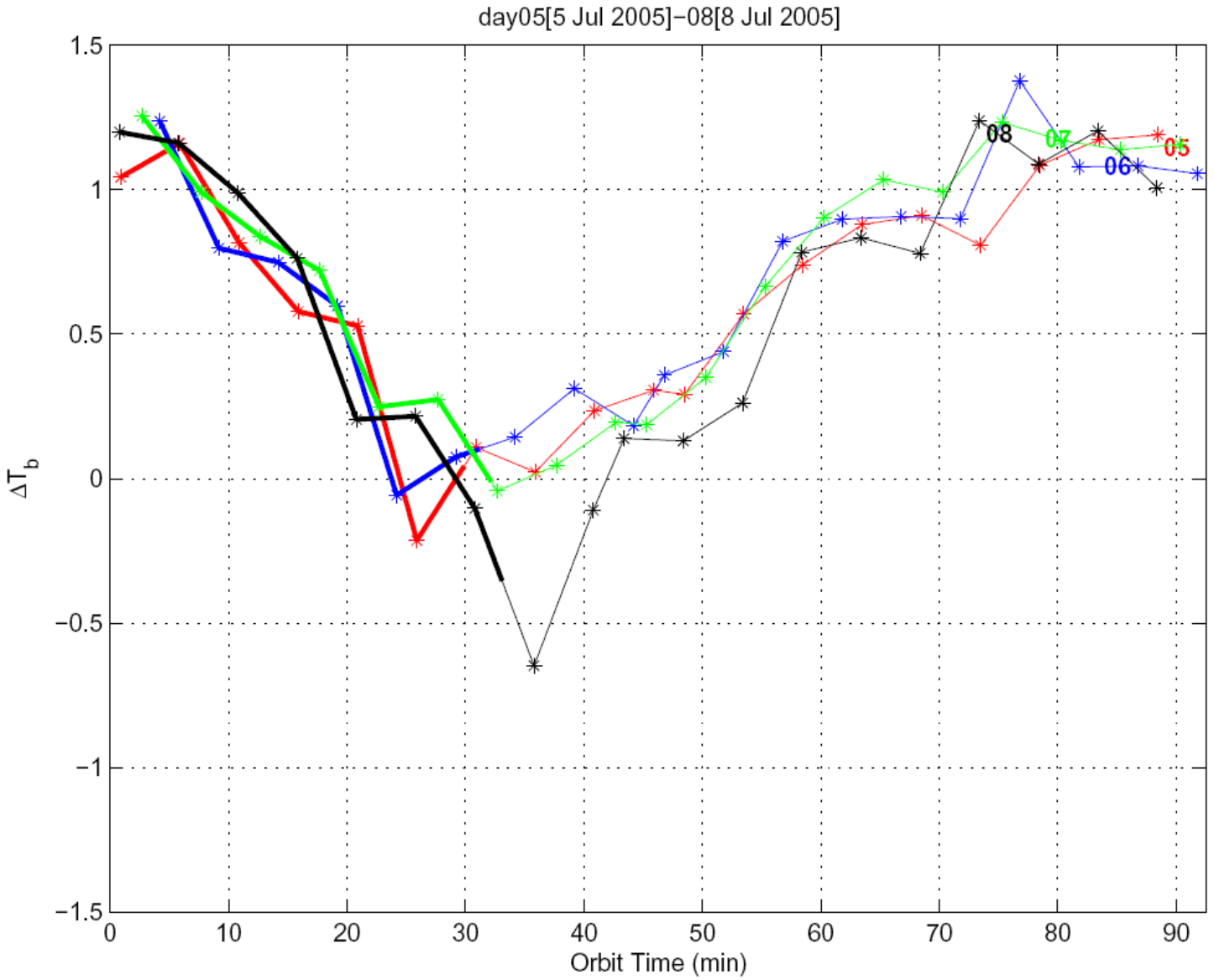
TMI bias dependence on sun angles

- Analysis was primarily performed by Sayak Biswas
- Direct contributions from Linwood Jones, Kaushik Gopalan and Steve Bilanow

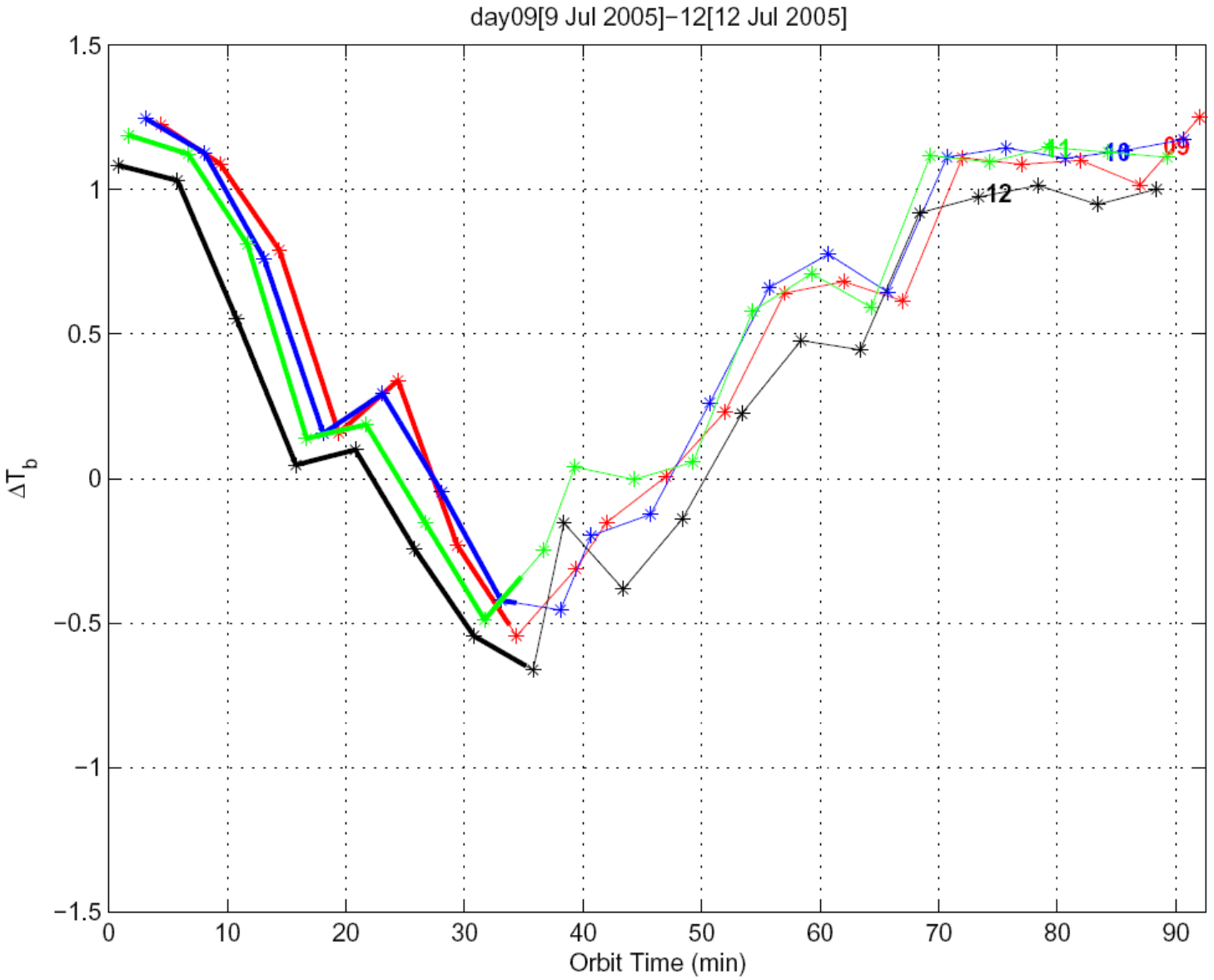
CFRSL


day01[1 Jul 2005]−04[4 Jul 2005]
ΔT_b
Orbit Time (min)
01
02
03
04
1.5
1
0.5
0
−0.5
−1
−1.5
0
10
20
30
40
50
60
70
80
90

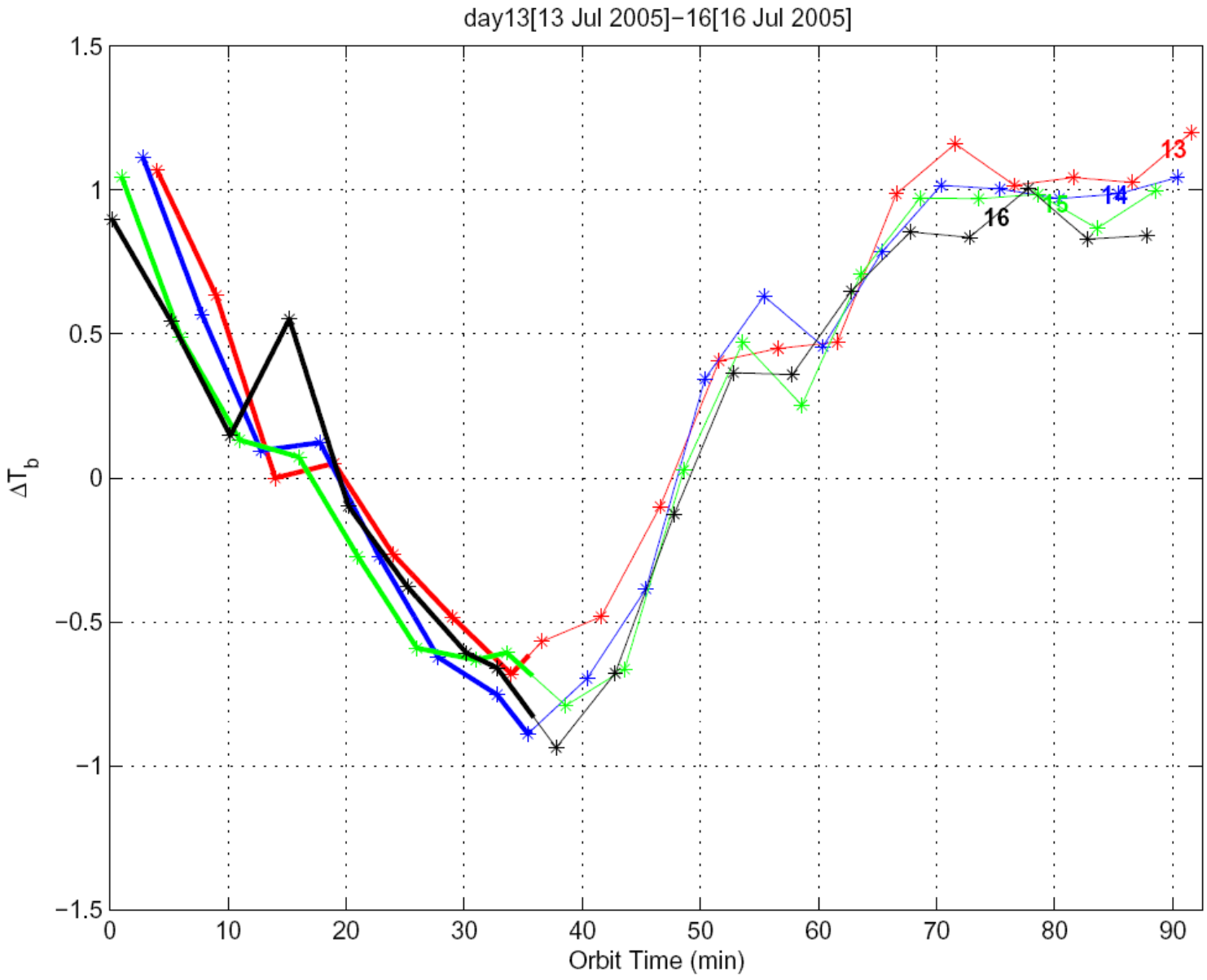
CFRSL


day05[5 Jul 2005]−08[8 Jul 2005]
1.5
1
0.5
0
−0.5
−1
−1.5
ΔT_b
0
10
20
30
40
50
60
70
80
90
Orbit Time (min)
08
07
06
05

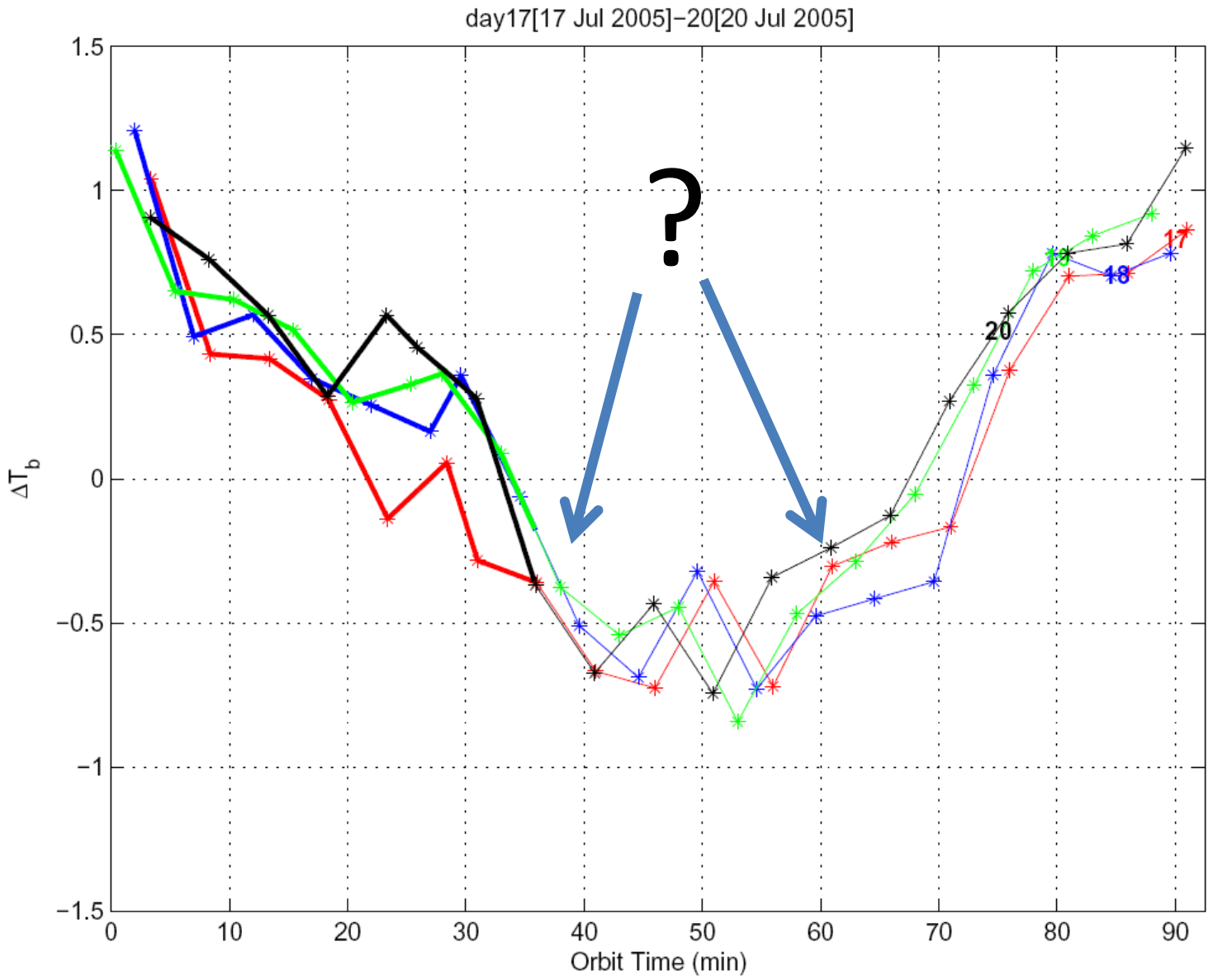
CFRSL


day09[9 Jul 2005]−12[12 Jul 2005]
1.5
1
0.5
0
−0.5
−1
−1.5
ΔT_b
0
10
20
30
40
50
60
70
80
90
Orbit Time (min)
11
10
09
12

CFRSL


day13[13 Jul 2005]−16[16 Jul 2005]
1.5
1
0.5
0
−0.5
−1
−1.5
ΔT_b
0
10
20
30
40
50
60
70
80
90
Orbit Time (min)
13
14
15
16

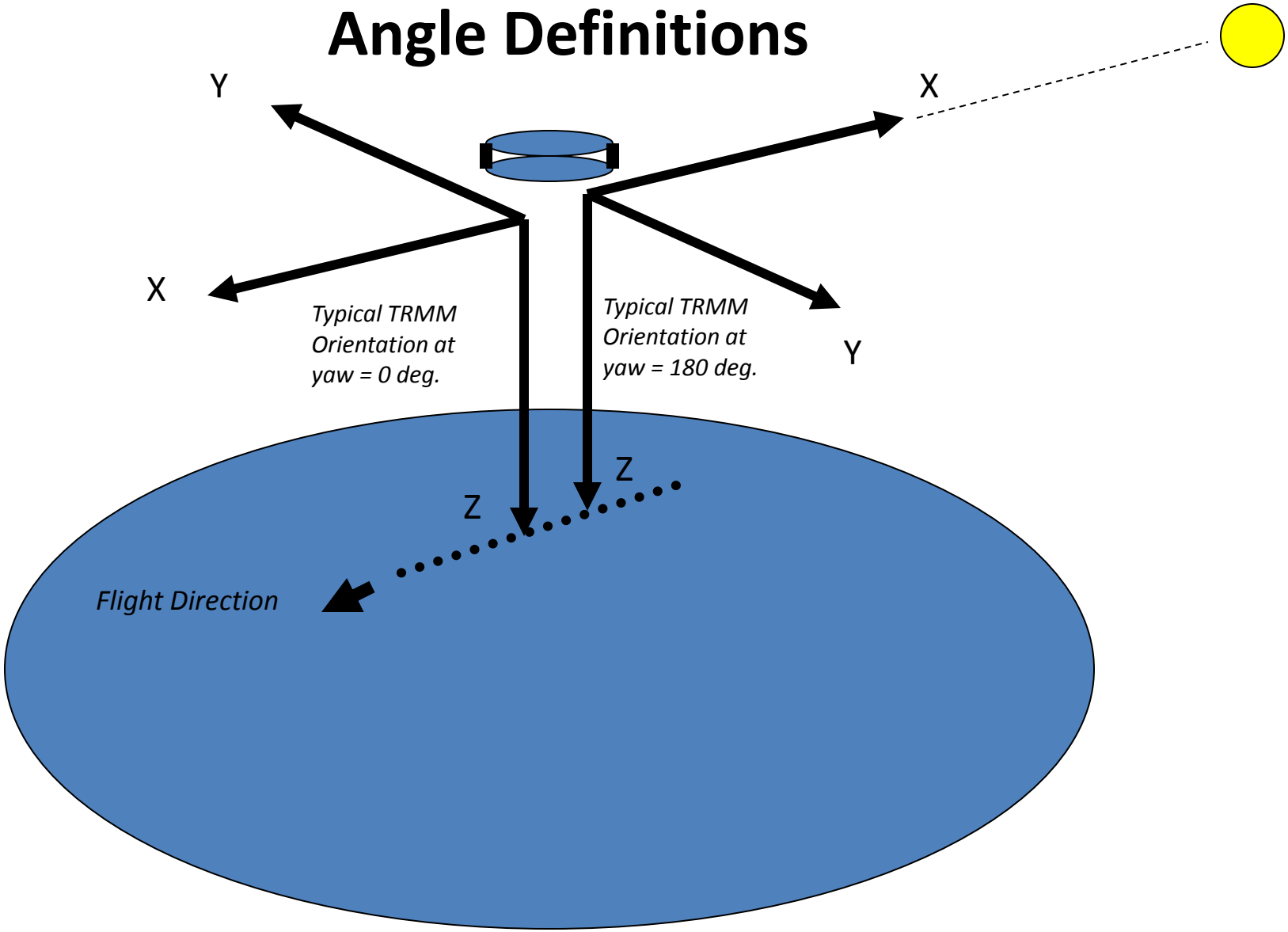
CFRSL


day17[17 Jul 2005]−20[20 Jul 2005]
?
17
18
19
20
ΔT_b
Orbit Time (min)
1.5
1
0.5
0
−0.5
−1
−1.5
0
10
20
30
40
50
60
70
80
90

CFRSL

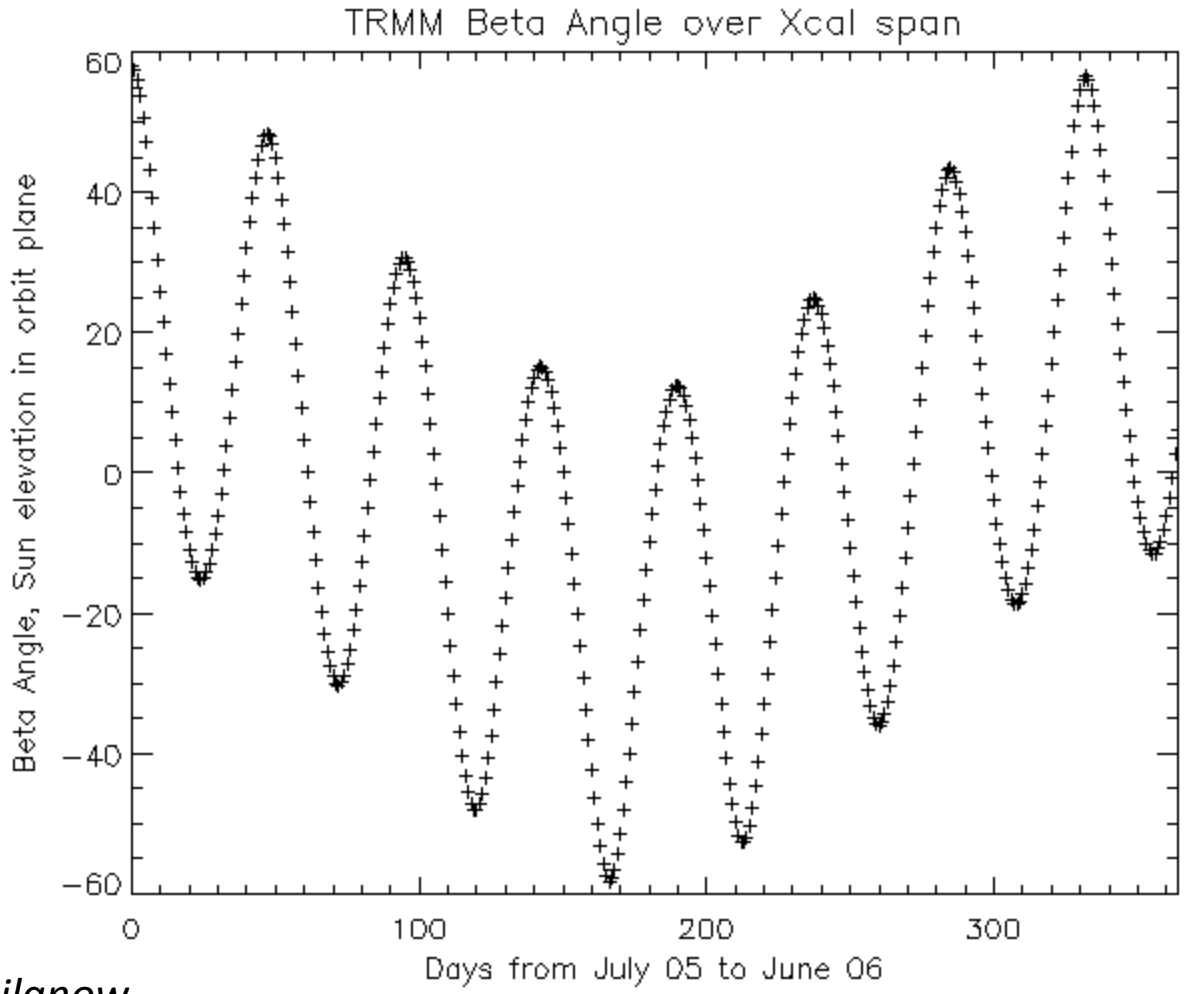
Courtesy: Steve Bilanow

Body or Instrument Coordinate Angle Definitions

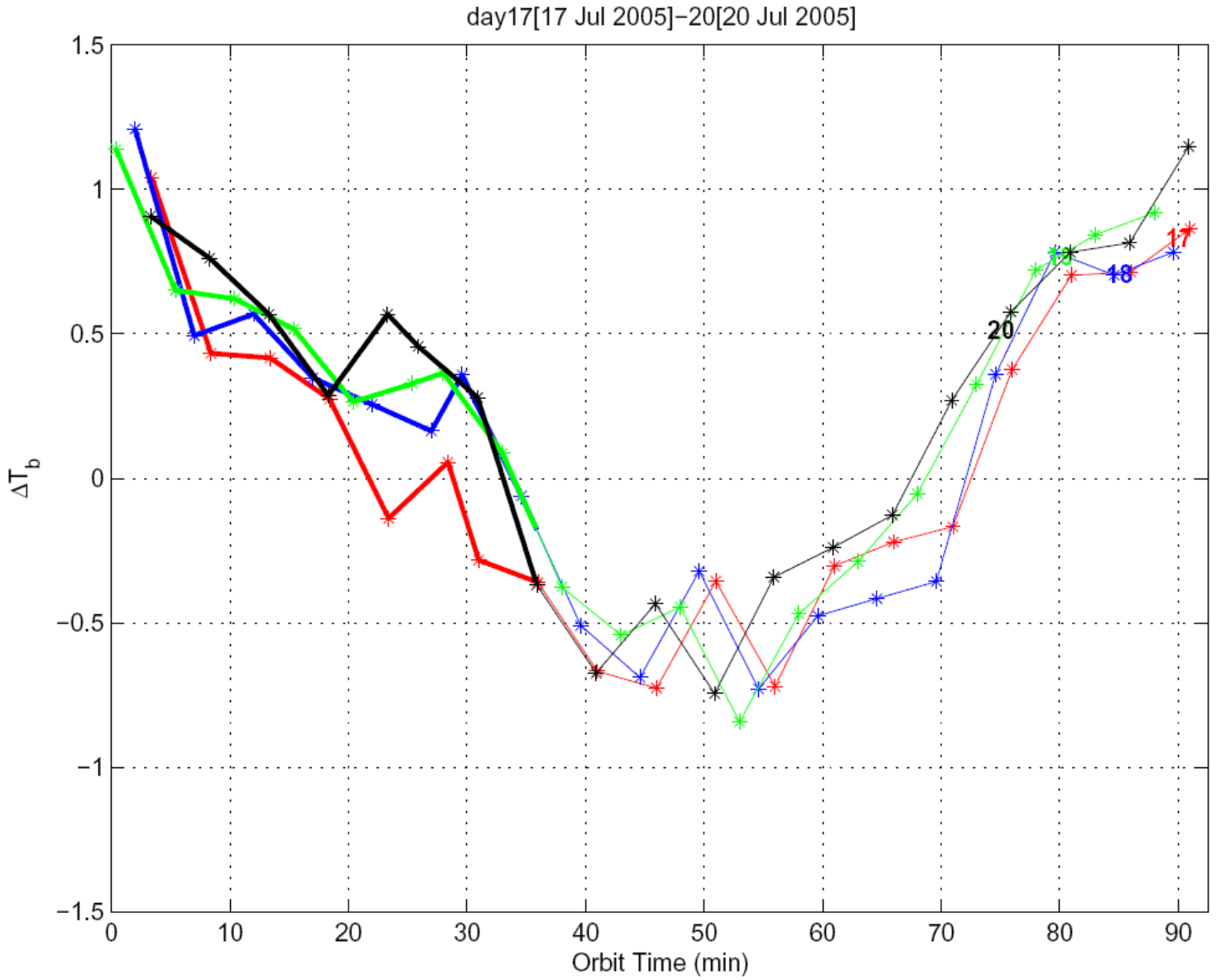


Solar beta angle : Sun elevation above X-Y plane positive toward –Z

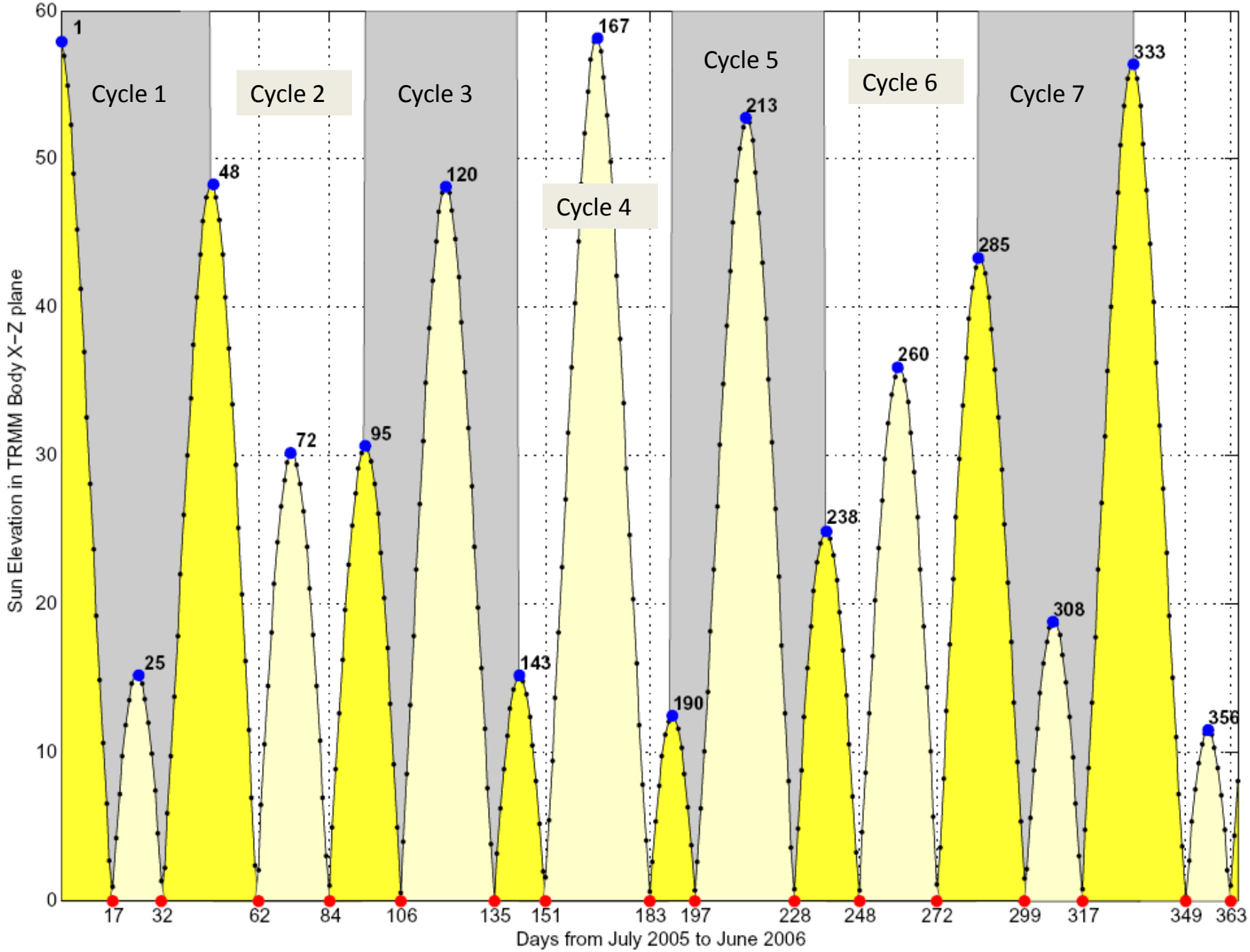
TRMM Solar Beta Angle Variation over 1 year is a combination of +/- 35 degrees due to the orbit inclination on a 46 or 47 day cycle, and the annual variation of +/- 23.5 degrees due to the Earth's axis tilt.



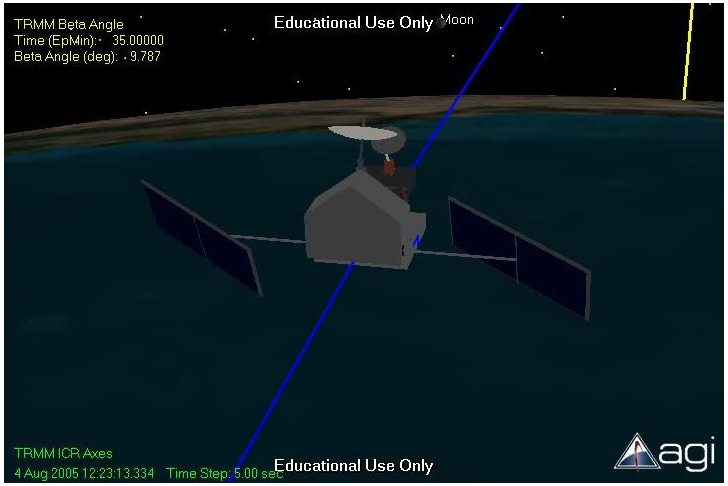
Courtesy: Steve Bilanow


day17[17 Jul 2005]−20[20 Jul 2005]
1.5
1
0.5
0
−0.5
−1
−1.5
ΔT_b
0
10
20
30
40
50
60
70
80
90
Orbit Time (min)
20
19
18
17

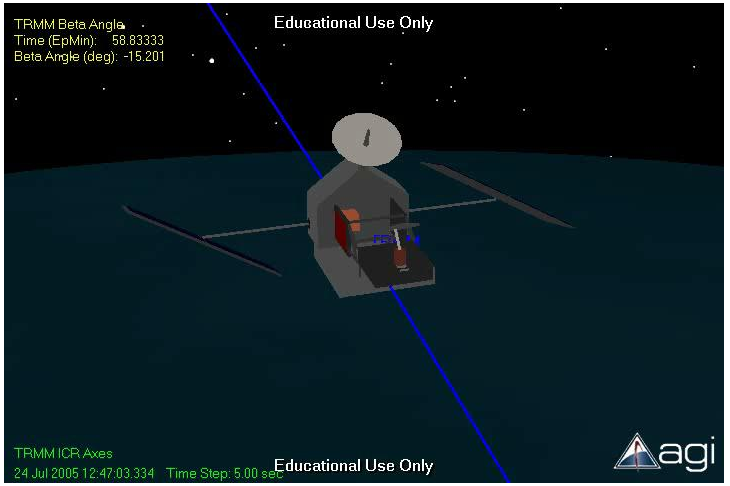
CFRSL


Cycle 1
Cycle 2
Cycle 3
Cycle 4
Cycle 5
Cycle 6
Cycle 7
1
25
48
72
95
120
143
167
190
213
238
260
285
308
333
356
17
32
62
84
106
135
151
183
197
228
248
272
299
317
349
363
0
10
20
30
40
50
60
Sun Elevation in TRMM Body X−Z plane
Days from July 2005 to June 2006

Yaw Flip



Beta > 0^0
+X body axis forward
yaw angle = 0^0

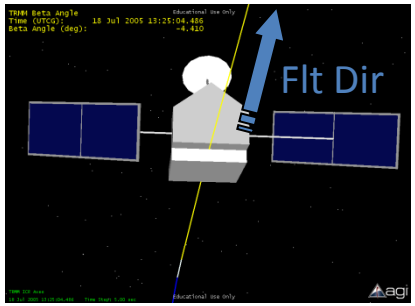


Beta < 0^0
-X body axis forward
yaw angle = 180^0

CFRSL

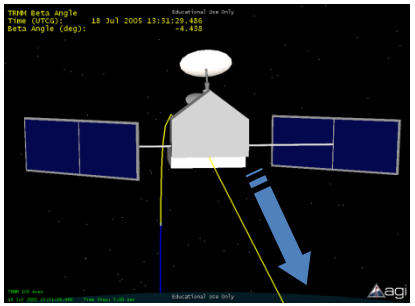
View From The Sun (negative beta angle)

Spacecraft Aft Structure Shadowing of TMI - Jul 18, 2005 [β= -4.4^0]



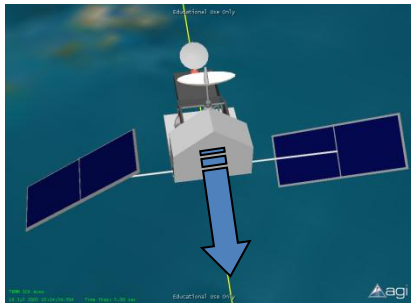
TRMM exits eclipse (TMI in shadow)

A



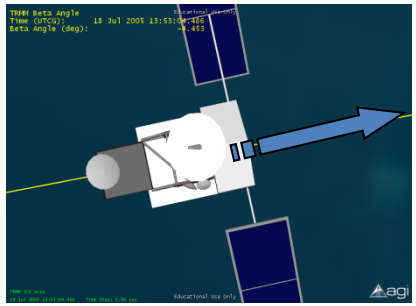
TMI exits S/C shadow

B



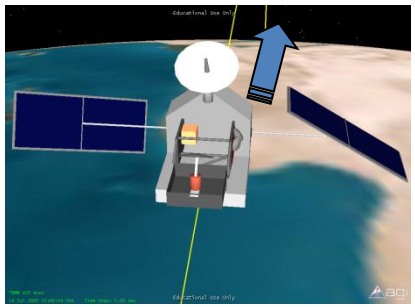
TMI in sunlight

C



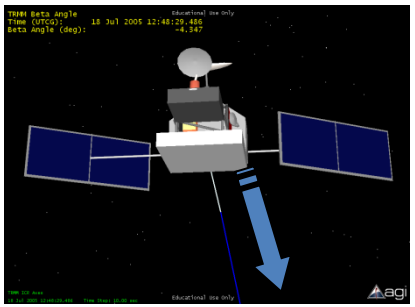
TMI in sunlight

D



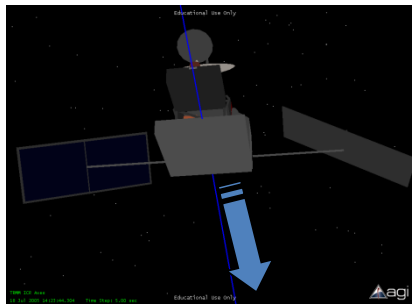
TMI in sunlight

E



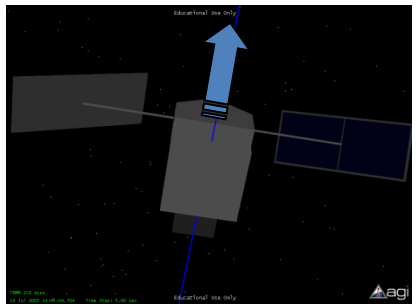
TMI reflector face illuminated before eclipse

F



TMI in eclipse

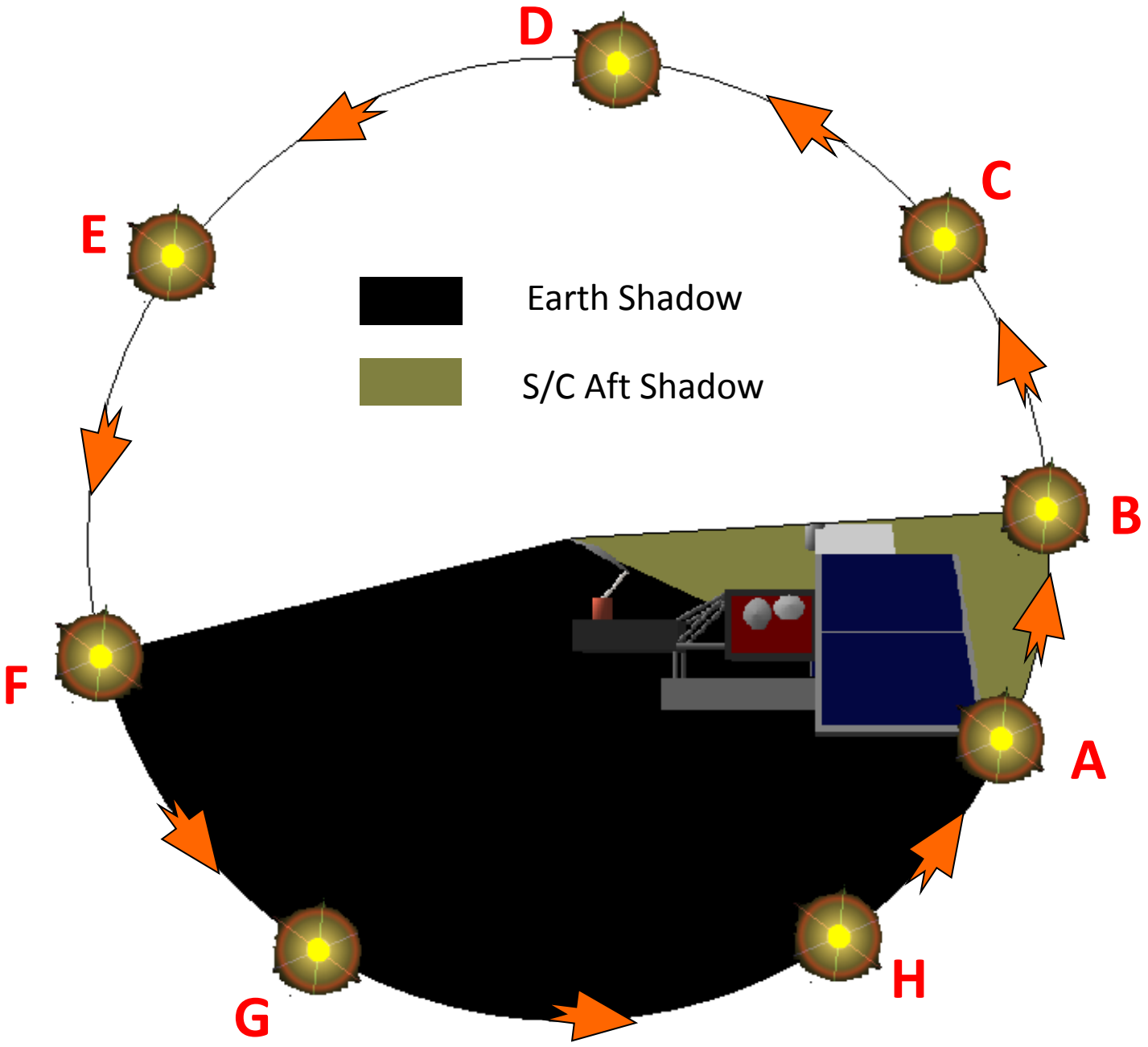
G



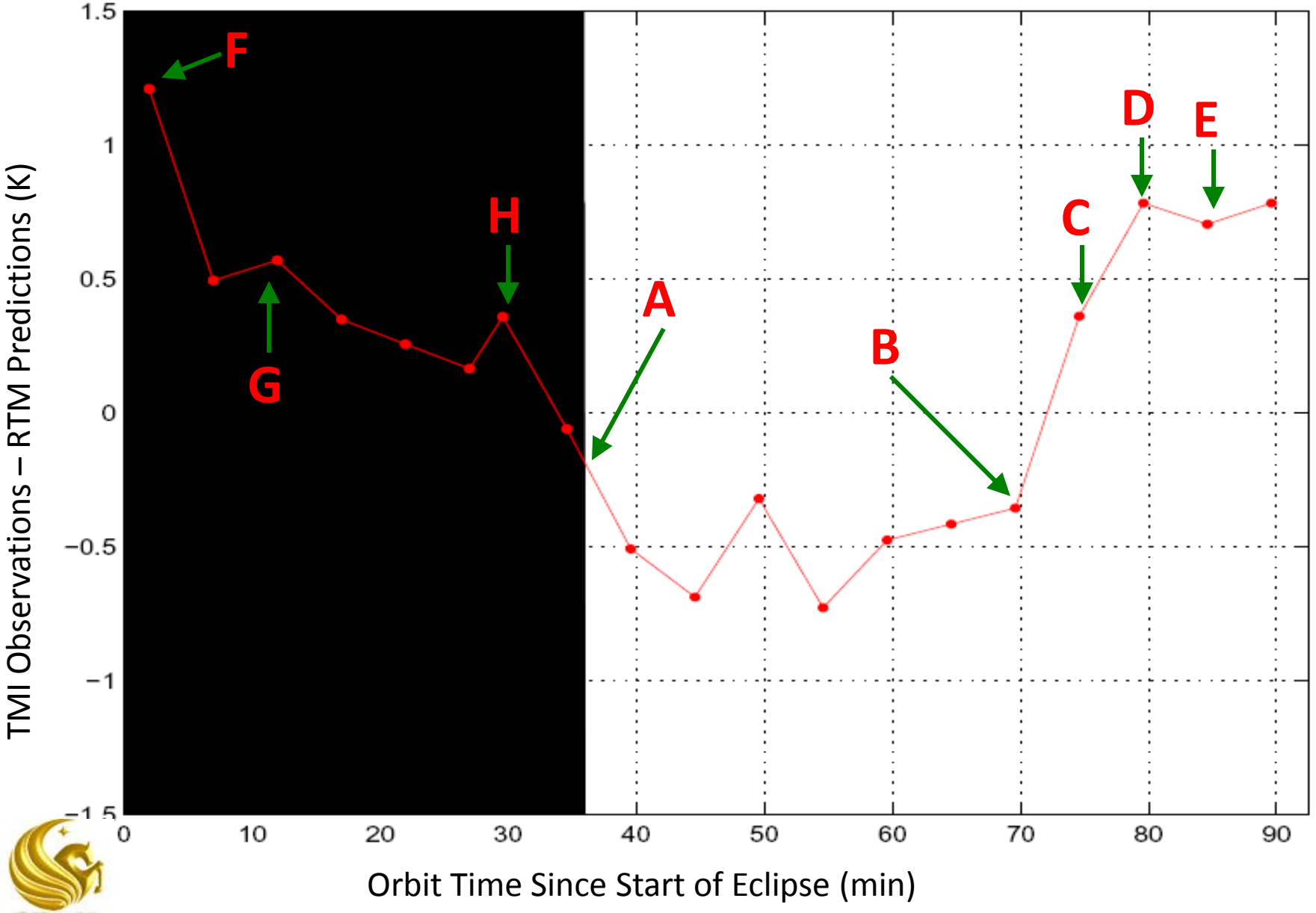
TMI in eclipse

H

CFRSL


D
C
E
Earth Shadow
S/C Aft Shadow
B
F
A
G
H

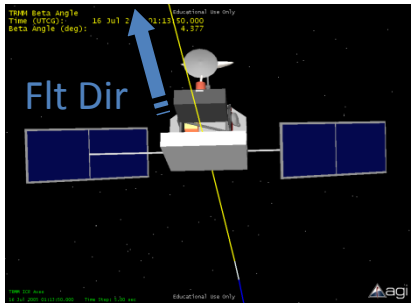
Spacecraft Aft Structure Shadowing of TMI - Jul 18, 2005 [β= -4.4^0]



CFRSL

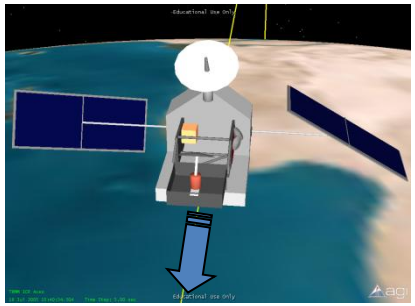
View From The Sun (positive beta angle)

Spacecraft Aft Structure Shadowing of TMI – Aug 02, 2005 [β= +4.3^0]



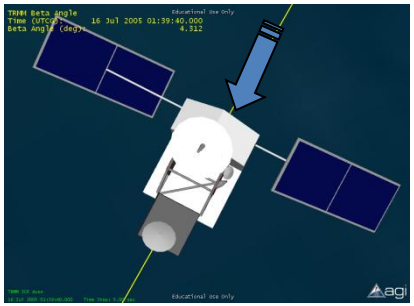
TRMM exits eclipse (TMI in sunlight)

A



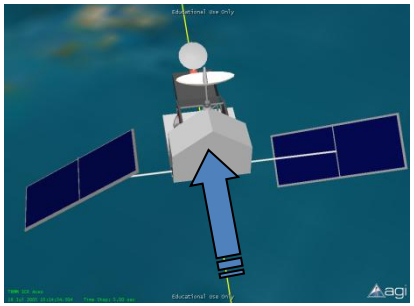
TMI in sunlight

B



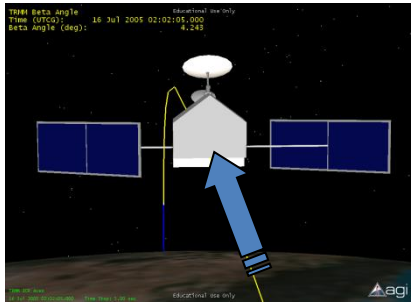
TMI in sunlight

C



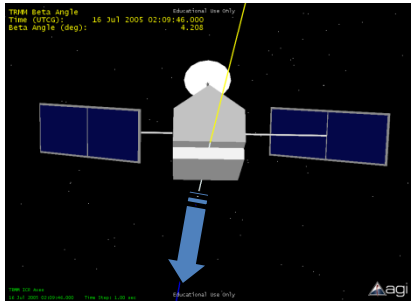
TMI in sunlight

D



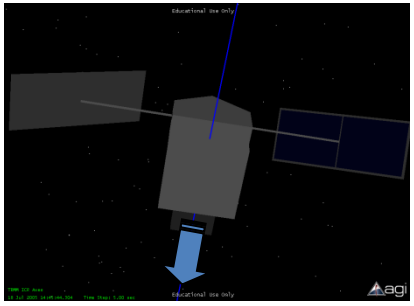
TMI enters S/C shadow

E



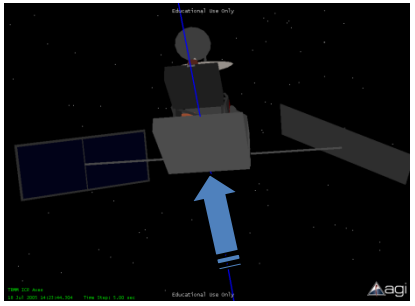
TMI in S/C shadow before eclipse

F



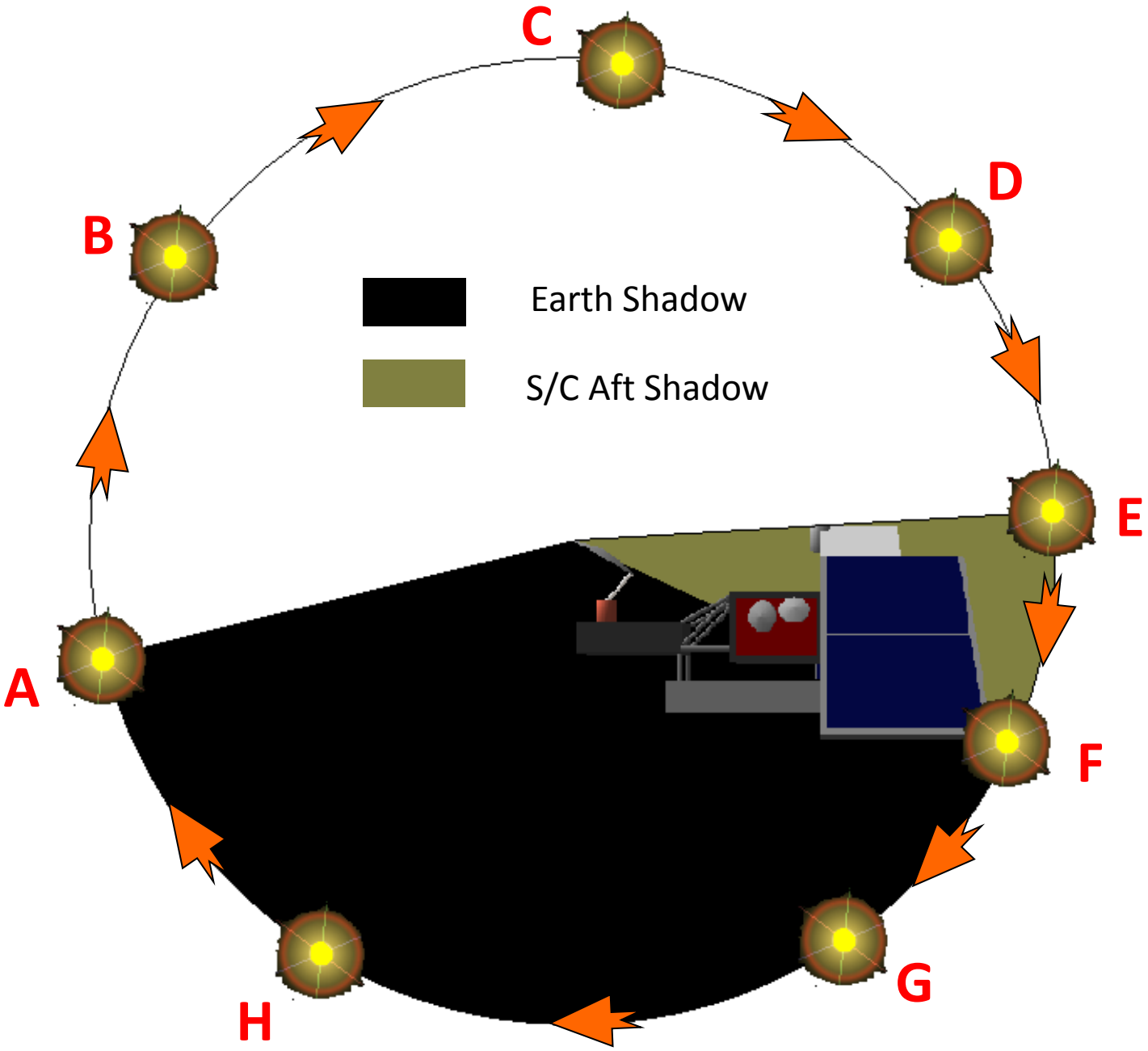
TMI in eclipse

G

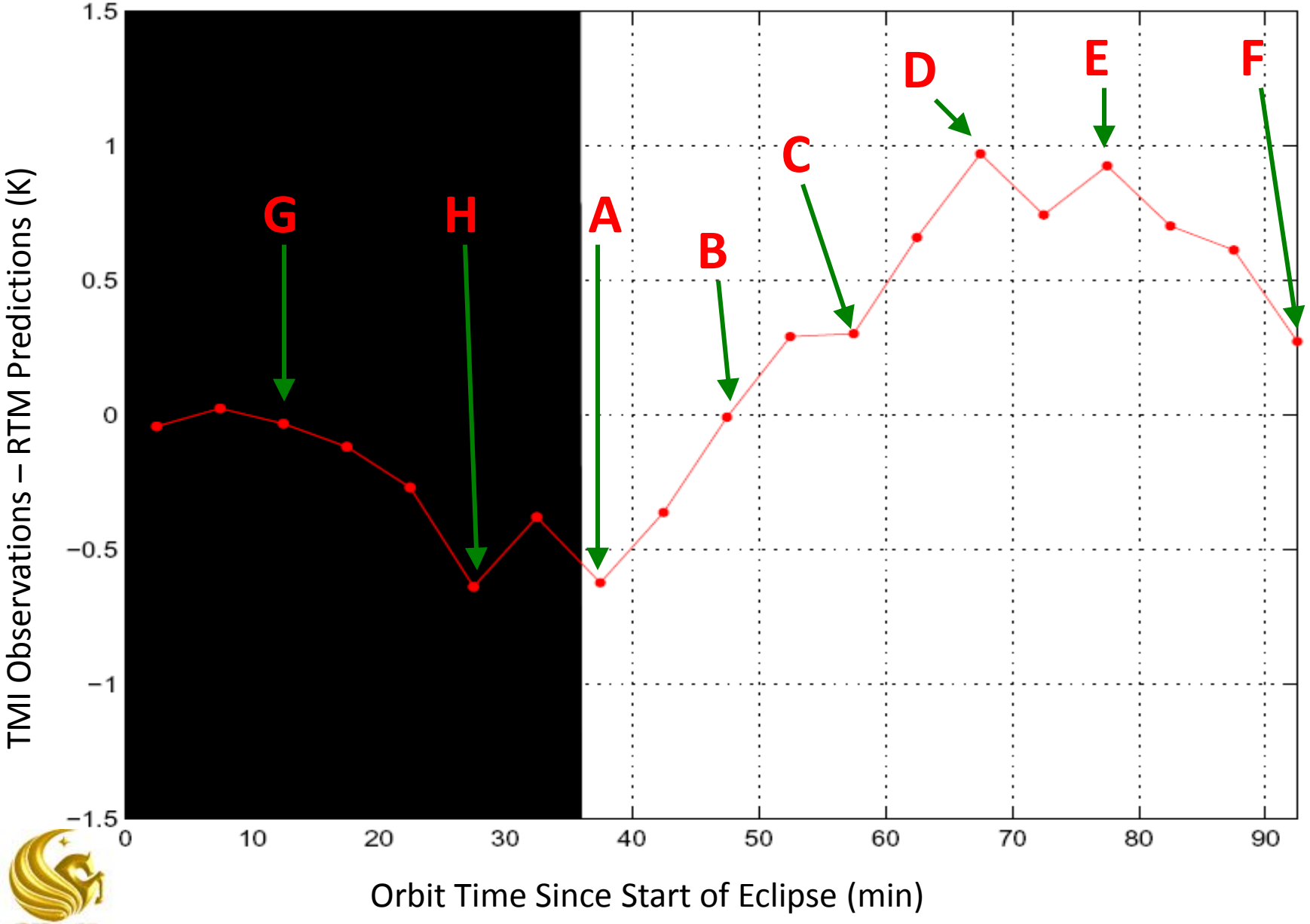


TMI in eclipse

H


C
D
B
Earth Shadow
S/C Aft Shadow
E
A
F
H
G

Spacecraft Aft Structure Shadowing of TMI – Aug 02, 2005 [β= +4.3^0]



CFRSL