In-Flight Calibration of the MMS Fluxgate Magnetometers

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Background

- The Magnetospheric Multiscale Mission (MMS) consists of 4 satellites, each with an identical Fluxgate Magnetometer (FGM) instrument suite consisting of an Analog Fluxgate (AFG) and a Digital Fluxgate (DFG). All 8 magnetometers were successfully deployed by 17 March 2015.
- Detailed and accurate ground calibrations were performed for each magnetometer.
- In order to meet mission goals, in-flight calibrations are necessary to evaluate and track changes in offset, alignment, gain and orthogonality.
- In addition, calibrated magnetometer data is necessary for instrument suite operations as well as ground data processing for other instruments.
- The calibration effort for the MMS Analog Fluxgate (AFG) and Digital Fluxgate (DFG) magnetometers is a coordinated effort between three primary institutions:
  - University of California, Los Angeles (UCLA)
  - Space Research Institute, Graz, Austria (IWF)
  - NASA Goddard Space Flight Center (GSFC)
- This presentation will focus on the calibration effort at GSFC.

MMS Mission Requirements and Goals for FGM

- Shall provide science quality FGM data (Level 2) within 30 days of data downlink.
- Mission goals for Level 2 FGM accuracy
  - Absolute accuracy: 0.3 nT.
  - Relative accuracy between spacecraft: 0.1 nT
  - High relative accuracy between spacecraft is needed to assure accurate measurements of electric current density using curlometer
- Provide preliminary calibrated magnetometer data (L2pre) for instrument suite operations and ground data processing within 2 weeks of data downlink.

Fundamentals of In-flight Calibration

- The calibration fundamentally consists of 12 parameters (e.g. 9 matrix elements and 3 offsets)
  - Offset, orthogonalization, alignment, and gain
  - Each instrument (AFG and DFG) has two ranges (Low-field and High-field), each of which has its own set of 12 parameters.
  - Total of 24 parameters for each instrument.
- Full determination of all parameters requires application of different calibration methods
  - Orthogonalization
  - Spin-axis offset from EDI
  - Earth Field Comparison
  - Range Joining and Instrument cross-calibration
- Each method has an effect on some subset of the 24 parameters for each instrument.

Leveraging the Ground Calibrations

- Ground calibrations, performed largely at TUBS, provide measurements that are difficult, if not impossible to measure more accurately in space:
  - Temperature-dependence of gain
  - Non-linearity of gain
- These calibrations are applied to all data as the first step of data processing.
  - In-flight *gain* parameters thus indicate a delta relative to the ground calibration
  - Ground calibrations provide initial values for most other parameters, which may be compared to the in-flight calibration results.

Temperature-Dependence of Gain

$$B_{123temp} = B_{123} \cdot (g + m_s \cdot T_s) \cdot \left(1 + m_e \cdot (T_e - T_{eC})\right)$$

where

$B_{123temp}$	temperature and gain pre-calibrated B123 data (3 element vector time series)
B_{123}	L1A data in pseudo-nT (3 element vector time series)
g	ground based gain delta factor relative to pseudo-nT preliminary calibration (3 element vector)
m_s	ground based temperature delta factor relative to pseudo-nT preliminary calibration (3 element vector)
T_s	onboard sensor temperature (scalar time series)
m_e	electronics temperature coefficient from ground calibration (3 element vector)
T_e	onboard electronics temperature (scalar time series)
T_{eC}	reference temperature of electronics from ground calibration (scalar)

High Field Gain Non-Linearity

$$\boldsymbol{B}_{\mathbf{123}\boldsymbol{precal}} = \boldsymbol{\sigma}_{\mathbf{1}} \cdot \boldsymbol{B}_{\mathbf{123}\boldsymbol{temp}} + \boldsymbol{\sigma}_{\mathbf{2}} \cdot \boldsymbol{B}^{\mathbf{2}}{}_{\mathbf{123}\boldsymbol{temp}} + \boldsymbol{\sigma}_{\mathbf{3}} \cdot \boldsymbol{B}^{\mathbf{3}}{}_{\mathbf{123}\boldsymbol{temp}}$$

Note: no correction is applied for AFG, hence,

σ_1 = 1.0, except for DFG High range.

σ_2, σ_3 = 0.0, except for DFG High range.

FGM Approach to In-flight Calibration

- The in-flight calibration is performed after the ground calibrations have been applied to the gains, so all gains are referred to as ‘delta-gains’.
- A method developed at IWF modifies the standard calibration equation to optimize physical parameters independently rather than in a joint way.
  - Allows keeping parameters constant that may be considered “fixed” – at least in comparison to others.
  - Allows, e.g. keeping sensor orthogonality constant during maneuvers that affect the spin axis orientation, by treating the latter as pure rotations.
- In-flight calibration parameters are separated into the following categories:
  - Offset subtraction
  - Relative delta-Gain of spin plane sensors.
  - Absolute delta-gain of spin plane and spin axis.
  - Orthogonalization of the sensor triad
  - Alignment to spin axis
  - Absolute phase correction.

Orthogonalizing the Sensor Triad; Applying Gains and Offsets

Orthogonalization: referenced to spin-axis sensor	Absolute delta-gain	Relative spin-plane delta-gain	Offset subtraction

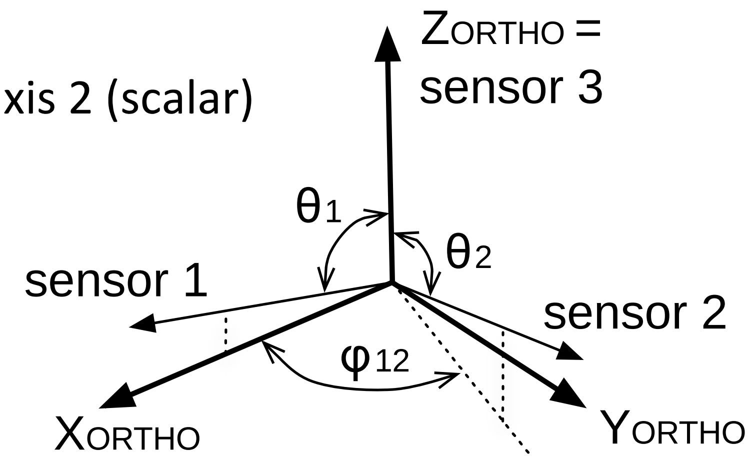
$$B_{ORTHO} = \begin{pmatrix} \sin\vartheta_1 & 0 & \cos\vartheta_1 \\ \cos\varphi_{12}\sin\vartheta_2 & \sin\varphi_{12}\sin\vartheta_2 & \cos\vartheta_2 \\ 0 & 0 & 1 \end{pmatrix}^{-1} \cdot \begin{pmatrix} dg_{SP\_abs} & 0 & 0 \\ 0 & dg_{SP\_abs} & 0 \\ 0 & 0 & dg_{SA\_abs} \end{pmatrix} \cdot \begin{pmatrix} dg_{SP} & 0 & 0 \\ 0 & 1/dg_{SP} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} B_{1precal} - O_1 \\ B_{2precal} - O_2 \\ B_{3precal} - O_3 \end{pmatrix}$$

where we use 9 parameters:

ϑ_1, ϑ_2	elevation angles of axis 1 and 2 in respect to axis 3 (scalar)
φ_{12}	angle between axis 1 and 2 (scalar)
dg_{SP_abs}	absolute delta-gain of spin plane (scalar)
dg_{SA_abs}	absolute delta-gain of spin axis (scalar)
dg_{SP}	relative delta-gain between axis 1 and axis 2 (scalar)
O_1, O_2	spin plane offsets
O_3	spin axis offset

To yield the result:

B_{ORTHO}	orthogonalized B field data



Aligning the Sensor Triad

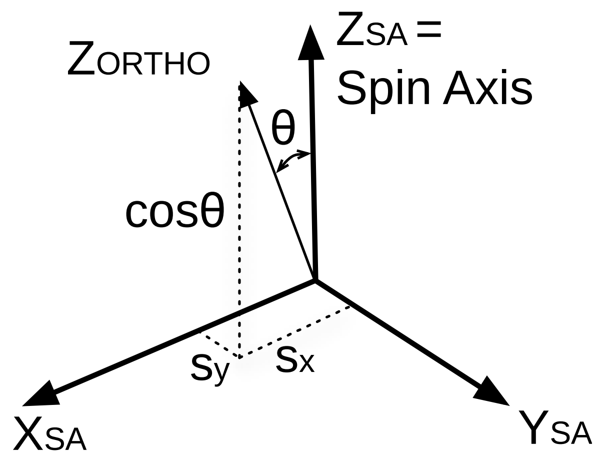
Alignment to spin-axis via solid-body rotation

s_x, s_y The X and Y components of the spin-axis sensor, with respect to Spin-Aligned (SA) Sensor Coordinates.

SA coordinates

X-axis To a good approximation, ORTHO X-axis is in the SA X-Z plane.

Z-axis Aligned with the major principal axis of inertia (MPA).



Absolute Phase Correction

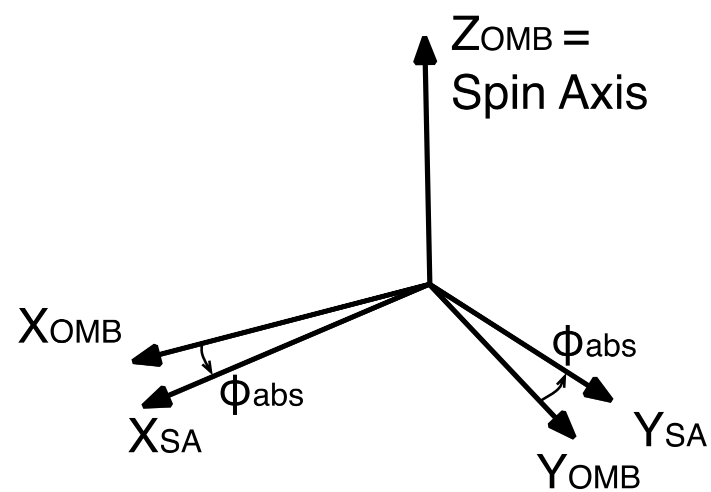
φ_{abs} absolute rotation around spin axis

OMB Coordinates

X-axis Defined by the nominal AFG boom coordinates. AFG X-axis is in the OMB X-Z plane.

Y-axis Completes Right-handed system

Z-axis Aligned with MPA



Team Approach to In-flight Calibration

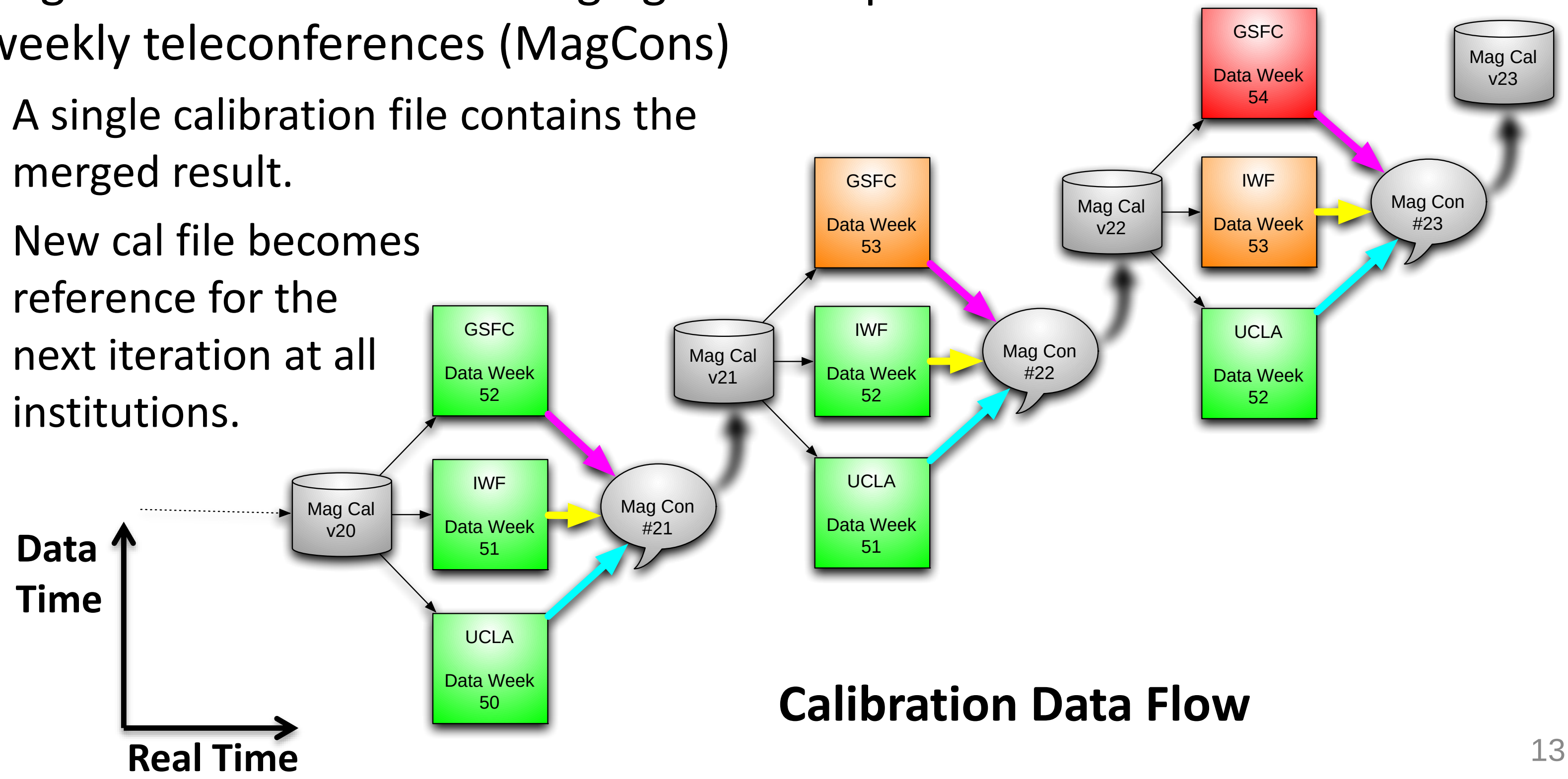
- A benefit of the IWF arrangement of the calibration equation is that it yields parameters for the in-flight calibration parameters which can be ‘owned’ by a single optimization process.
  - In contrast, for example, when using a coupling matrix, each element may be affected by Orthogonalization, Earth Field Comparison, Range Joining, etc.
  - Full responsibility for a subset of parameters is delegated to each of the teams, according to the calibration methods they will employ.
- The order in which the in-flight calibration methods are applied is determined by
  - The probability of change for a given parameter.
  - Required integration time and need for “look-ahead”.
- The final result can be clearly understood in terms of the contributions of each of the teams and their respective calibration methods.

Mapping Parameters to Calibration Processes, Calibration Processes to Institutions

		Calibration Parameters	Parameter Names: Low field range	Parameter Names: High Field Range	Physical Methods Used	Owner
CALIBRATION PROCESS	"ORTHOGONALIZATION"	spin plane offsets	o_1, o_2	o_1, o_2	Minimize spectral power at ω_{spin} in the spin plane.	GSFC
CALIBRATION PROCESS	"ORTHOGONALIZATION"	spin plane gain differential and non-orthogonality	dg_SP ϕ_{12}	dg_SP ϕ_{12}	Minimize spectral power at $2\omega_{spin}$ in the spin plane.	GSFC
CALIBRATION PROCESS	"ORTHOGONALIZATION"	elevation angles of spin plane sensors	θ_1, θ_2	θ_1, θ_2	Minimize slope of regression between apparent spin-plane sensor offset and the spin-axis field.	GSFC
CALIBRATION PROCESS	"ORTHOGONALIZATION"	spin axis alignment	S_x, S_y	S_x, S_y	Minimize spectral power at ω_{spin} on the spin axis.	GSFC
CALIBRATION PROCESS	EDI	spin axis offset	o_3		Electron time of flight method: Electron Drift Instrument (EDI) provides |B|.	IWF
CALIBRATION PROCESS	EARTH FIELD	high range: absolute gains, absolute phase		dg_SA_abs dg_SP_abs ϕ_abs	Fit to Data to Earth Field Model using weighted linear regression.	UCLA
CALIBRATION PROCESS	RANGE JOINING and INTERSPACECRAFT	spin axis: low range gain, high range offset	dg_SA_abs	o_3	Propagate high range gains to low range, cross-calibrating AFG, DFG, 4 observatories. Propagate low range offset to high range.	UCLA
CALIBRATION PROCESS	RANGE JOINING and INTERSPACECRAFT	low range spin plane: absolute gain, absolute phase	dg_SP_abs ϕ_abs		Match gain and phase of low range data to high range data, cross-calibrating AFG, DFG, 4 observatories.	UCLA

Bringing Everything Back Together

- An interval of data (typically one week) is calibrated successively at GSFC, IWF, UCLA
  - Each institution submits proposed changes to the calibration.
  - A ‘change’ is not a delta, but a new value for a given parameter, to be used over a specific interval.
- Configuration control and merging is accomplished in weekly teleconferences (MagCons)
  - A single calibration file contains the merged result.
  - New cal file becomes reference for the next iteration at all institutions.



Calibration Data Flow

Results Merged into a Single Calibration

- Latest time interval in calibration file contains L2pre calibration.
  - L2pre data are processed and made available for ground processing by other instruments.
- Magcon decides when all parameters have been fully updated for a given interval.
  - L2 data are processed and made available to the science community.
- There are 16 calibration files in all:
  - 4 observatories
  - x2: AFG and DFG
  - x2: High field range and Low field range

Parameters	Data Week 50	Data Week 51	Data Week 52	Data Week 53	Data Week 54
o_1, o_2, φ_{12}, dg_SP, S_x, S_y, θ_1, θ_2	v19	v20	v21	v22	v23
o_3 (low range)	v20	v21	v22	v23	
o_3, dg_SA_abs, dg_SP_abs, φ_abs	v21	v22	v23		

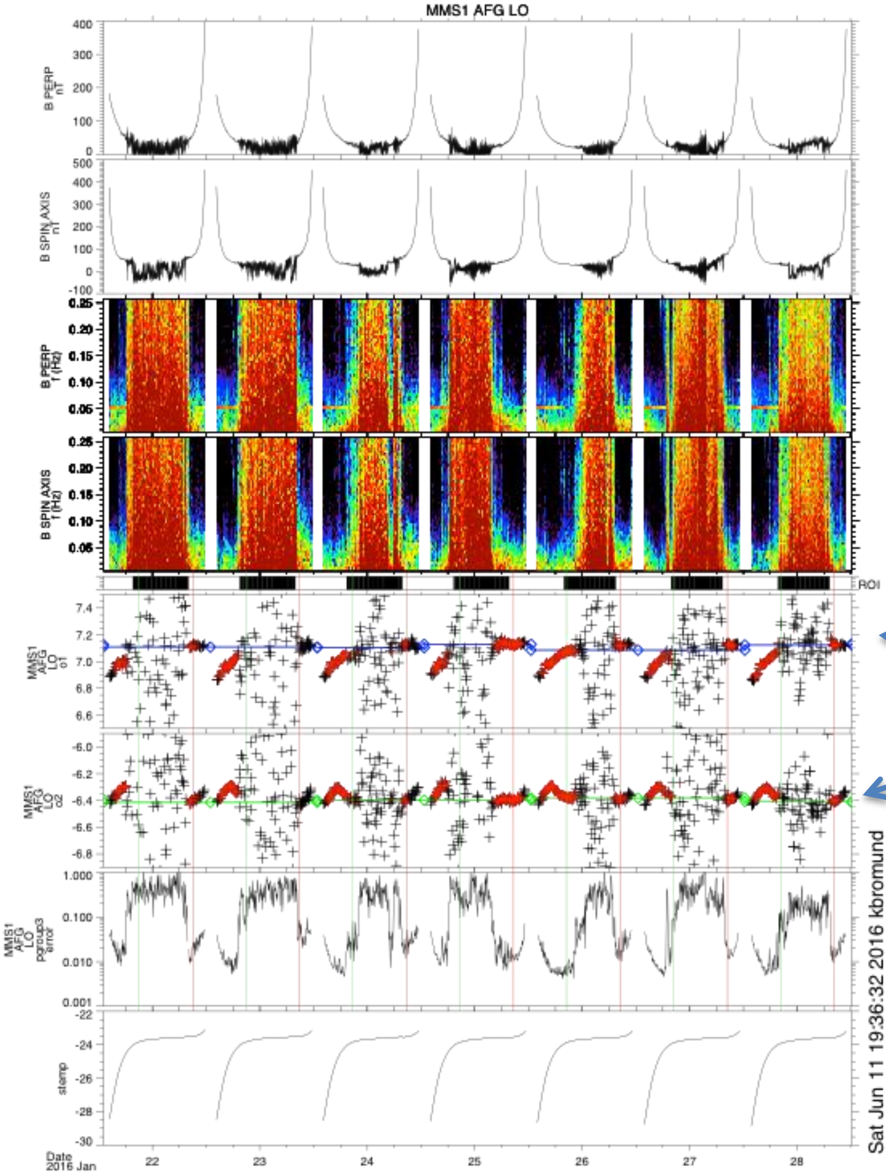
Best Calibration (L2)

Prelim. (L2pre)

Snapshot of Calibration File

CALIBRATION ACTIVITIES AT GSFC

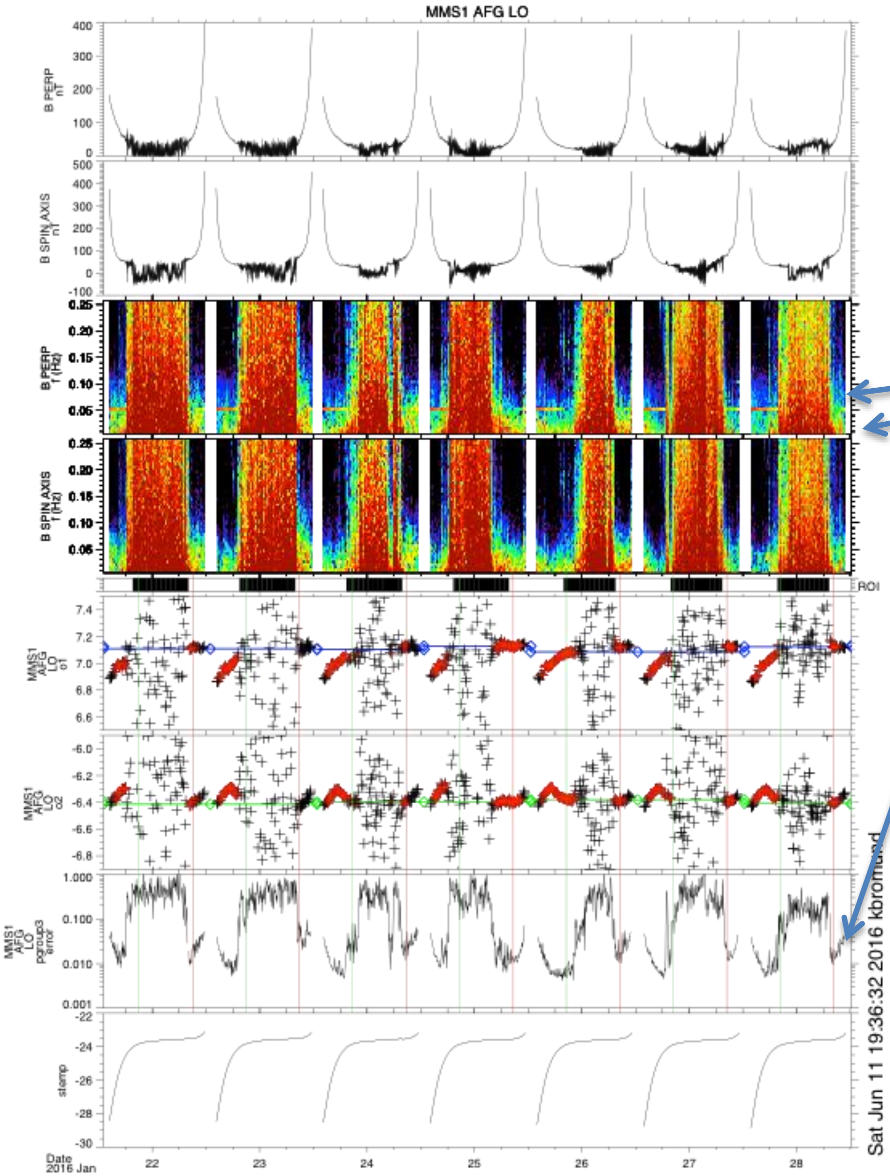
Approach to Spin-Plane Offset Calibration



- Divide each orbit into ~15 minute intervals with 5 min. cadence.
- On each interval, optimize offsets to minimize power at ω_S.

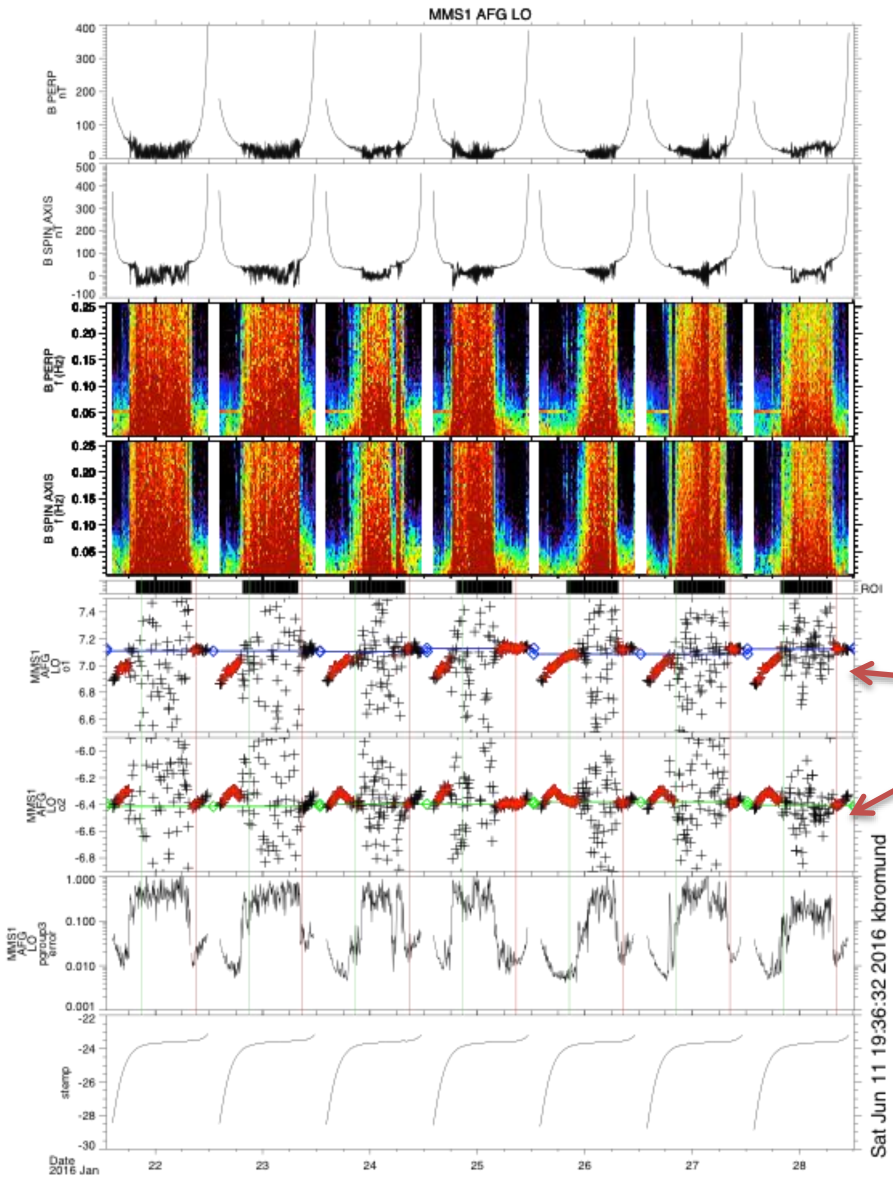
Dynamic Offsets:
o1
o2

Approach to Spin-Plane Offset Calibration



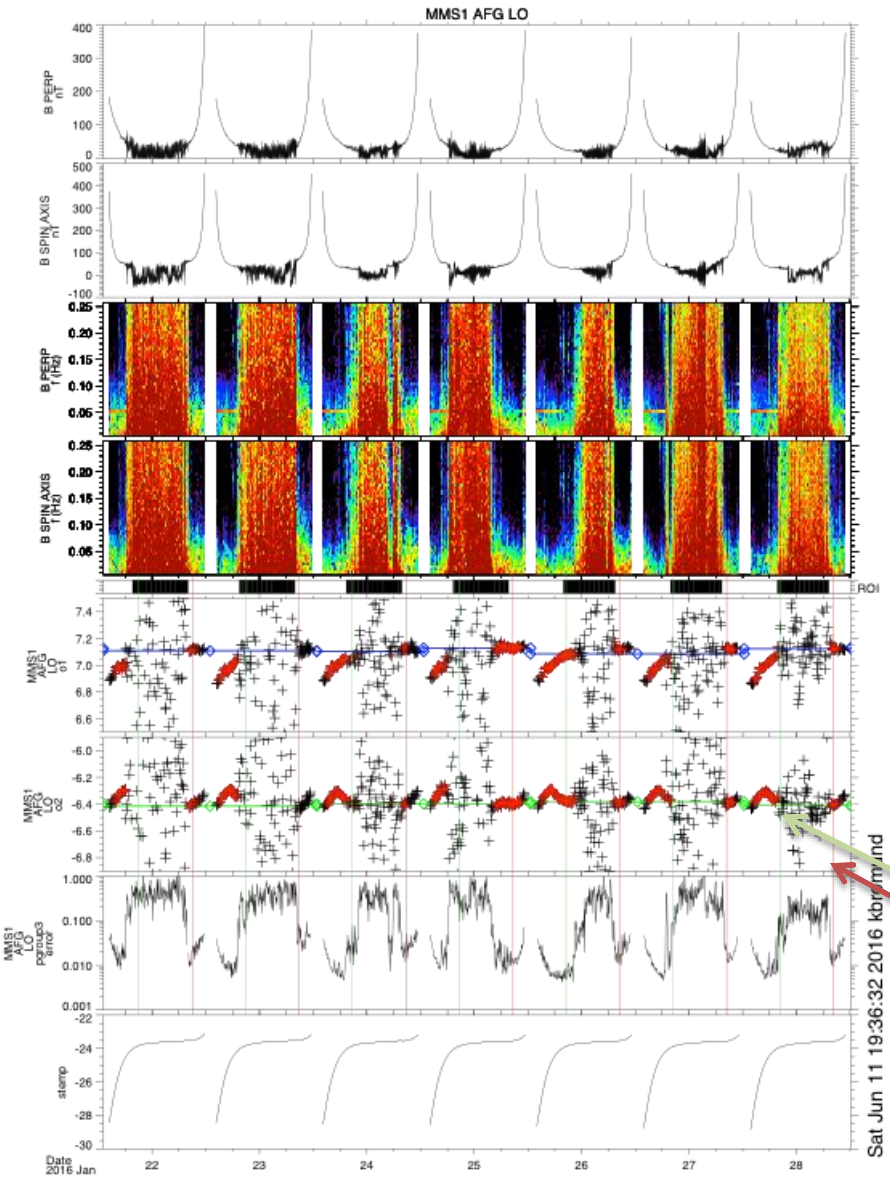
- Divide each orbit into ~15 minute intervals with 5 min. cadence.
- On each interval, optimize offsets to minimize power at ω_S.
- Evaluate spin plane magnitude (B PERP) around ω_S to derive empirical "error value"

Approach to Spin-Plane Offset Calibration



- Divide each orbit into ~15 minute intervals with 5 min. cadence.
- On each interval, optimize offsets to minimize power at ω_S.
- Evaluate spin plane magnitude (B PERP) around ω_S to derive empirical “error value”
  - Disregard offsets on intervals (shown in black) with ‘error value’ > error threshold
  - Only use the ‘red’ points!

Approach to Spin-Plane Offset Calibration



- Divide each orbit into ~15 minute intervals with 5 min. cadence.
- On each interval, optimize offsets to minimize power at ω_S.
- Evaluate spin plane magnitude (B PERP) around ω_S to derive empirical “error value”
  - Disregard offsets on intervals (shown in black) with ‘error value’ > error threshold
  - Only use the ‘red’ points!
- Choose one pair of offsets for each orbit.
  - avoring the ROI:
  - Average of ‘red’ points in a nominal ROI, indicated by green and red vertical bars.

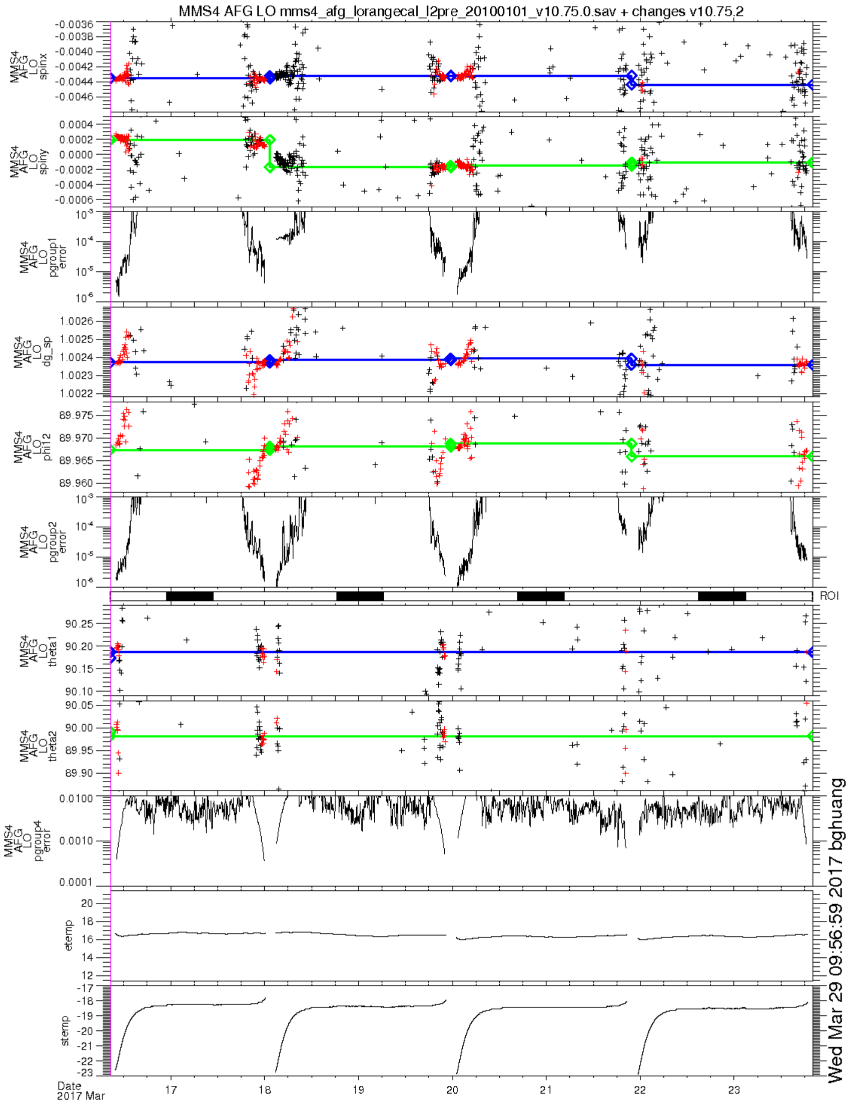
GENERAL APPROACH TO ORTHOGONALIZATION

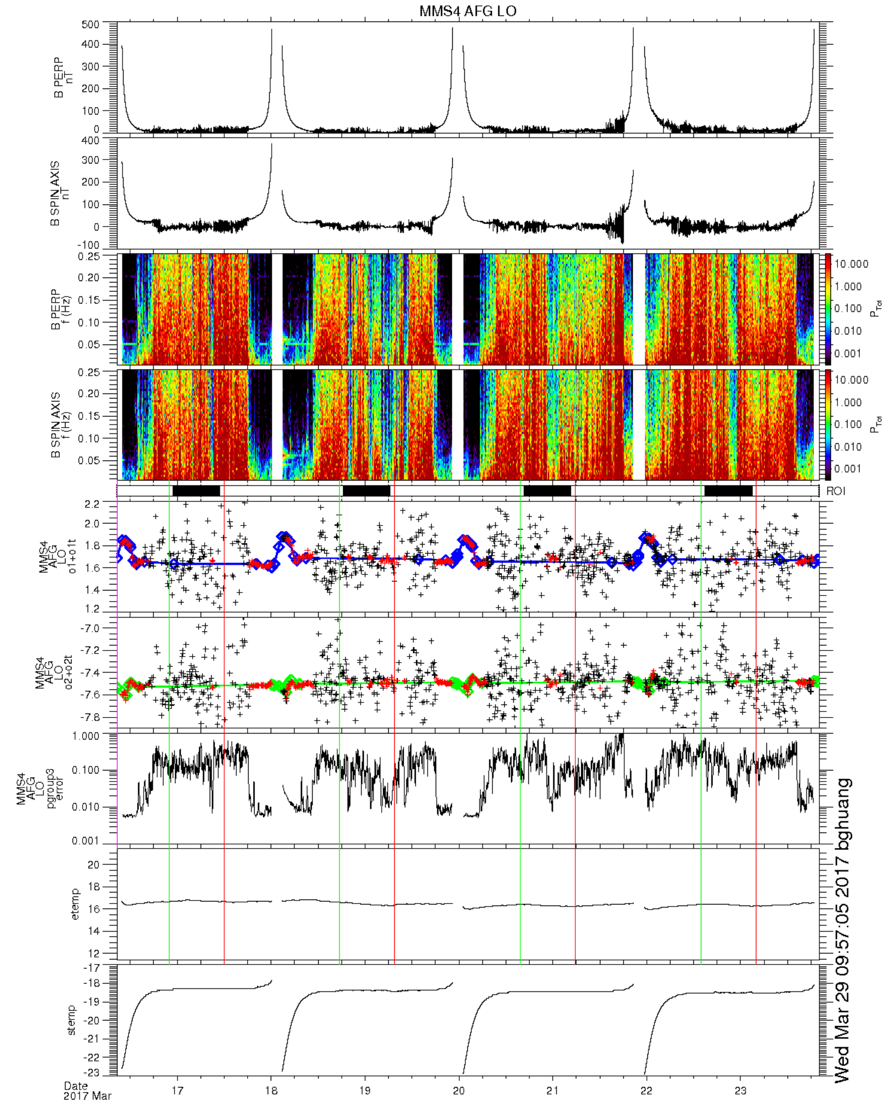
Summary of Methods for all Parameters in GSFC "Orthogonalization" Process

Calibration Parameters	Parameter Names	Physical Methods Used	Dynamic Parameter Integration Time	Error value of interval increases with:	Integration Time for final result	
					Low field range	High Field Range
spin plane offsets	o_1, o_2	Minimize spectral power at ω_{spin} in the spin plane	~15 min (44 spins)	ambient activity around ω_{spin}; high spin-axis field*	1 orbit / 5-7 orbits for o(Ts)	Inbound, outbound
spin plane gain differential and non-orthogonality	dg_SP ϕ_{12}	Minimize spectral power at $2\omega_{spin}$ in the spin plane.	~15 min (44 spins)	ambient activity around $2\omega_{spin}$; low spin-plane field	1 orbit	
elevation angles of spin plane sensors	θ_1, θ_2	Minimize slope of regression between apparent spin-plane sensor offset and the spin-axis field.	~30 min (88 spins)	ambient activity around ω_{spin}; $1/\Delta B_z$; rate of change of sensor temperature	7 orbits (sometimes more)	
spin axis alignment	S_x, S_y	Minimize spectral power at ω_{spin} on the spin axis	~15 min (44 spins)	ambient activity around ω_{spin}; low spin-plane field; deviation from reference sensor temperature	1 orbit	

3 More Parameter Pairs

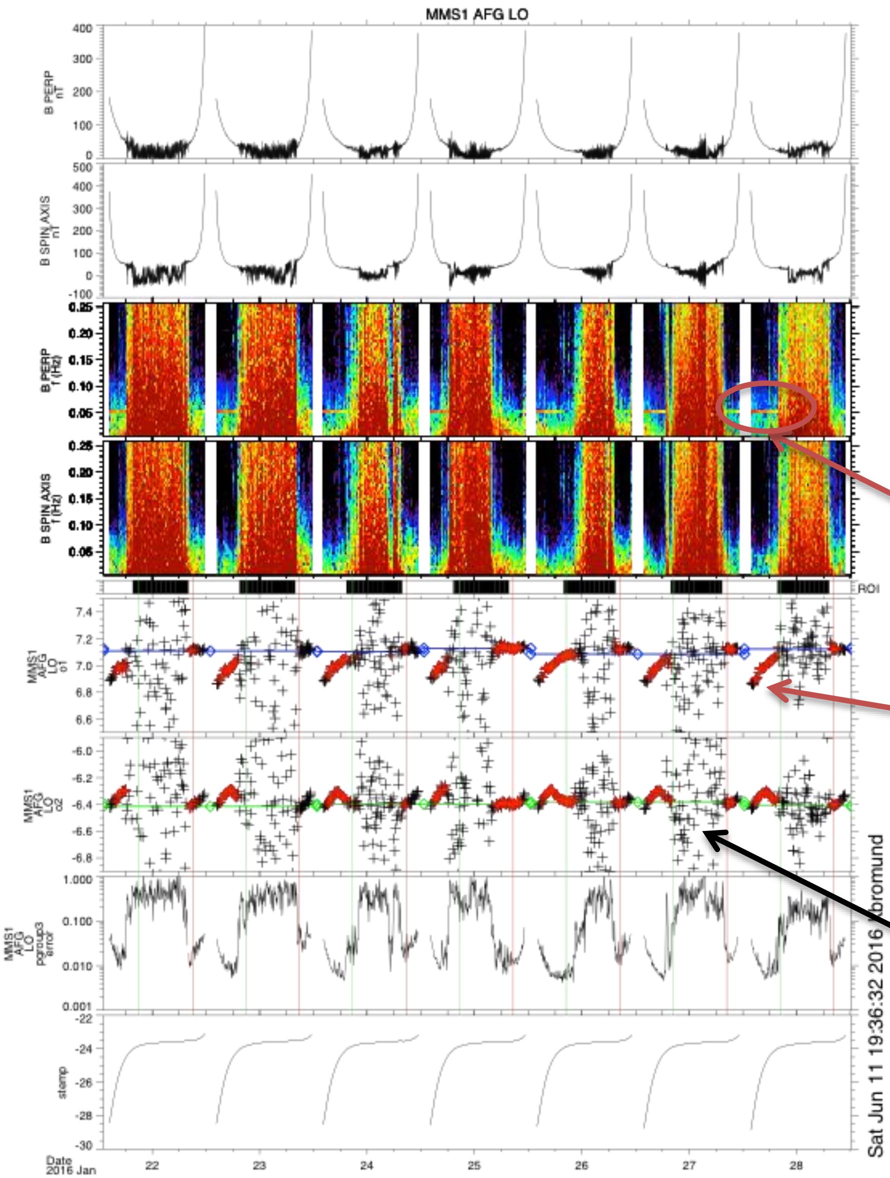
spinx/spiny, dg_sp/phi12, theta1/theta2





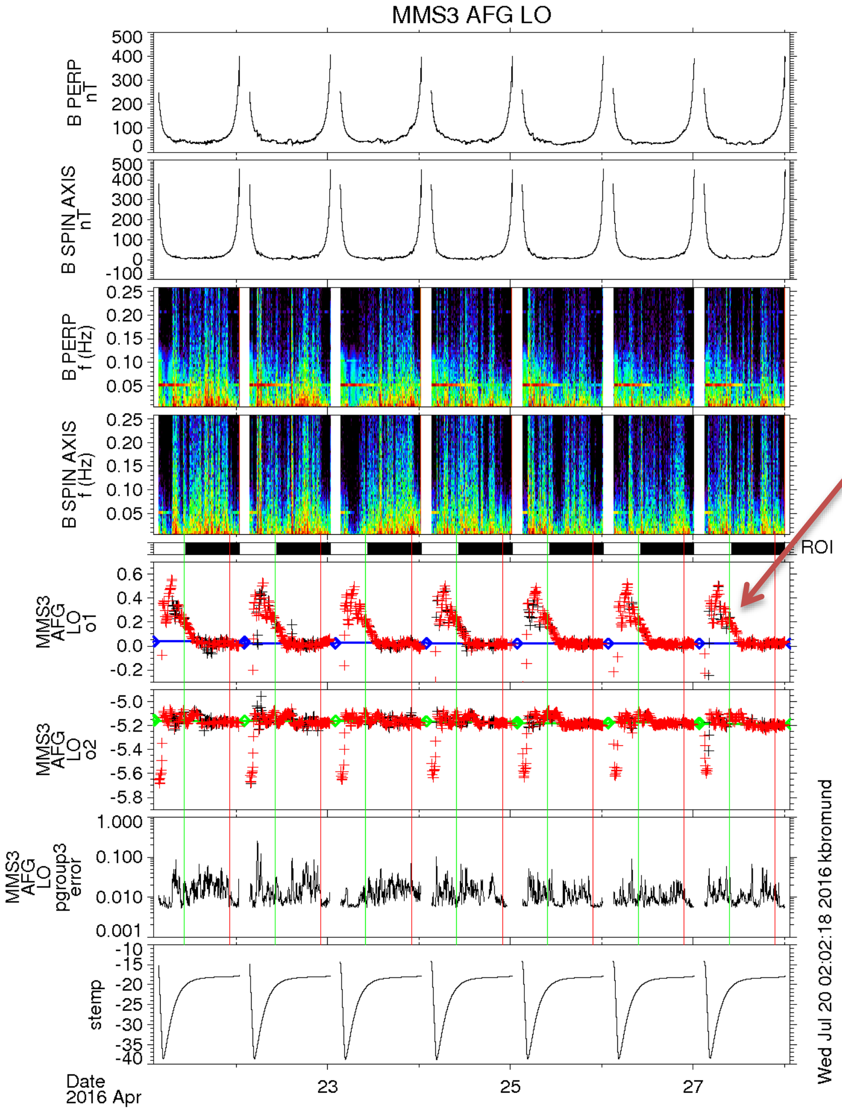
TEMPERATURE-DEPENDENT OFFSETS

A Typical Week Without Shadows



- Typical week: 21-28 January, 2016
  - No eclipses
  - Temperature variations in low range is minimal (~2 degrees).
  - Temperature changes are mostly outside the ROI.
  - We applied constant offsets for each orbit, optimized for the ROI
    - Small amount of spin tone is noticeable outside of the ROI.
    - Amplitude of residual spin tone generally < 0.2 nT
  - Spin tone is much lower than the ambient signal within the ROI.
  - Due to geophysical activity, some orbits have insufficient statistics to calculate offset: use value from last orbit.

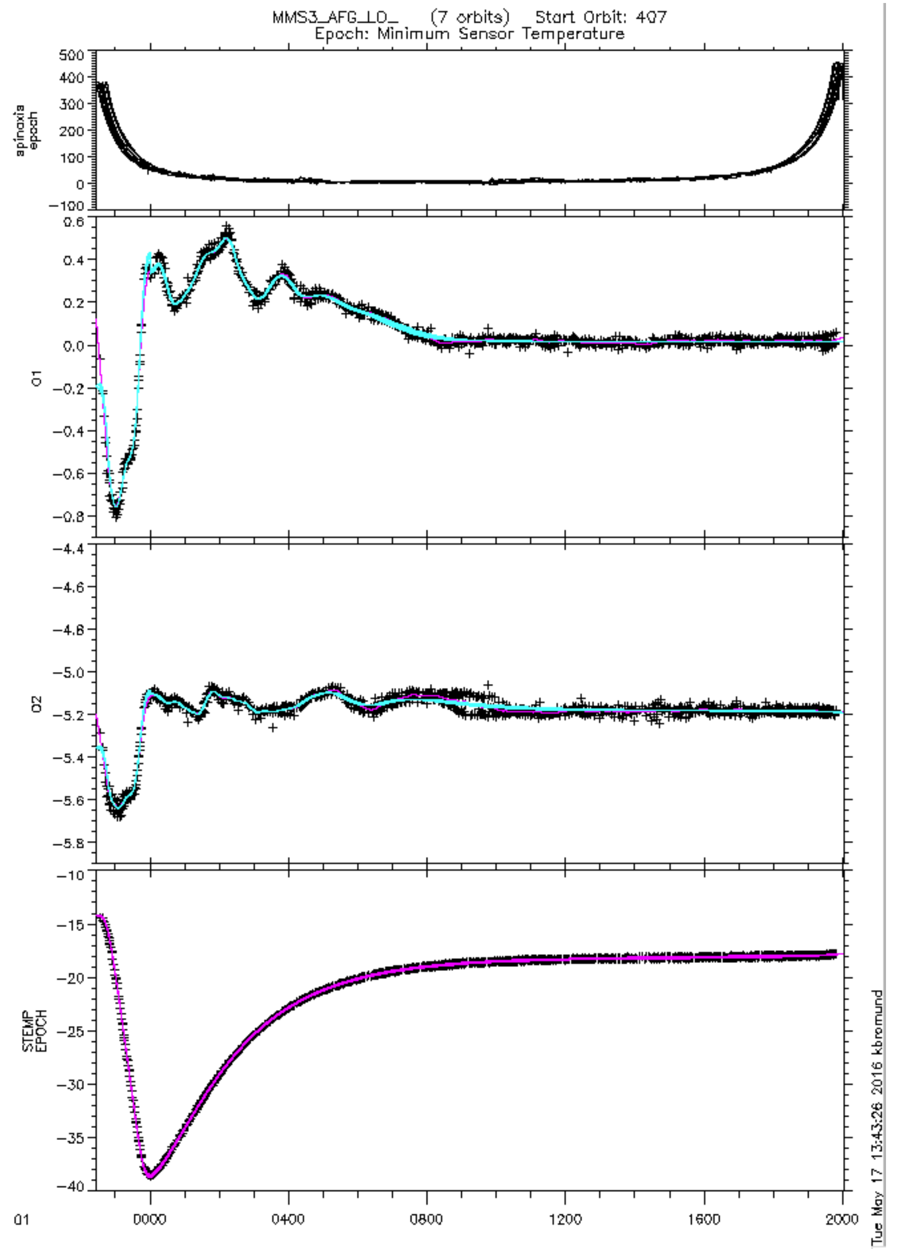
A Typical Week With Shadows



- Constant offsets fail to remove spin tone during and after eclipses in this week of 21-27 April, 2016.
  - Dynamic offsets differ from the orbit average by 0.3 – 0.5 nT for a significant time after eclipse.
  - In Phase 2, this will affect primary science.
- Dynamic offsets are too noisy and sparse to be applied directly to the data.
  - The ‘noise’ may be geophysical signal at spin freq. that we do not want to remove.
- The dynamic offsets appear to follow a consistent pattern from orbit to orbit.

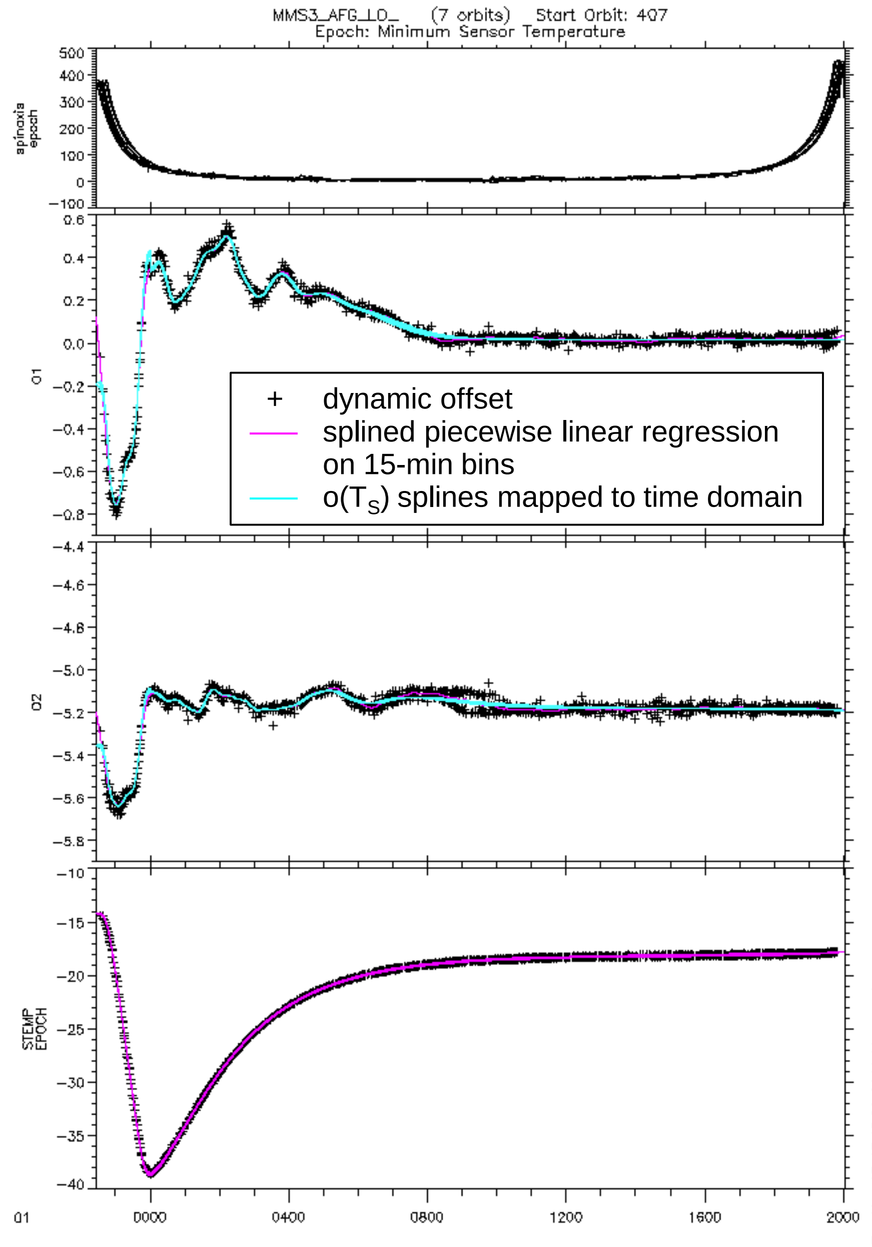
Mapping Temperature Fits Back to the Time Domain

- Excellent match to
- Two possible approaches that characterize variations in offsets:
  - Spline fit to superposed epoch (magenta in two middle panels)
  - Spline fit to offset vs. temperature, then map back into the time domain (cyan)
- Temperature-based approach has a sound physical interpretation.



Superposed-Epoch Analysis of Spin-Plane Offsets

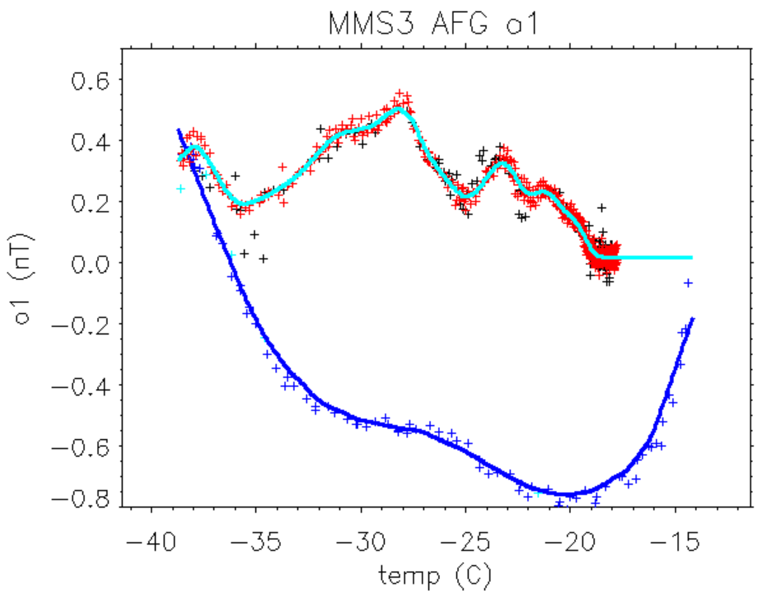
- o1, o2, and sensor temperature (STEMP) for 7 orbits from the previous slide plotted superposed-epoch.
  - This analysis considers only the points with sufficiently low error values.
  - Epoch 00:00 is the time of minimum temperature on each orbit (end of eclipse).
  - Offsets stabilize 8 hours after end of eclipse.
- Spline fit to superposed epoch
  - Variations show multiple time scales.
  - 15-minute bins required to capture detail in eclipse recovery.
  - Overly variable where offset seems stable.
  - Spline fit to offset vs. temperature, then map back into the time domain (cyan)
- Temperature-based approach has a

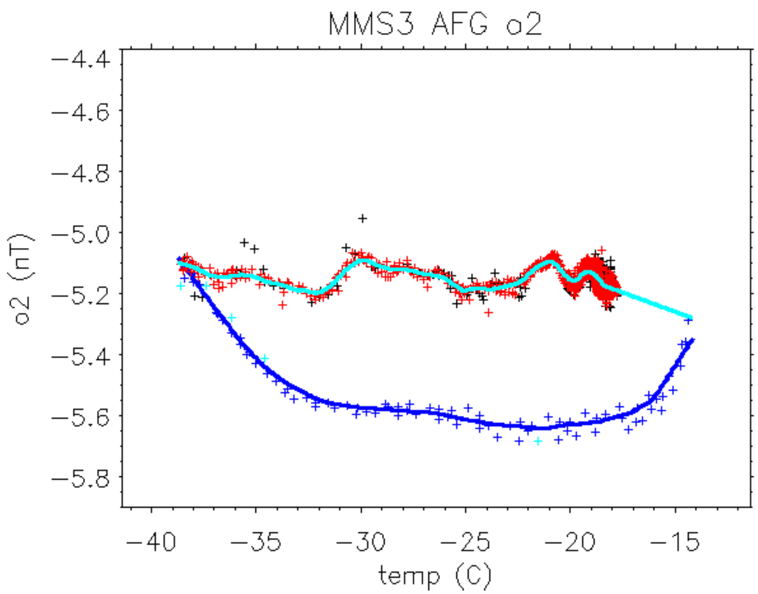


Spline Fits to Temperature Trends

For each sensor, offsets are characterized by two distinct functions of sensor temperature.

1. 'Adiabatic' (red points)
   - Increasing temperatures during Eclipse Recovery
   - Slowly decreasing temperatures (e.g. cooling after Earth's albedo).
   - Science requirement applies to data in this set.
2. Eclipse (blue points)
   - Rapidly decreasing temperatures.
   - Rapid change in offset: data can be improved, with limited accuracy.
   - No science requirement.

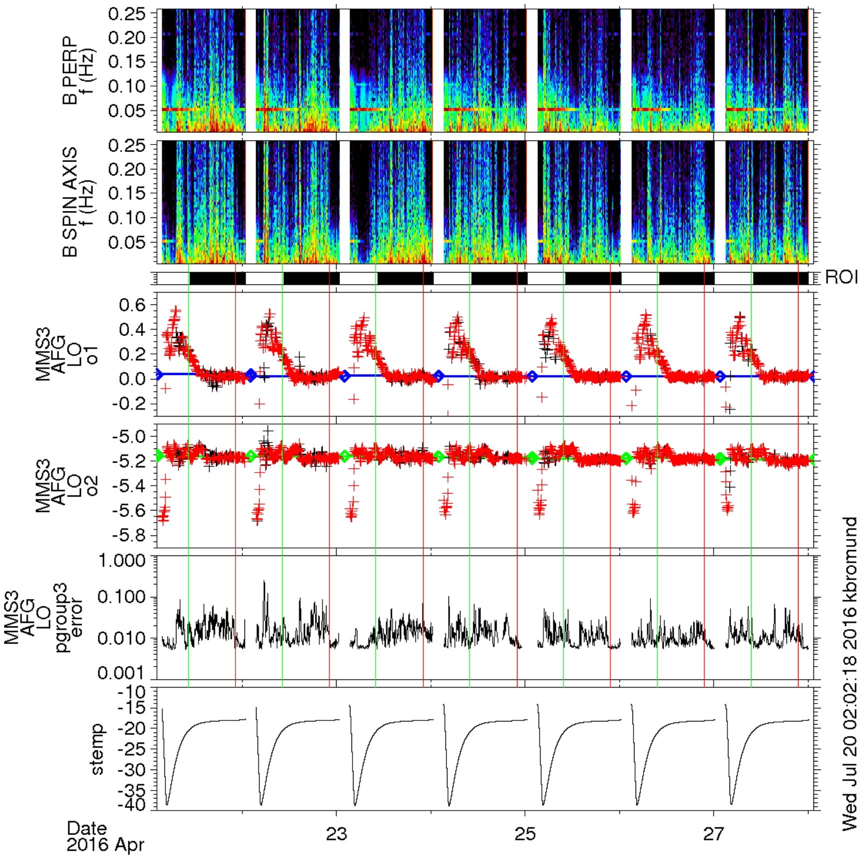




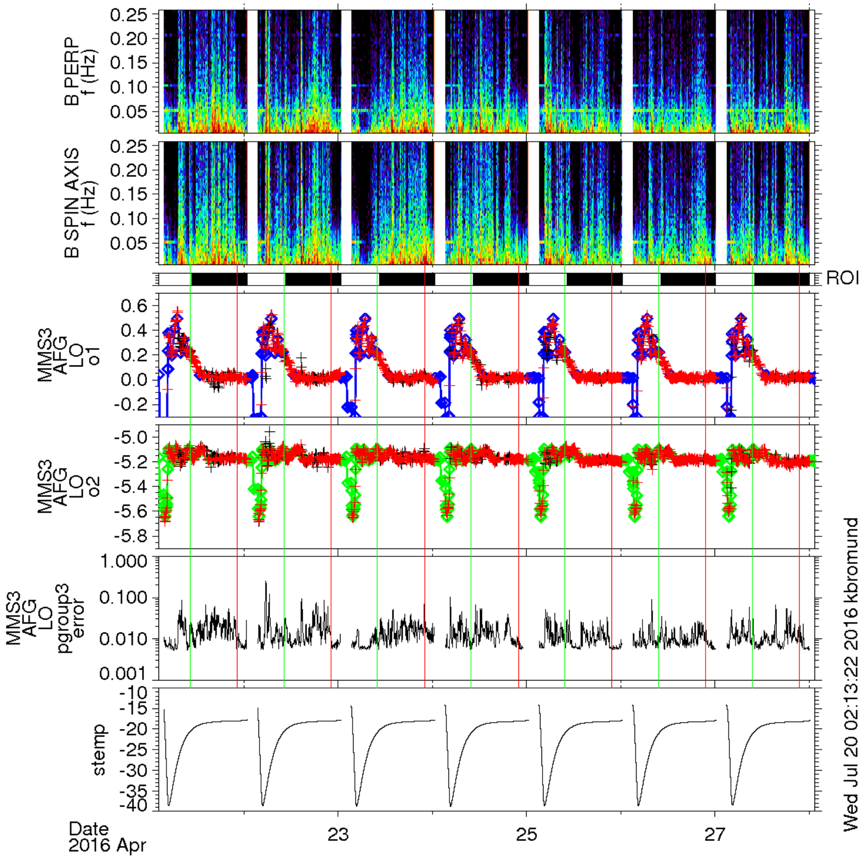
Orbit-constant offsets

Temperature-dependent offsets

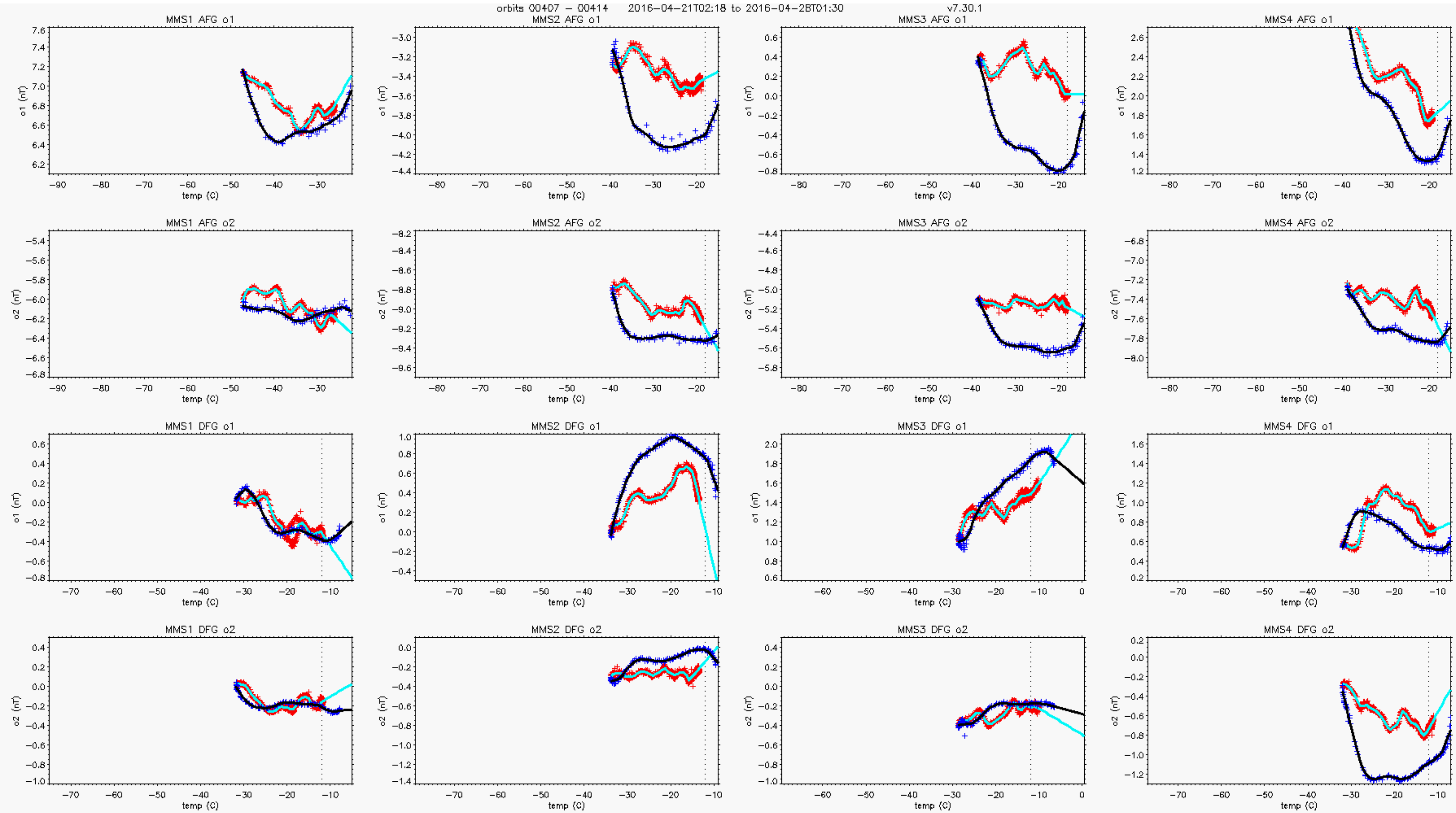
before



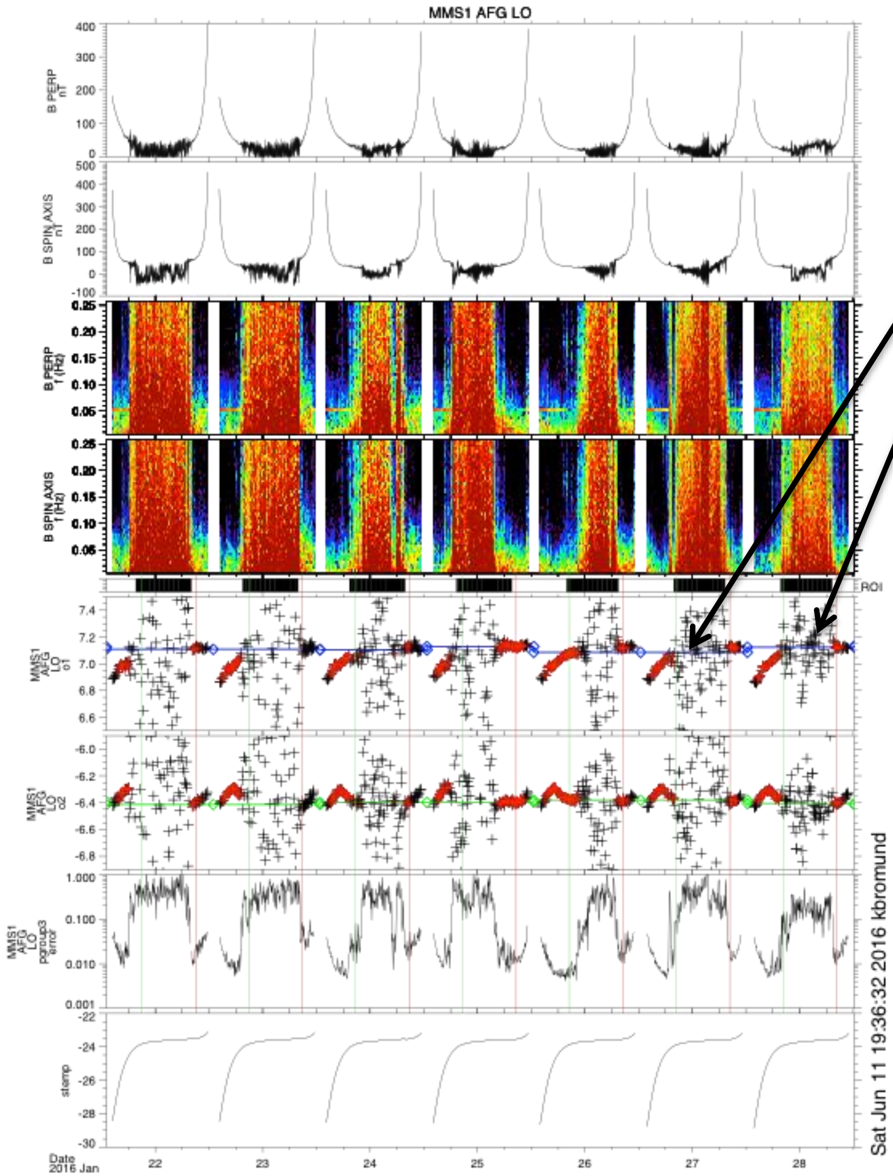
after



Temperature Trends of All Spin-Plane Sensor Offsets



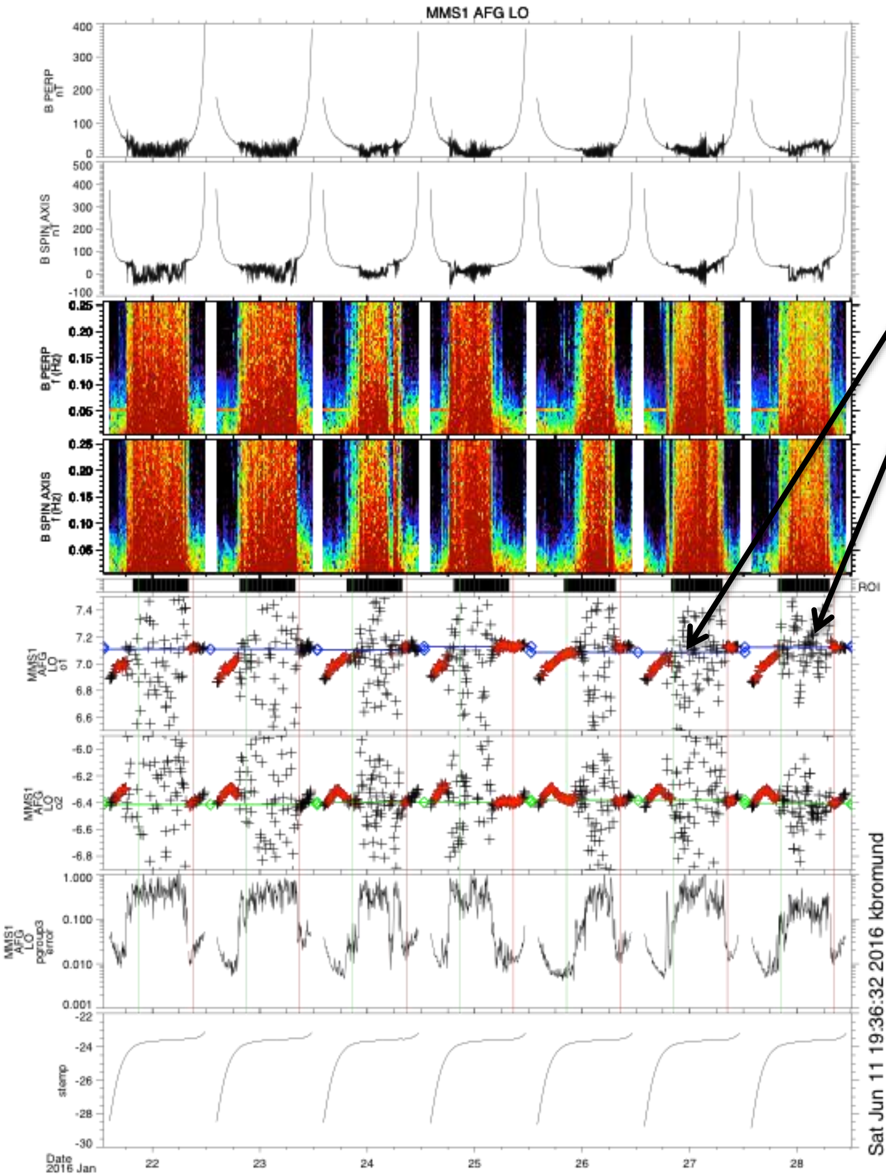
Application in Phase 1B (and improving Phase 1A)



- Old Method:
  - When the ambient noise is large, there are few good intervals in the ROI.
  - Poor statistics can cause errors in the offset from orbit to orbit.

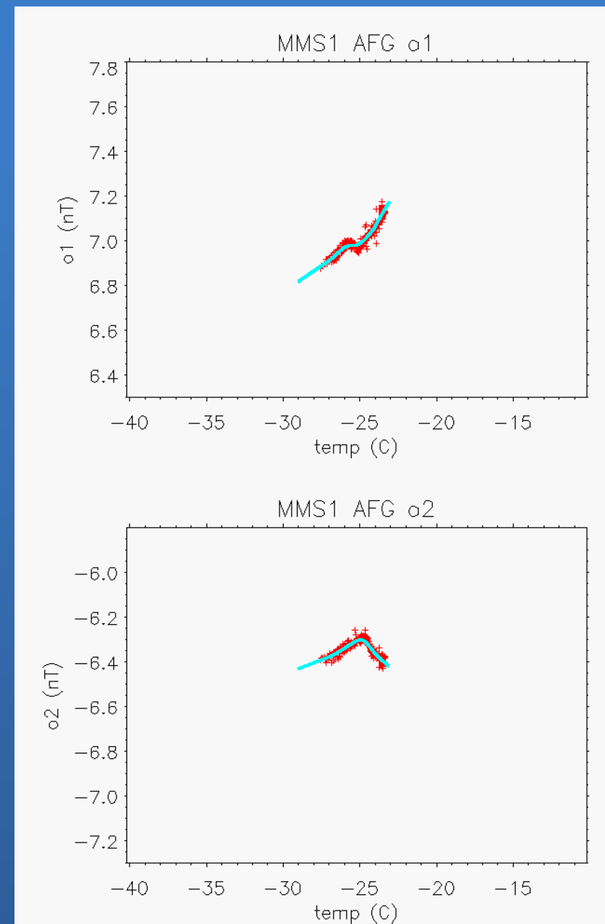
Application in Phase 1B (and improving Phase 1A)

- Old Method:
  - When the ambient noise is large, there are few good intervals in the ROI.



New Method:

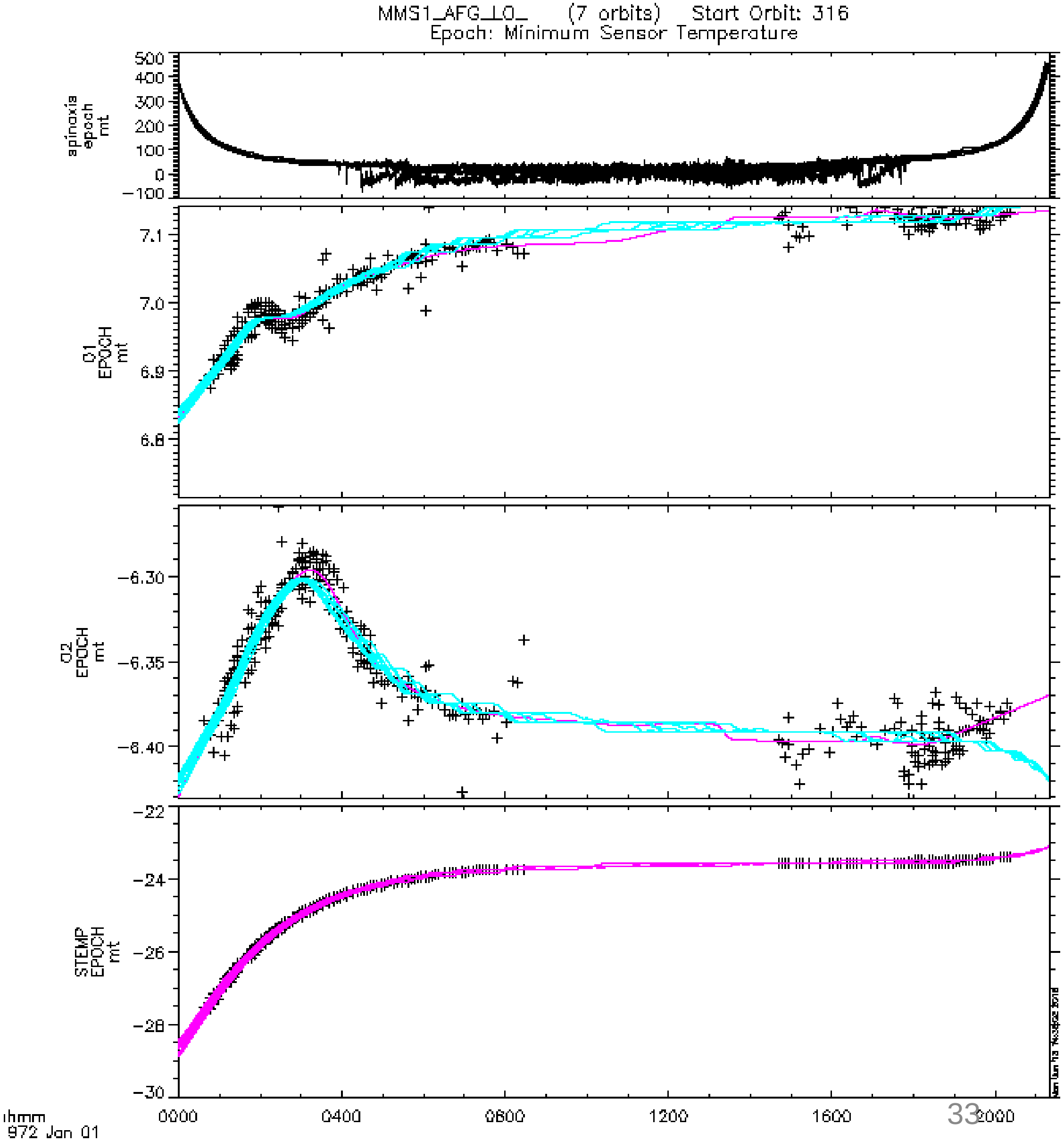
The temperature distribution of offsets for the 7 orbits is fully sampled!



Application in Phase 1B (and improving Phase 1A)

- Mapping the STEMP fits to time domain (cyan traces)
    1. Leverages the statistics from outside of the ROI to give better results in the ROI.
    2. Improves results outside of the ROI.

- Alternatively, 1-hour time-spline bins give comparable results
    - 1-hour bins would wash out most variations seen after eclipse: A general implementation with time-domain splines would require an adaptive bin size.



Conclusions

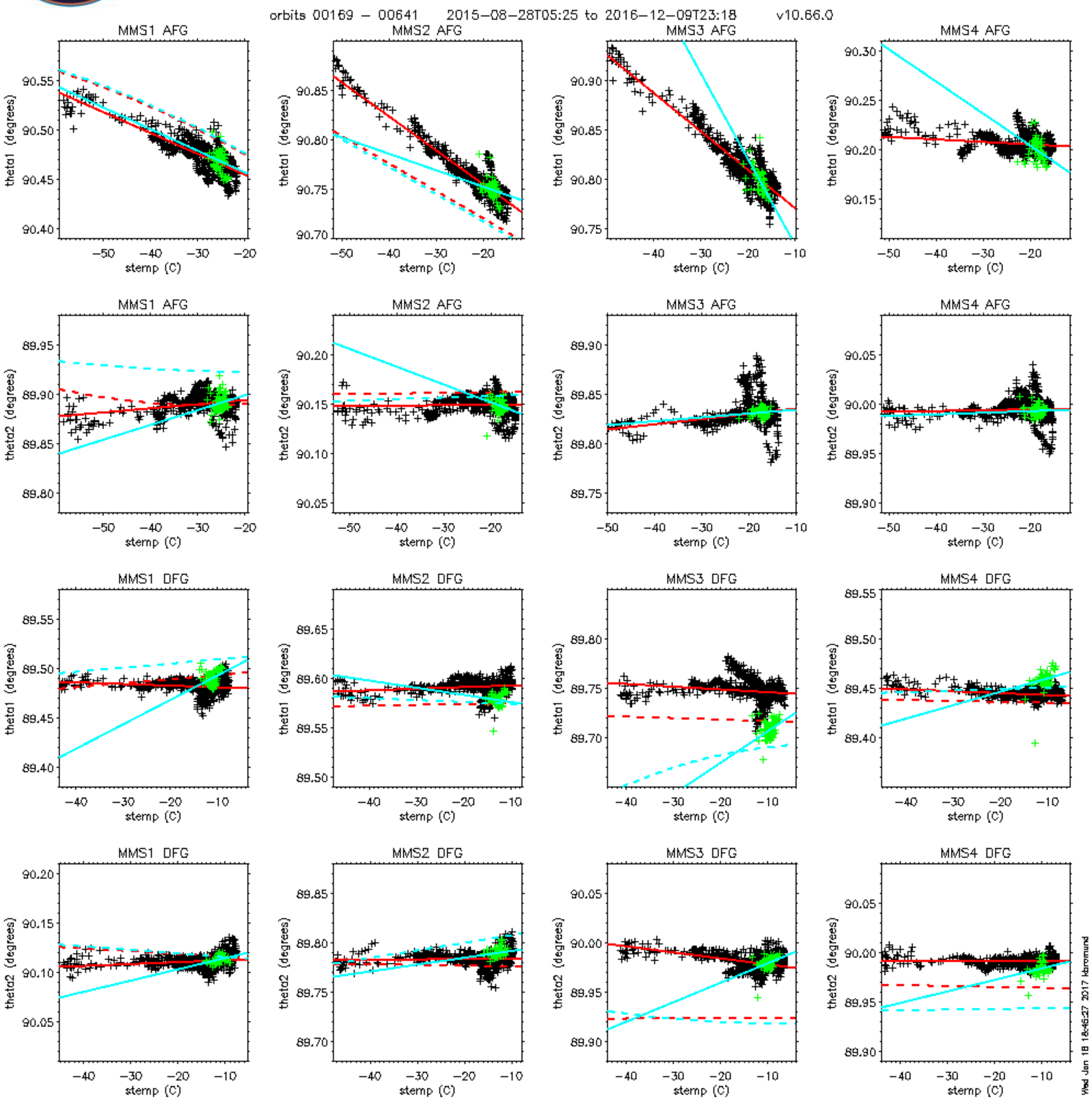
- In Phase 1A we achieved 0.2 nT accuracy in the offsets when reducing dynamic offsets to a single offset for each orbit.
- Temperature changes due to eclipse are accompanied by offset changes as large as 1 nT. Eclipses are followed by a recovery period as long as 12 hours where the offsets continue to change as temperatures stabilize.
- The changes in offset with temperature are deterministic.
  - At time scales of about a week, temperature-offset curves are well defined.
  - Each sensor has a distinct temperature-offset curve, thus there are implications for any inter-spacecraft data analysis.
  - Spin AXIS sensors likely exhibit similar, but distinct, temperature-dependent offsets.
- The temperature-dependent offset correction is in production for L2pre and L2 as of orbit 479 (2016-07-01 18:07:46). This includes most of the Phase 1X season of long eclipses. The algorithms are in place for Phase 2.
- Future work:
  - Account for electronics temperature and discrete jumps in offset during the week.
  - Re-process L2 to correct the remainder of Phase 1X and before.
  - Explore temperature dependence of Spin AXIS offset

References

- Bromund, Leinweber, Plaschke, et al. (2015), ”In-Flight Calibration Processes for the MMS Fluxgate Magnetometers,” Abstract SM51A-2555 presented at 2015 Fall Meeting, San Francisco
- Bromund, et al. (2016), “In-Flight Calibration Methods for Temperature-Dependent Offsets in the MMS Fluxgate Magnetometers”, Abstract SM21A-2455 presented at 2016 Fall Meeting, San Francisco
- Russell, et al. (2014). “The Magnetospheric Multiscale Magnetometers.” Space Sci Rev.; DOI: 10.1007/s11214-014-0057-3

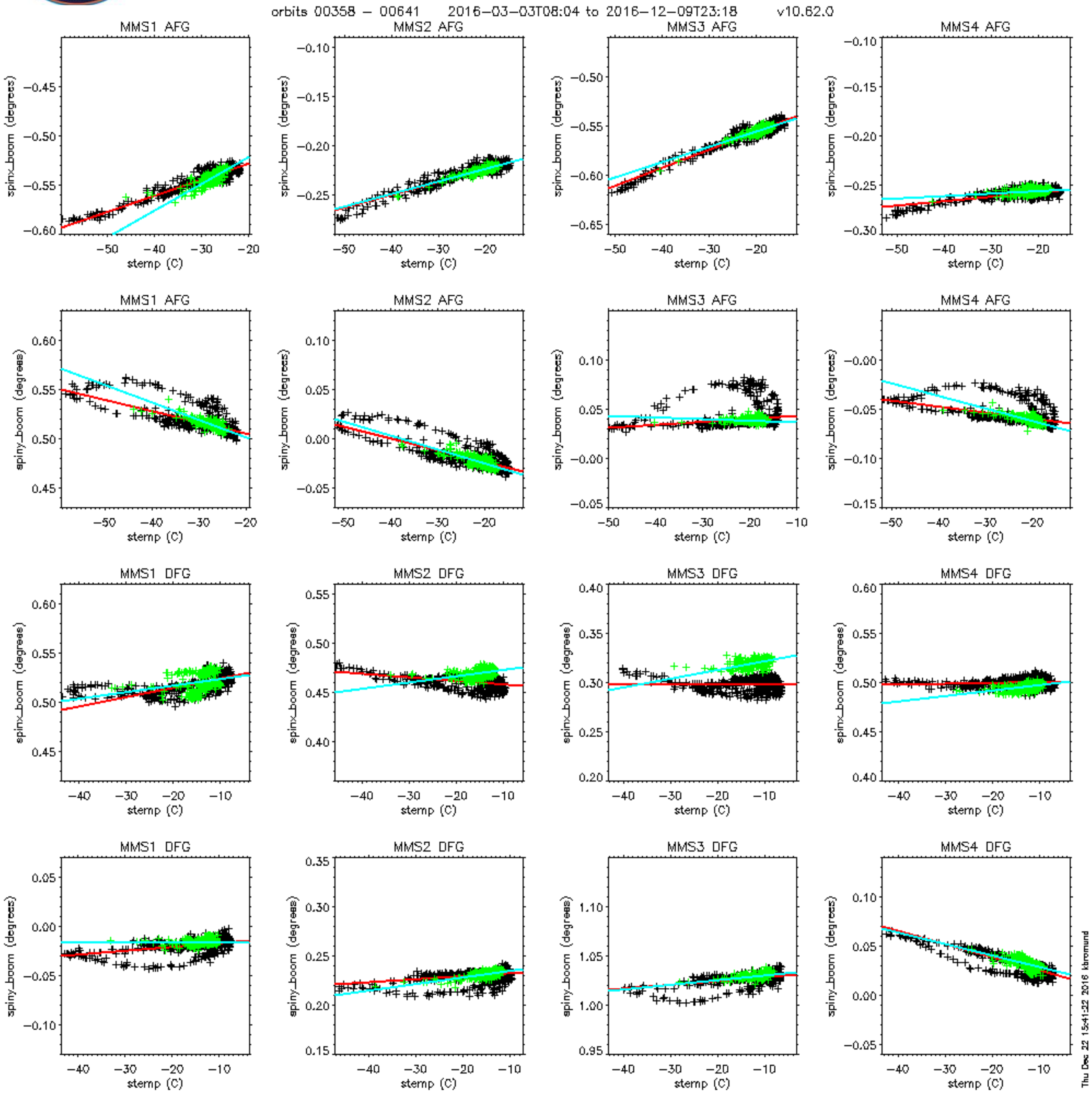
BACKUP

Theta Angles vs Sensor Temperature



- Each high-range point represents an inbound or outbound leg of an orbit.
- Each low-range point represents one week of data.
- Generally good agreement between high and low range
- MMS3 DFG Theta1 is an exception.
  - TUBS ground cal also showed significant difference between high and low.

Spin Axis Alignment vs Temperature

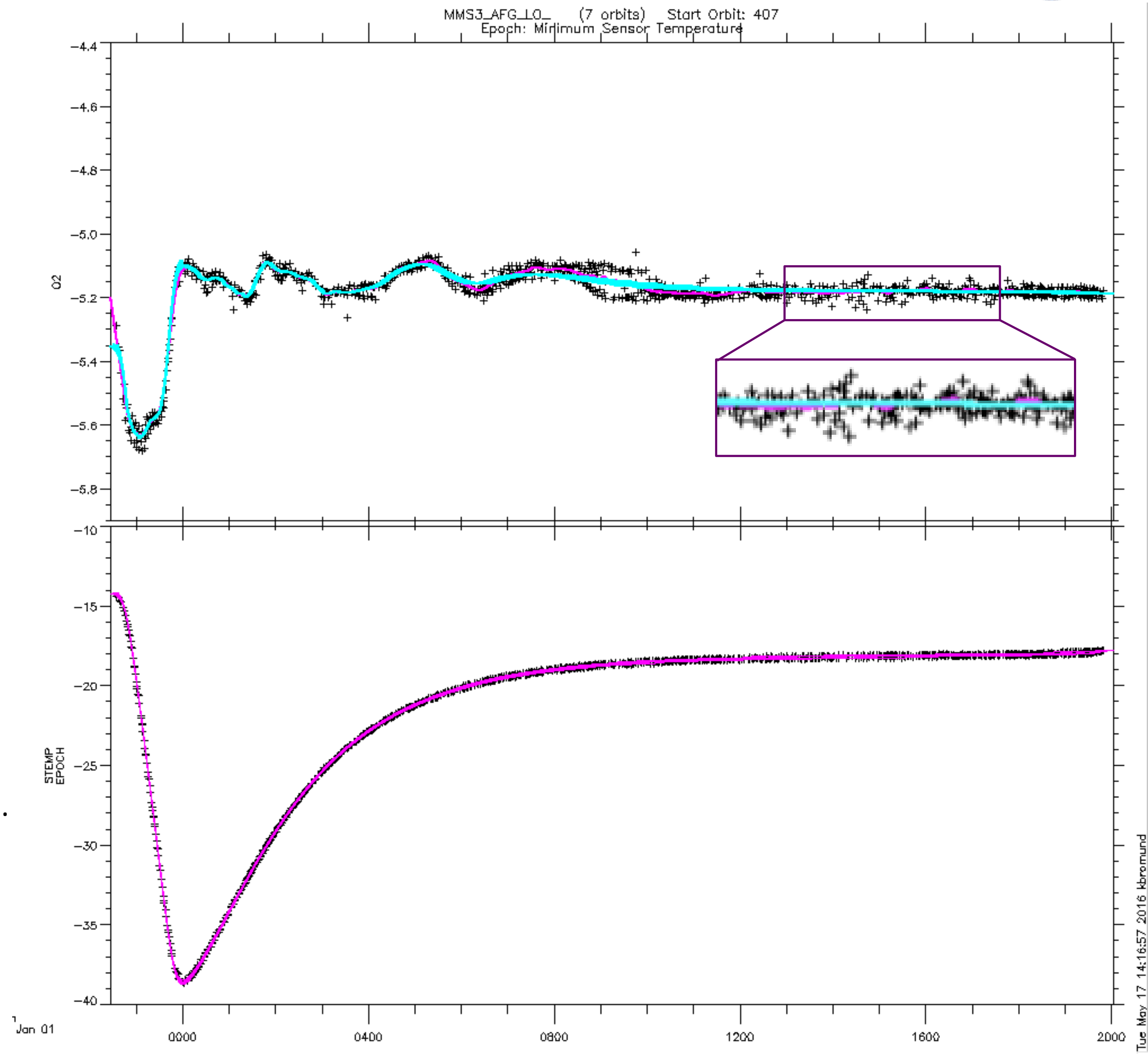


- \+ High range in-flight cal
- High range in-flight linear fit
- \+ Low range in-flight cal
- Low range in-flight linear fit

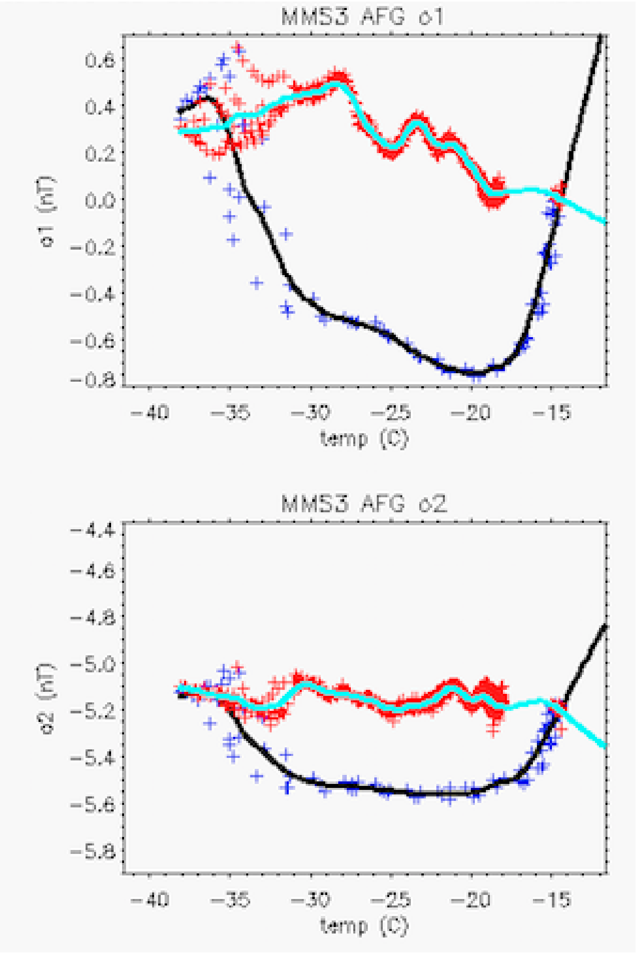
- Effective orientation of spin axis sensor in S/C coordinates
- Includes combined thermal effect on sensor, electronics, boom, and bus.
- Excellent agreement between low range and high range, except for MMS3 DFG, whose difference corresponds to the difference in Theta1.
- On AFG
  - $d(spinx)/dT_S \approx 0.5\ d(theta1)/dT_S$ suggests spin-axis sensor is partly responsible for change in orthogonality.
- On AFG and MMS4 DFG,
  - Change in spin_y without corresponding change in theta2 suggests twisting of boom.

Comparison of temperature vs time fit

- Temperature-domain splines, mapped back into the time domain (cyan), closely match time-domain splines (magenta).
- Features of Temperature splines:
  - 1-degree bins follow the significant trends
  - Gives stable results in the ROI
- Features of time-domain splines
  - 15-minute bin size captures essential temperature variations.
  - Too much variation when temperature is stable. TODO: let bin size increase as temperature stabilizes.



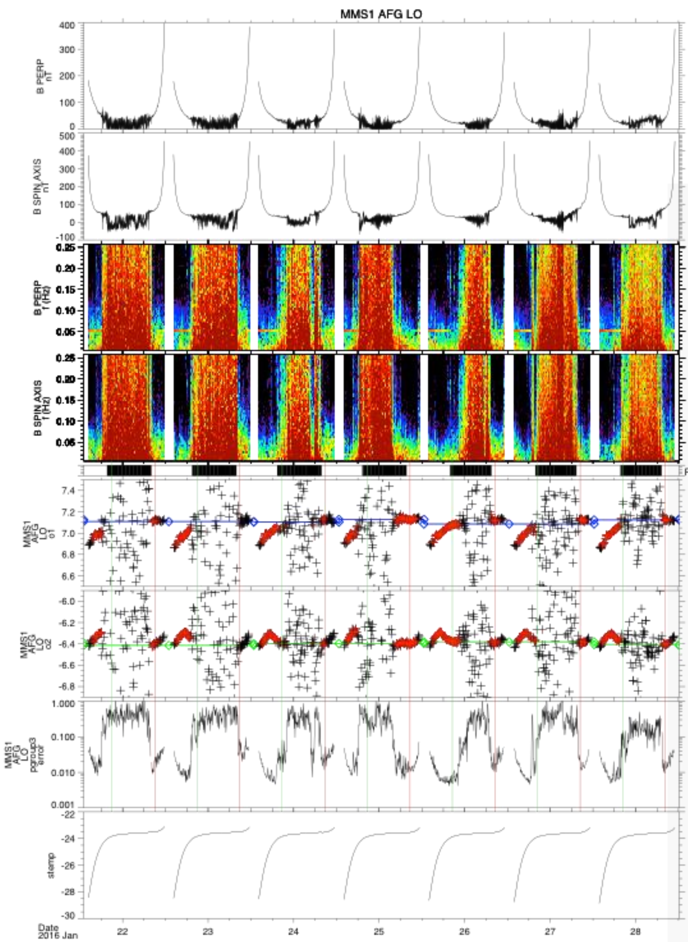
A less ideal case



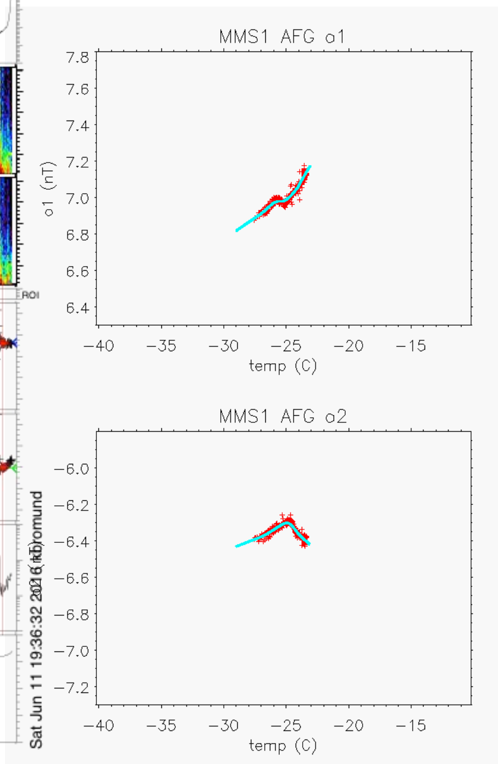
- The temperature trend of each orbit is not always identical.

Determining offsets when there is geophysical activity

- Current Method takes orbit-averaged offsets in the ROI.
    - Few good fits in the ROI
    - Don’t have good statistics when we need them.

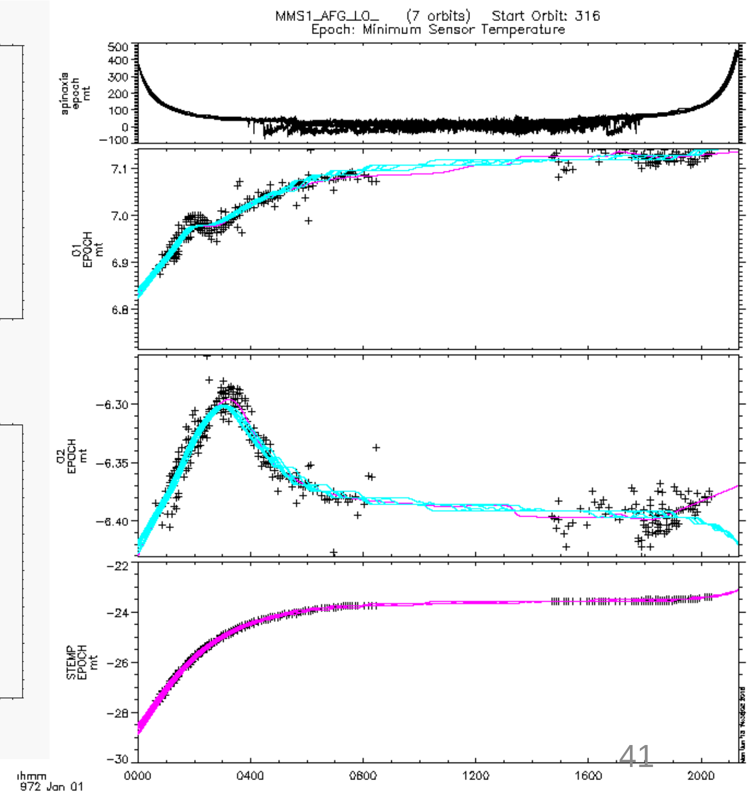


However, the temperature range is fully sampled!

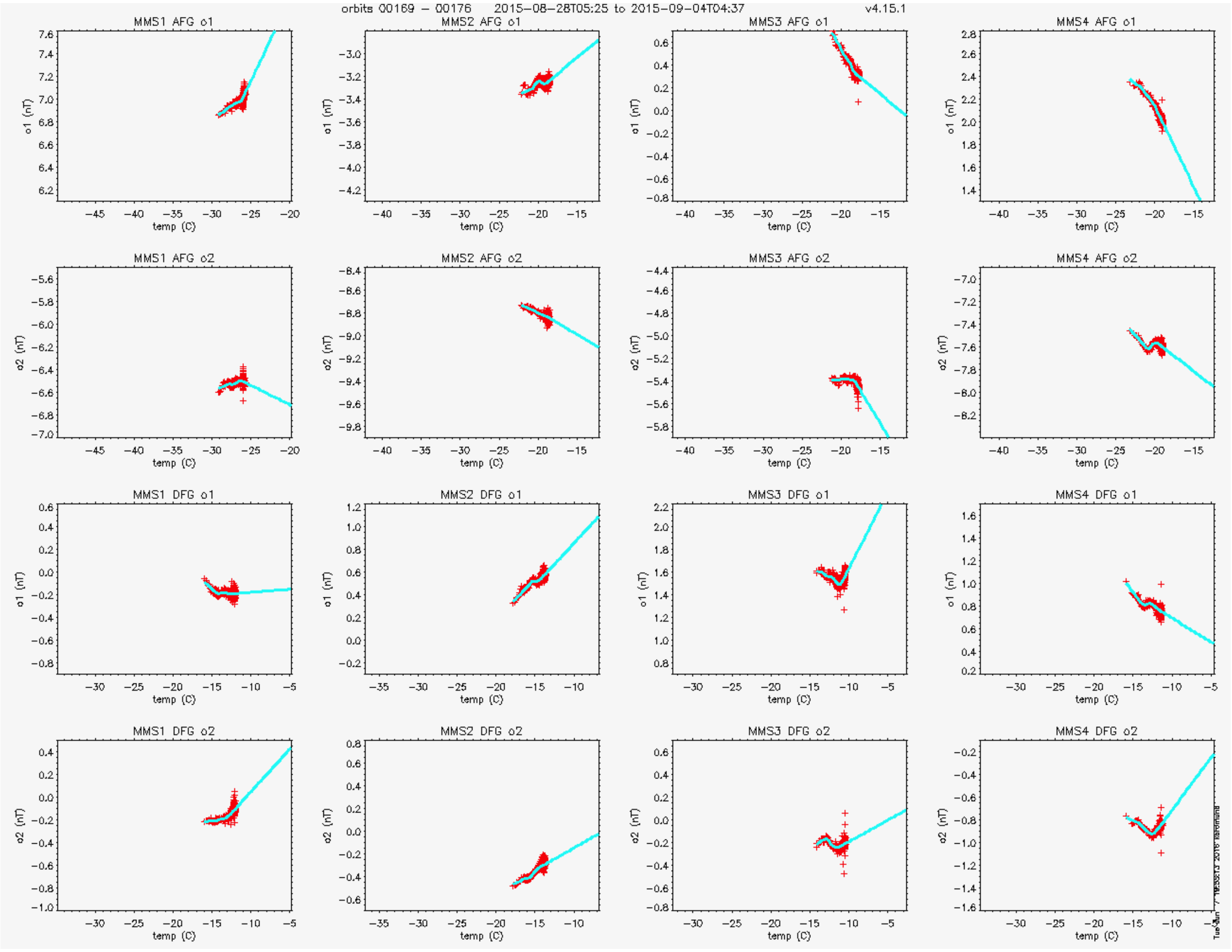


- 1-hour time-spline bins give comparable results.

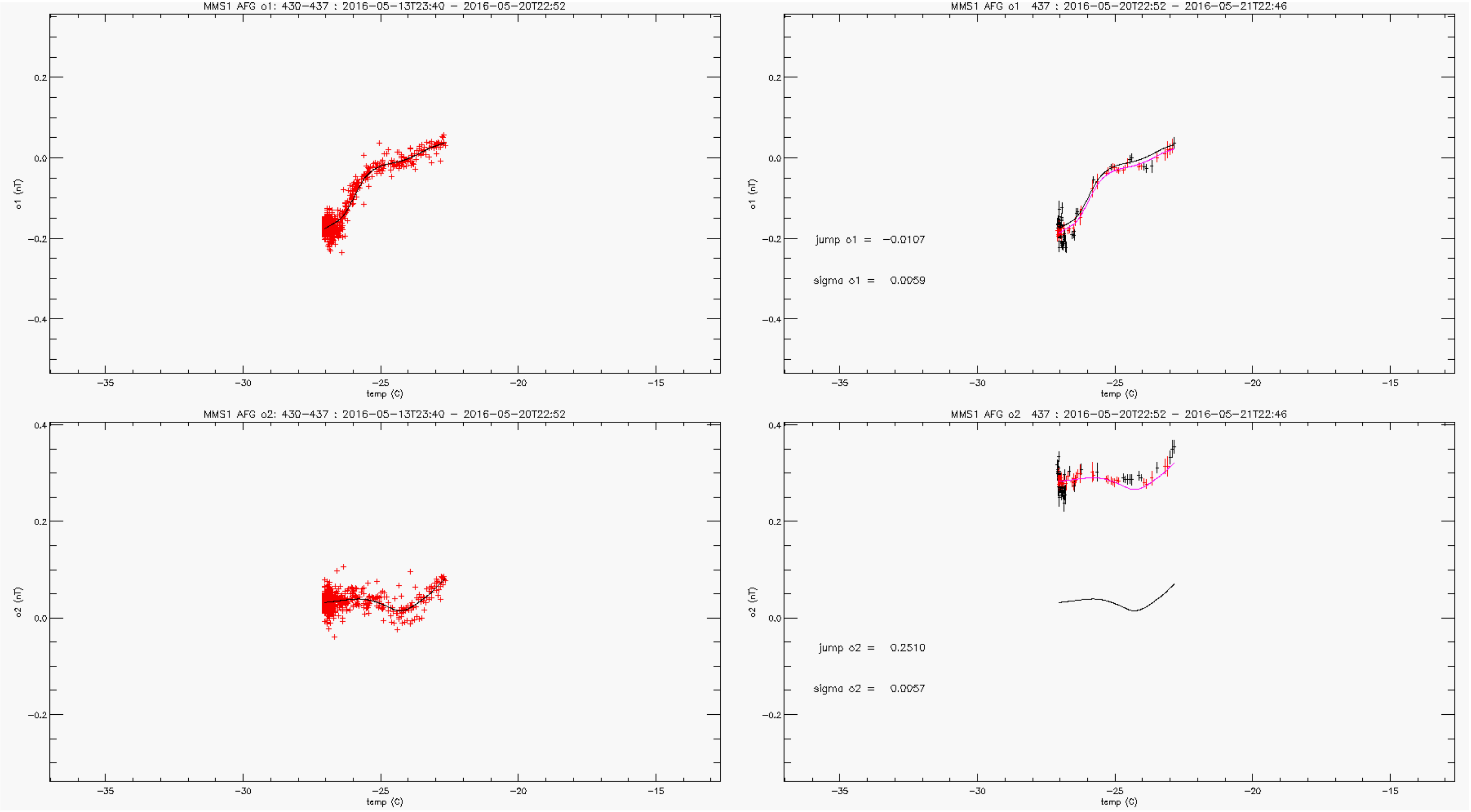
- Mapping the STEMP fits to time domain gives excellent results in the ROI
    - questionable at the end, but differences are < ~0.05 nT, and these are v4 cals.



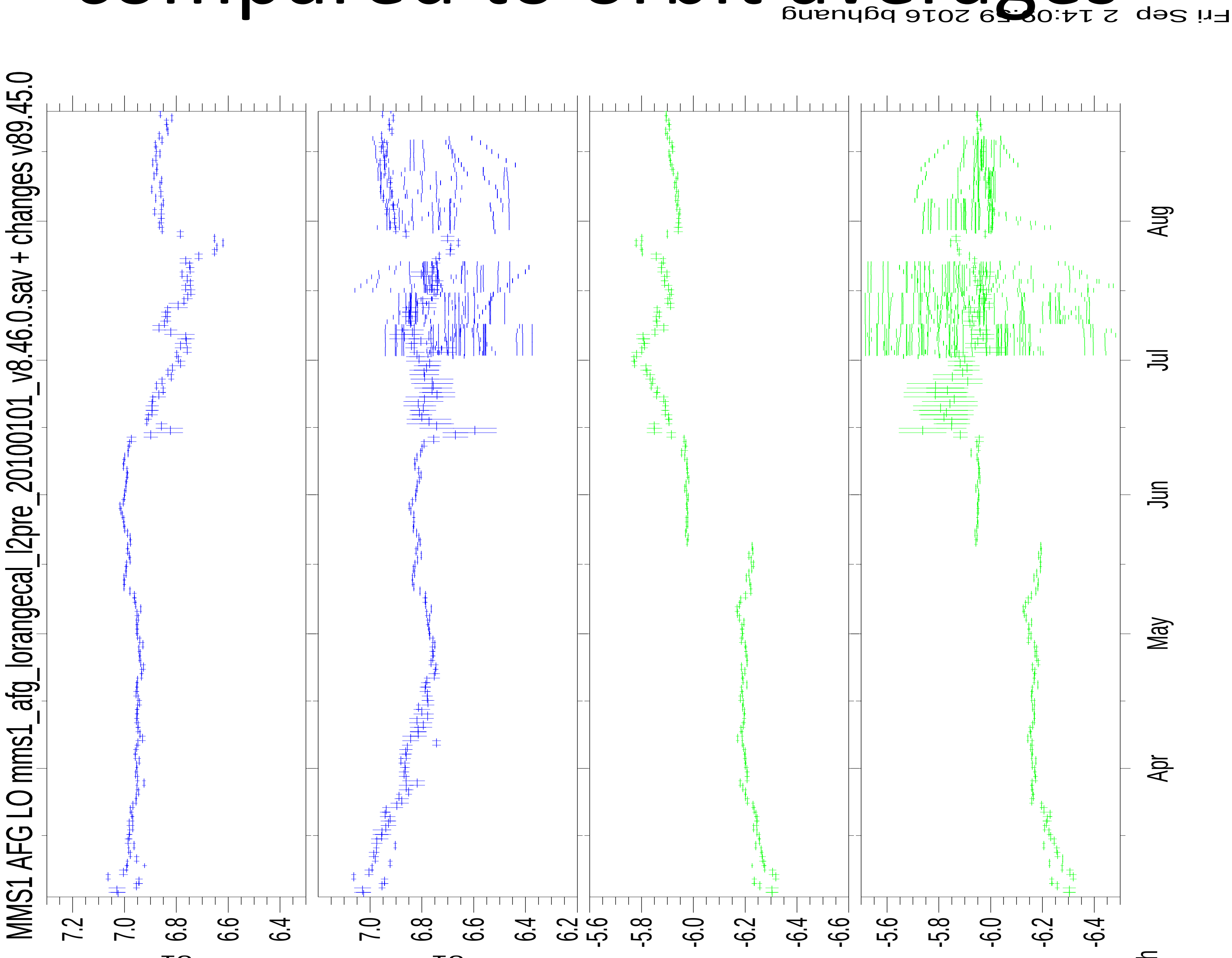
‘Tails’ in distributions at high temperature may be due to Theta



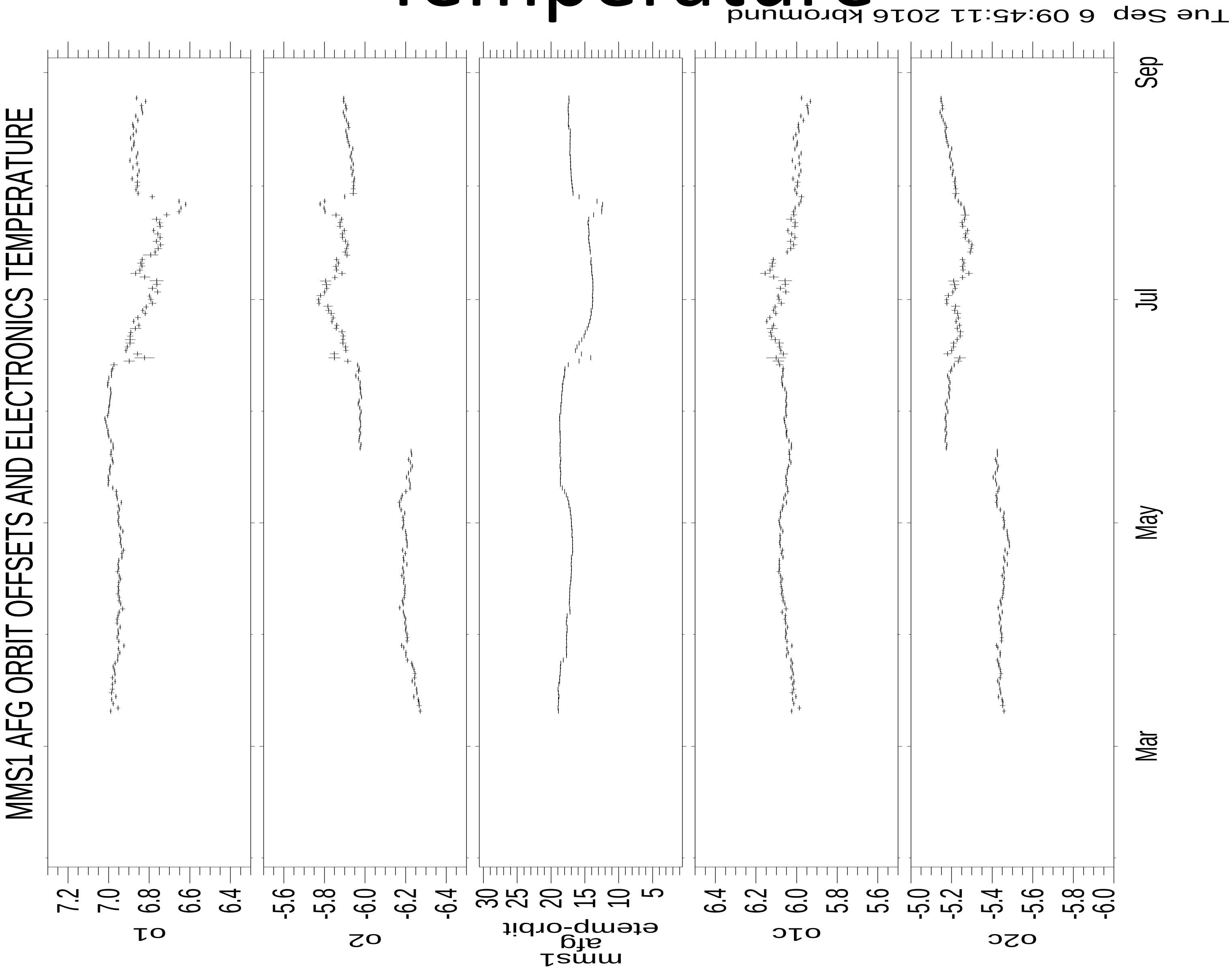
Offset for each orbit determined by fit to previous 7 orbits



Trend of orbit offsets, compared to orbit averages

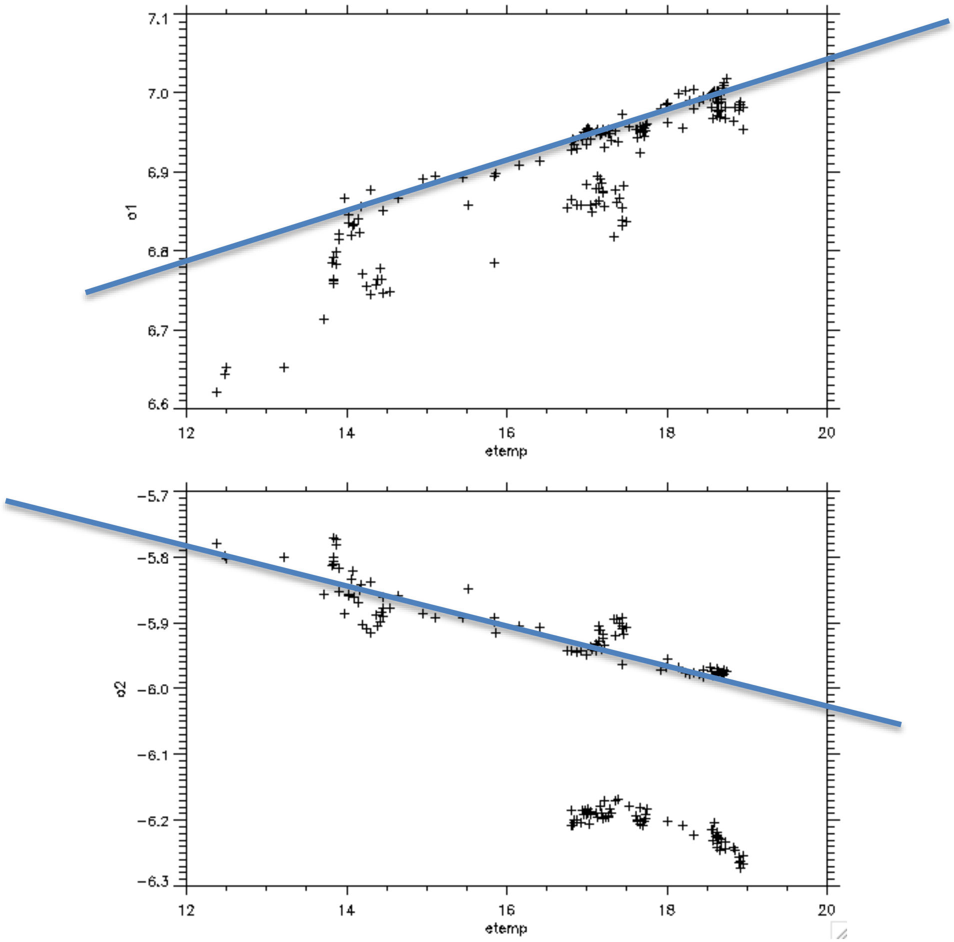


Comparing to Electronics Temperature



OFFSET vs ETEMP

MMS1 AFG

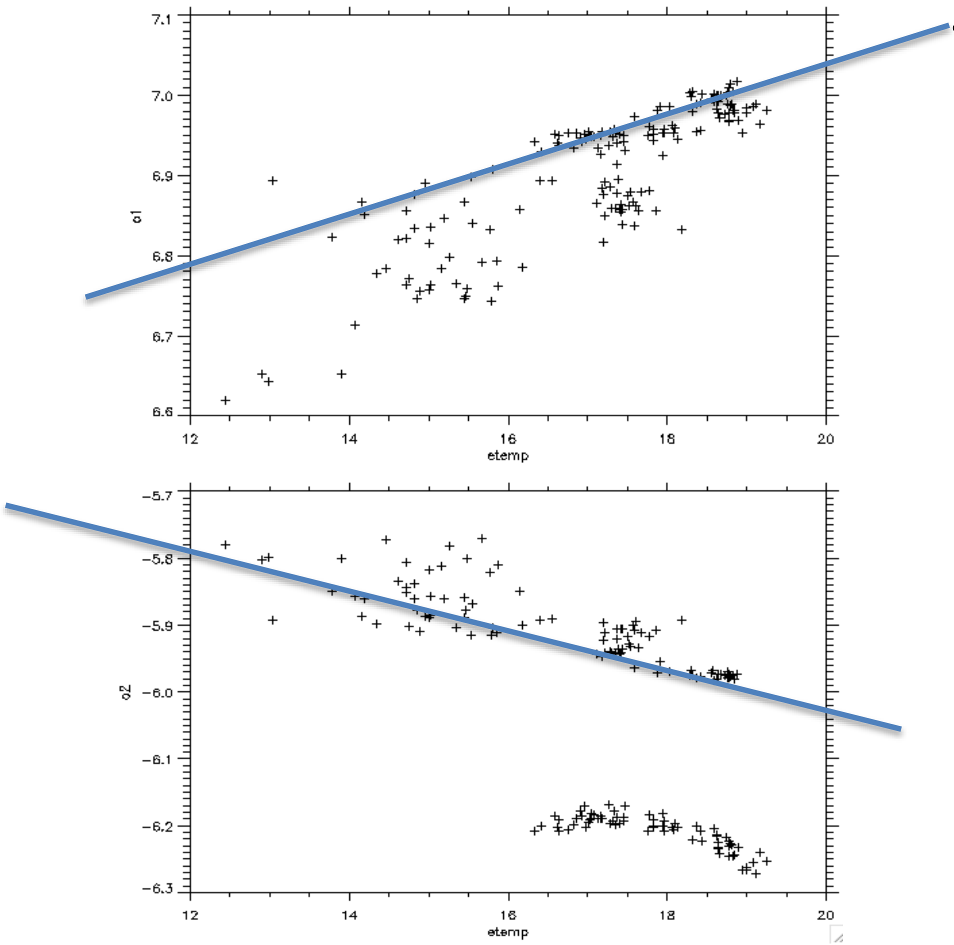


Regression by eye:

- O1: (7.04 - 6.79) / 8 = 0.03125
- O2: ((-6.03) - (-5.78)) / 8 = -0.03125

OFFSET vs ETEMP

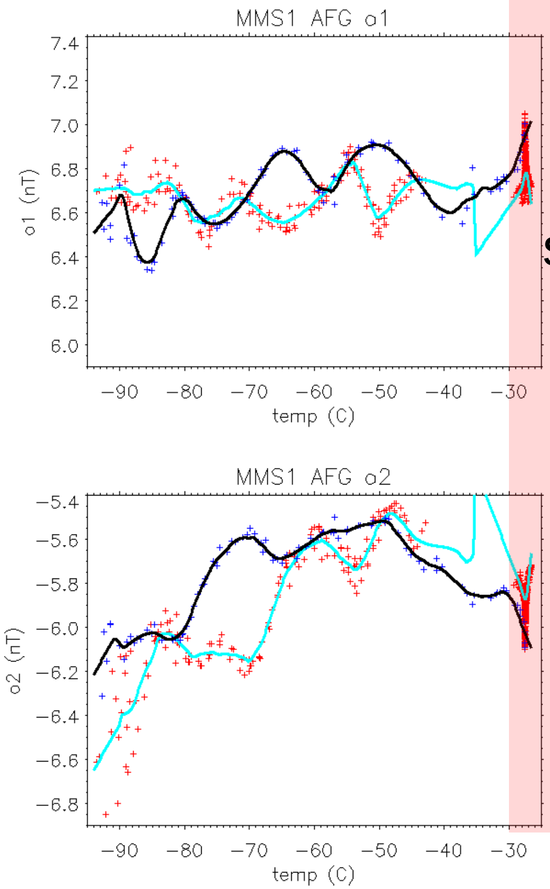
MMS1 AFG



This time, etemp calculated by averaging only the 'good' intervals.

Subtracting E-temp Trend

Before

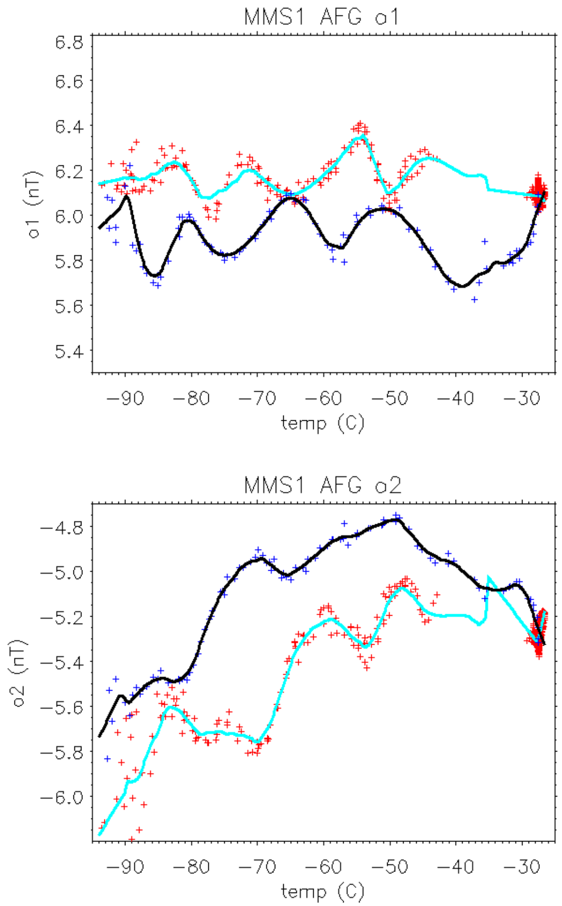


Find slope of Etemp (b1, b2): bilinear regress stemp > -30

b1 = 0.051

b2 = -0.043

After



Using Both Sensor Temperature and Electronics Temperature