The Constant Size and Shape of the Sun

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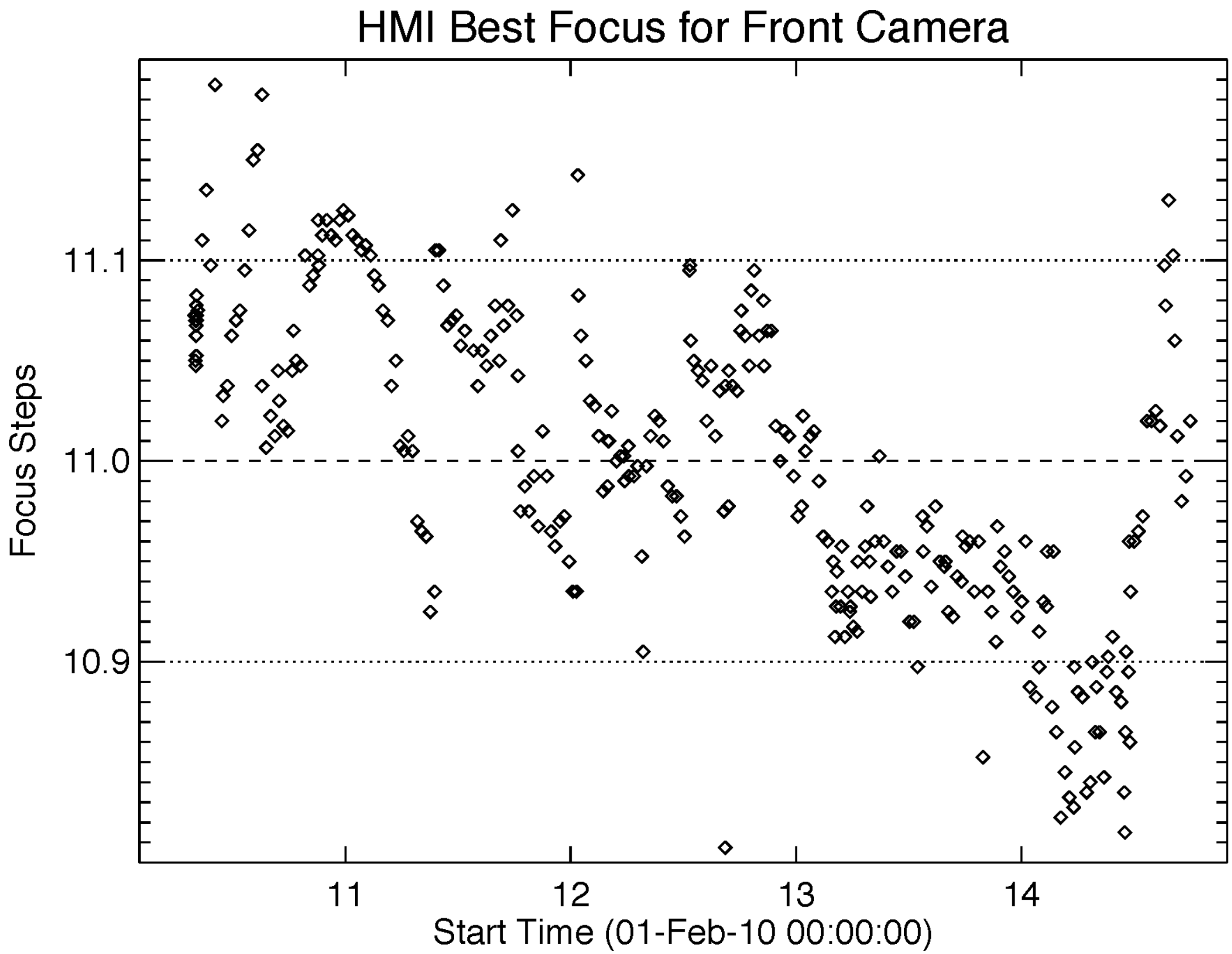
Introduction

- Over the last four years, the Helioseismic and Magnetic Imager (HMI) instrument on the Solar Dynamics Observatory (SDO) spacecraft has been measuring the radius and shape of the Sun.
- The primary observations for the solar radius are full Sun images taken twice per day in the continuum wing of the 617.3 nm Fe I absorption line. The solar radius is defined as the mean distance from the center of the Sun to the inflection point of the limb darkening function. After correcting for the varying Sun to spacecraft distance and temperature variation of the optics, the measured solar radius is essentially constant over the rising phase of the solar cycle.
- In April and October each year, the SDO spacecraft executes a roll calibration maneuver in which the spacecraft is rotated 360 degrees around the Sun-spacecraft line. HMI observations taken during these roll maneuvers allow the instrument distortion to be separated from the solar shape to determine the solar oblateness. The long term trend of the solar oblateness, however, does not show a correlation with the current solar sunspot cycle.

HMI On-Orbit Performance

- The HMI instrument started science observing on 1 May 2010 after a two month on-orbit commissioning period. The instrument has operated continually since then except for a two periods in April 2013 and May 2014 due to a reboot of the control processor.
- The pair of HMI cameras have taken a combined 76 million images during the last 4.6 years. The telemetry downlink has been exceptional with recovery of 99.96% of all the images taken.
- Loss of science data due to eclipses and periodic spacecraft maneuvers is less than 2% of total observing time.
- Calibration sequences are run weekly in order to track the instrument focus and filter tuning and to update the flatfields.
- The observing focus is maintained at a constant value by adjusting the front window heater settings. The exposure time and filter tuning settings are adjusted by updating the observing sequence parameters.

HMI Operating Focus

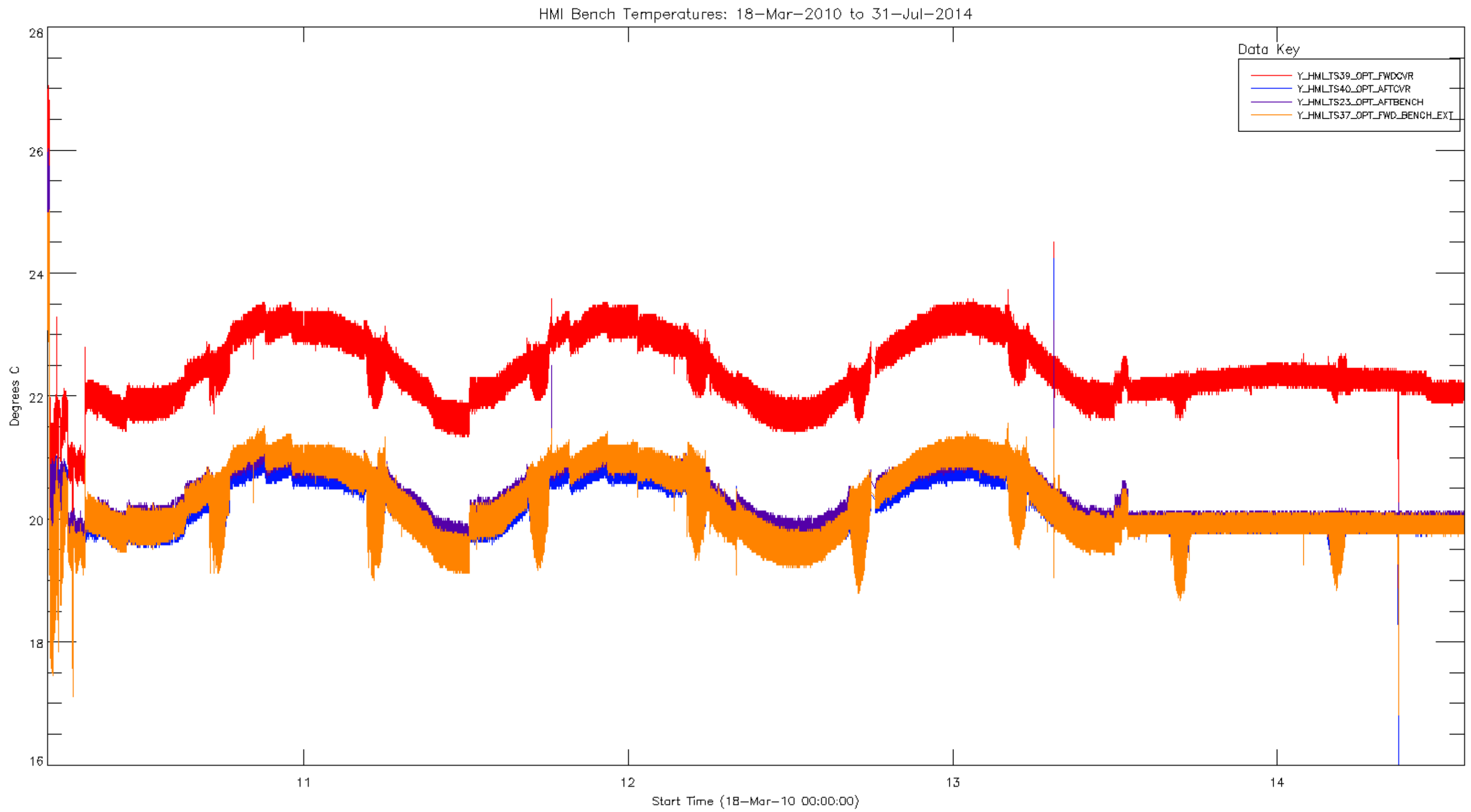


The HMI focus has been maintained at a roughly constant value by adjusting the temperature of the front window.

HMI Thermal Control

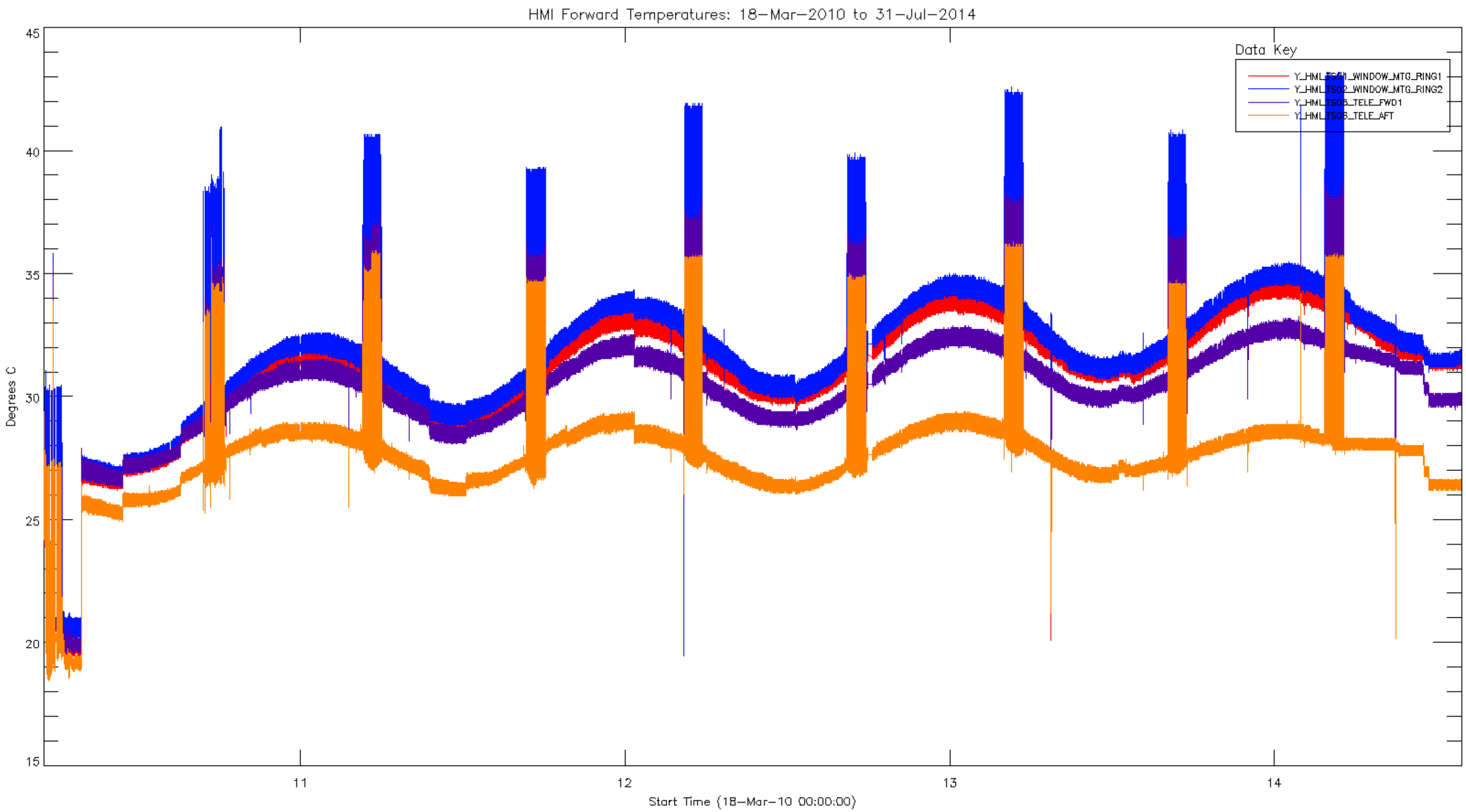
- Starting at launch, all the HMI optics package heaters were run with constant heater duty cycles (fixed heat input) similar to the thermal control method that was used during ground testing.
- Beginning in July 2013, the optical bench thermal control was modified to run at a constant temperature of 20°C in order to minimize seasonal temperature variations and their affect on the instrument focus.
- Starting in late February 2014, the HMI telescope tube heaters was also changed to constant temperature control.
- Finally in June 2014, the HMI front window heaters were set to constant temperature control. Because the varying spacecraft to Sun distance changes the heat input to the front window, the front window temperature set point needs to be updated regularly. This adjustment minimizes the temperature gradient on the front window and maintain the optimal observing focus.

HMI Optical Bench Temperatures



The optical bench temperatures show an annual variation because the initial thermal control scheme ran the heaters at a constant duty cycle. The thermal control scheme was modified in July 2013 to adjust the heater duty cycles to maintain a more uniform temperature of 20 degrees C.

HMI Front Window Temperatures

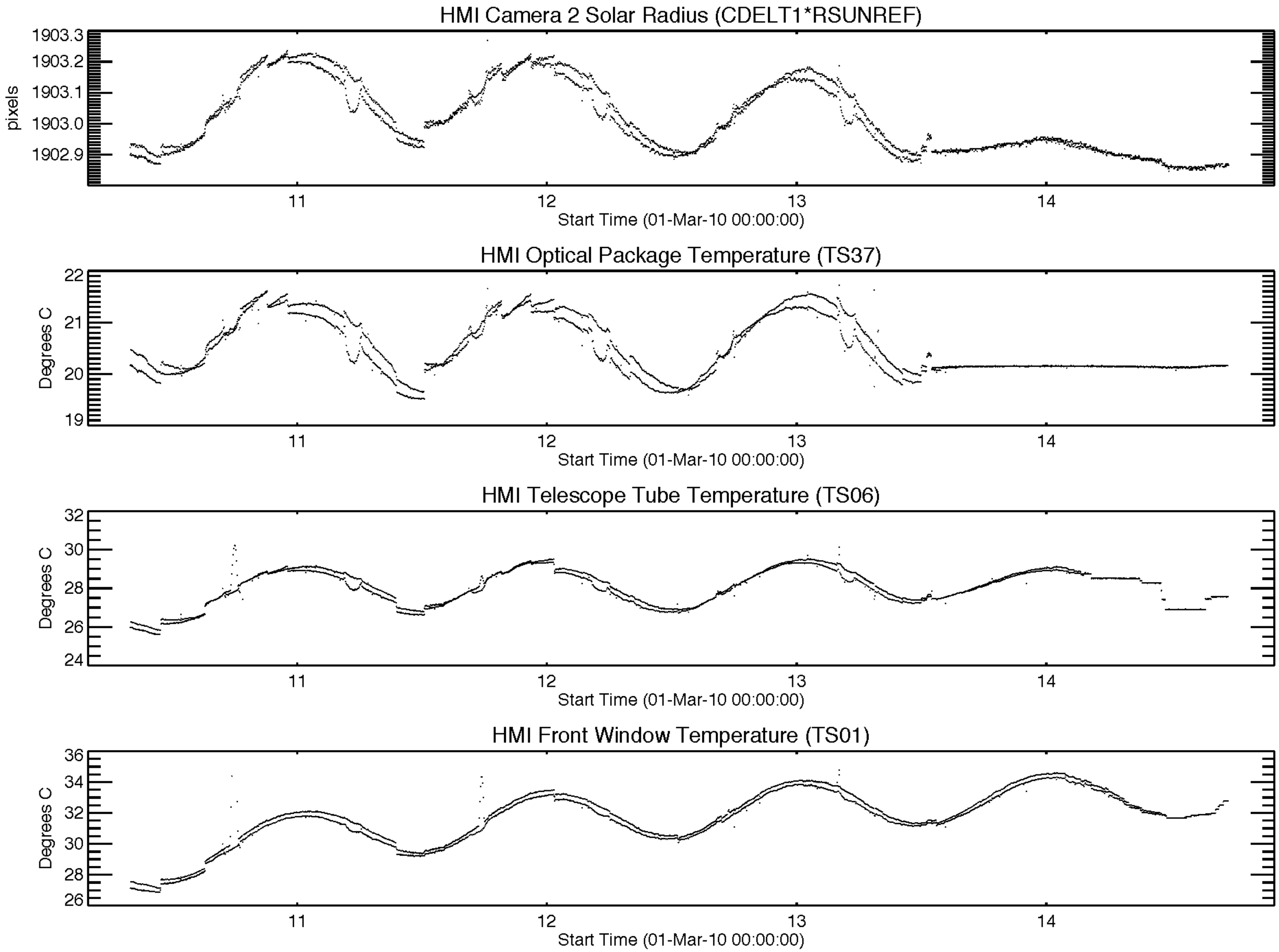


This plot shows the HMI front window and telescope temperatures from February 2010 through July 2014. The periodic temperature increases occur during the twice yearly eclipse seasons to prevent the front window from getting too cold. There is a long term increase in the temperature due to aging of the front window.

HMI Determination of Solar Radius

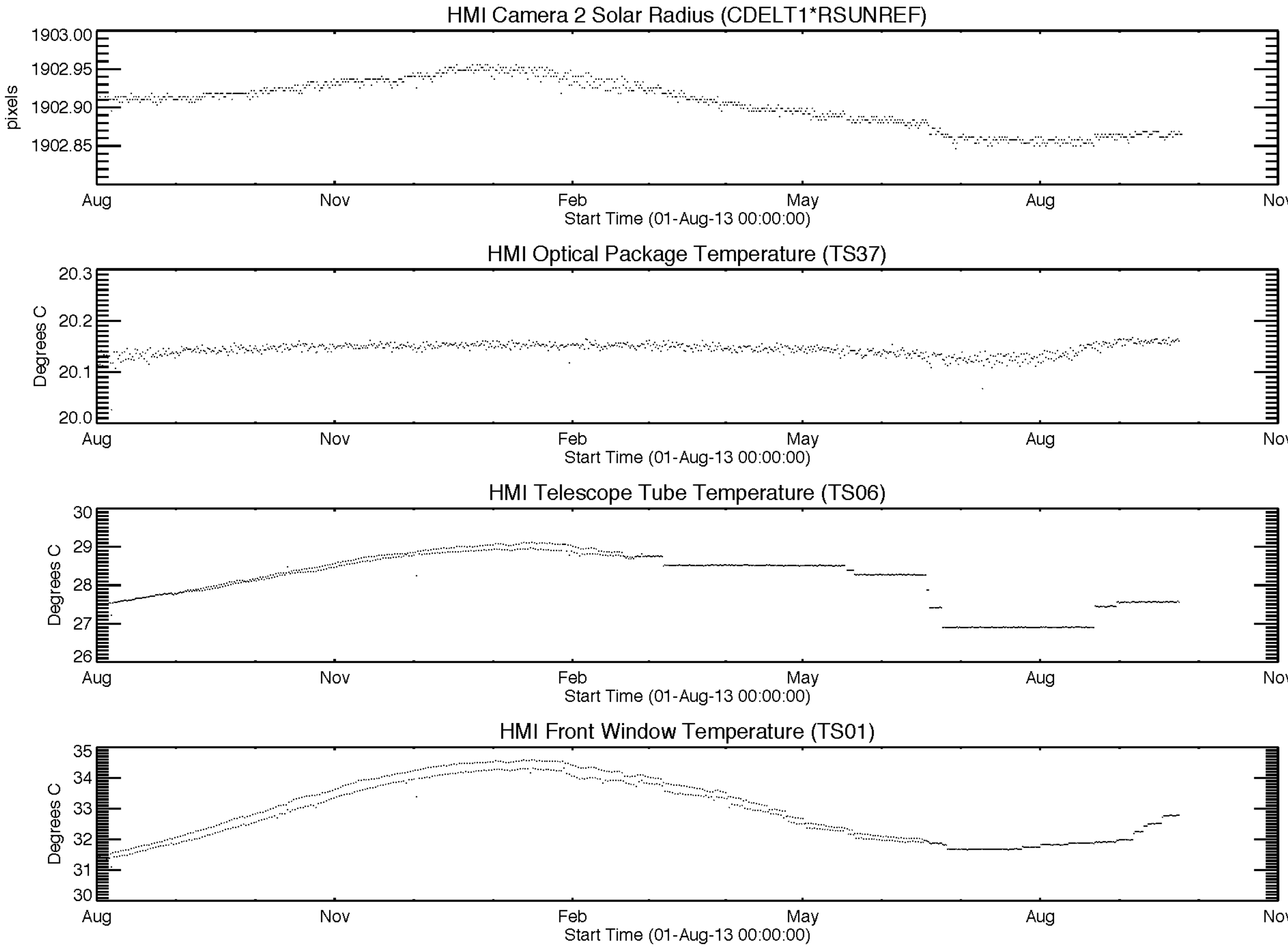
- The HMI image center and image radius are determined by fitting the observed solar limb in order to co-align the filtergram images used for the HMI observable processing.
- Daily calibration images in the continuum wing of the Fe line are taken at local noon and midnight. The solar limb determinations of these full disk images provides a consistent measure of the apparent solar radius.
- The mission long solar radius measurements shows a clear correlation with the optics package temperature.
- Before the change to the thermal control, the annual solar radius variation was approximately 2×10^{-4}. With the constant optics package temperature, this variation was reduced to 4×10^{-5} or approximately 38 milli-arcseconds (mas) annual variation.
- There does not appear to be any long term trend in the mean solar radius determined from the HMI images. Additional modeling of the front window thermal variation is being developed.

HMI Radius and Temperature Variation



The HMI solar radius is determined from fit to the solar limb and corrected for the spacecraft to Sun distance. There is a clear correlation between the optics package temperature and solar radius.

Correlation of Radius and HMI Temperature



This plot shows the last year of the solar radius determined from the HMI images and the adjustments to the optics package, telescope tube and front window temperatures.

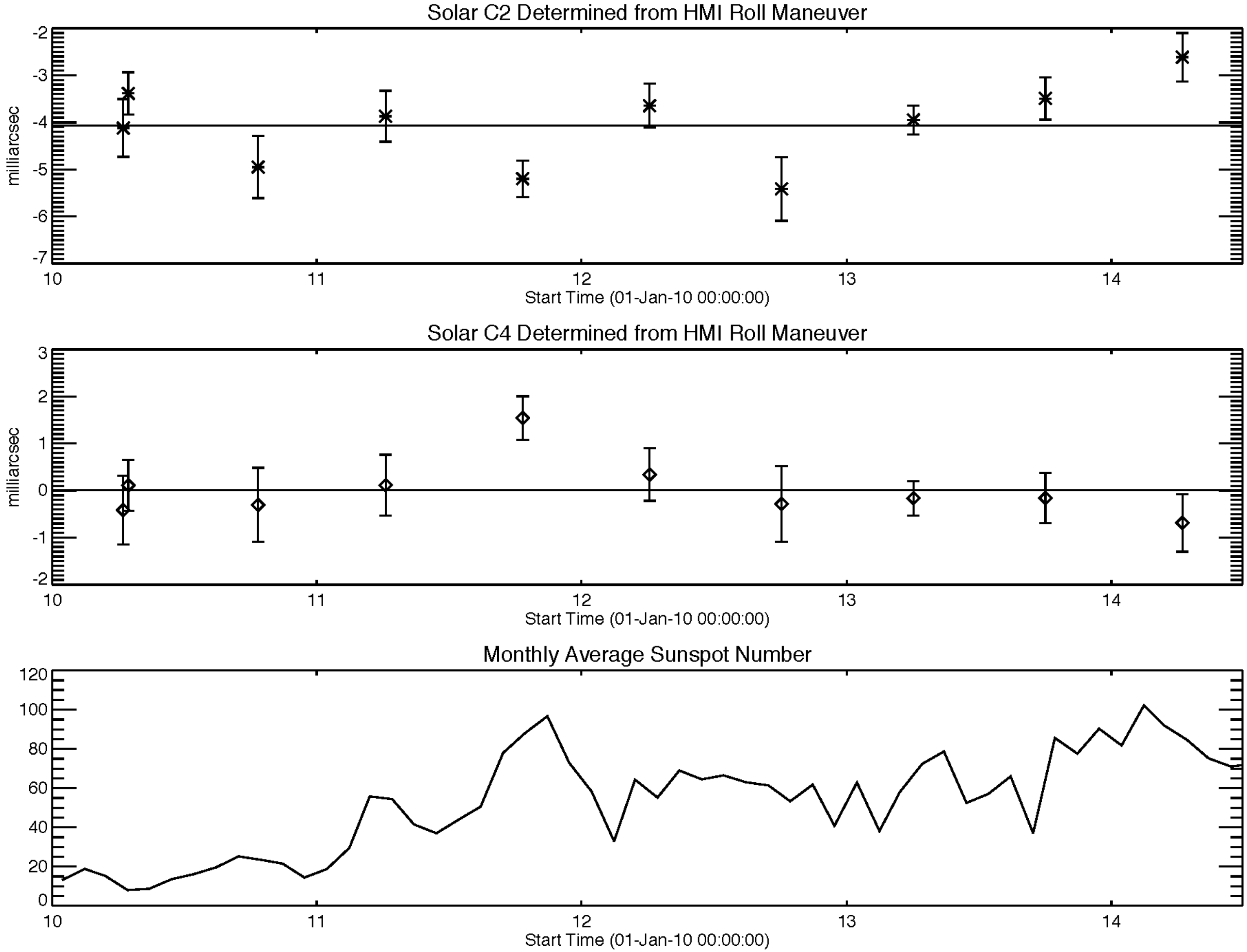
SDO Roll Calibration Maneuver

- **The SDO roll maneuver is essential to determining the solar shape because the rotated images allow the instrument optical distortion to be separated from the solar shape.**
- **The first two roll maneuvers were performed in April 2010 as part of the spacecraft commissioning activities. The 8 subsequent roll maneuvers have been performed at 6 month intervals in April and October. The spring and fall roll maneuvers rotate the spacecraft in opposite directions.**
- **A complete roll maneuver takes about 6 hours, and the HMI Image Stabilization System (ISS) loop is open during the roll slews and closed for the science observations. Each roll maneuver dwells at 32 uniformly spaced roll for 7.5 minutes.**
- **The HMI observing sequence takes continuum tuned and line core images on the side camera in 2 circular and 4 linear polarizations for the primary solar shape determination. Approximately 35 images are taken at each roll step and polarization state.**
- **The standard velocity/line of sight magnetic sequence of images is taken with the other camera to help calibrate the HMI observables.**

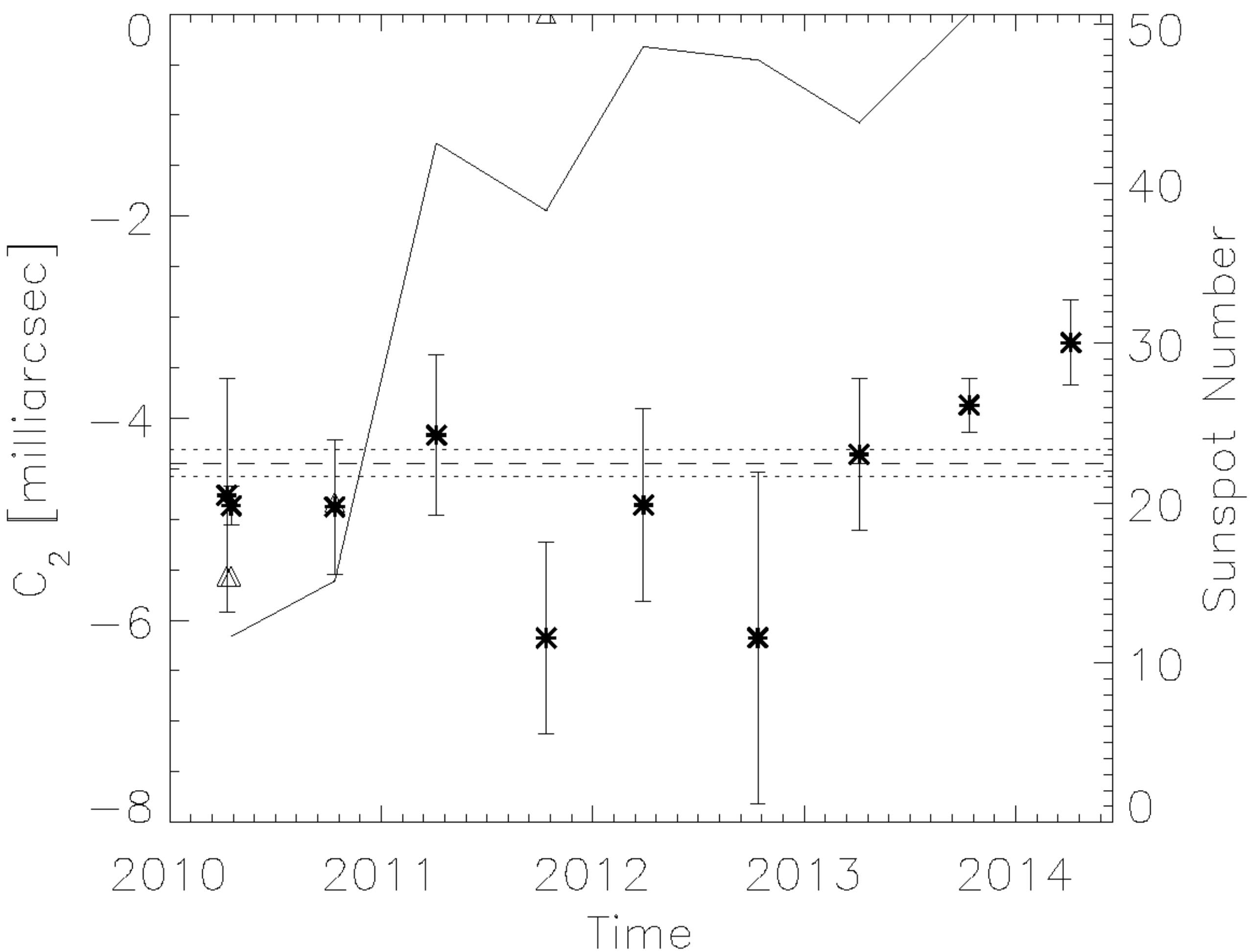
Oblateness Analysis Results

- The solar limb location is determined by fitting a limb darkening function for radial slices from each image. The average limb location for all the roll positions is used to correct the individual limb determinations in order to measure the solar limb shape.
- Two determinations of the c_2 parameter (= ⅔ΔR/R) are shown in the next two figures. The first is from the HMI production processing, the second is using a different averaging algorithm by J. Kuhn.
- The mean c_2 value of all the rolls is -4.1 ± 0.6 mas for the first analysis and -4.4 ± 0.2 mas for the second. This corresponds to a difference in the polar to equatorial radius of 6.3 to 6.6 ± 0.9 mas or a fractional difference of 6.6×10^{-6}.
- The c_2 determinations from the two analyses show similar trends and are consistent given the estimated error uncertainties.
- The mean c_4 value is 0.0 ± 0.6 indicating that there is no apparent higher order variation to the solar shape.
- The variation of the c_2/oblateness from this analysis does not appear to have any correlation with the solar cycle sunspot number.

Solar Shape Determination



Second Determination of Solar C_2 Parameter



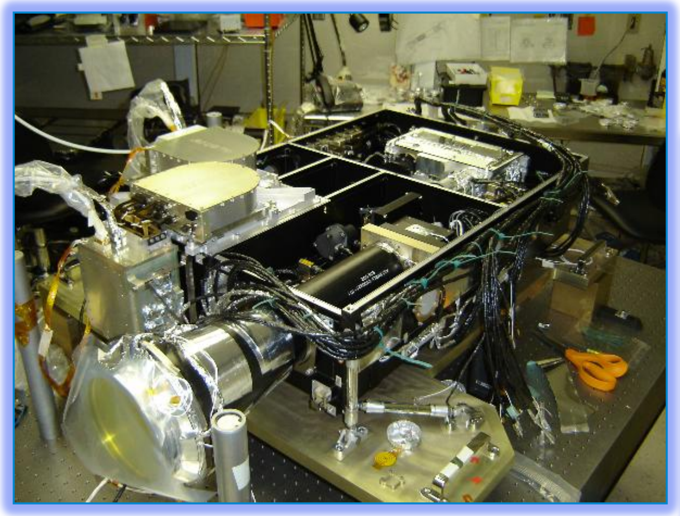
A second analysis by J. Kuhn shows a similar trend to the previous plot.

Summary

- The variation of the mean solar radius determined from the HMI images has an estimated upper limit of 4×10^{-5} or approximately 38 milli-arcseconds and does not appear to correlate with the solar cycle trends. Further modeling of the instrument temperature effects on the measured solar radius are being developed.
- Ten roll calibration maneuvers have been performed during the SDO mission to date with SDO roll maneuvers planned for the remainder of on-orbit operations. The next/current roll maneuver is scheduled for 8 October 2014.
- The analysis of the HMI limb shape indicates that the solar oblateness does not appear to correlate with the solar cycle sunspot number and is consistent with being constant over the initial 4.5 years of observation.
- Mercheri et al (Solar Physics 222, 191-197, 2004) estimate the solar oblateness at 9.1 to 11.4 x 10^{-6} which is significantly larger than the value of 6.6 x 10^{-6} determined from this analysis. Futher work on this difference is warranted.

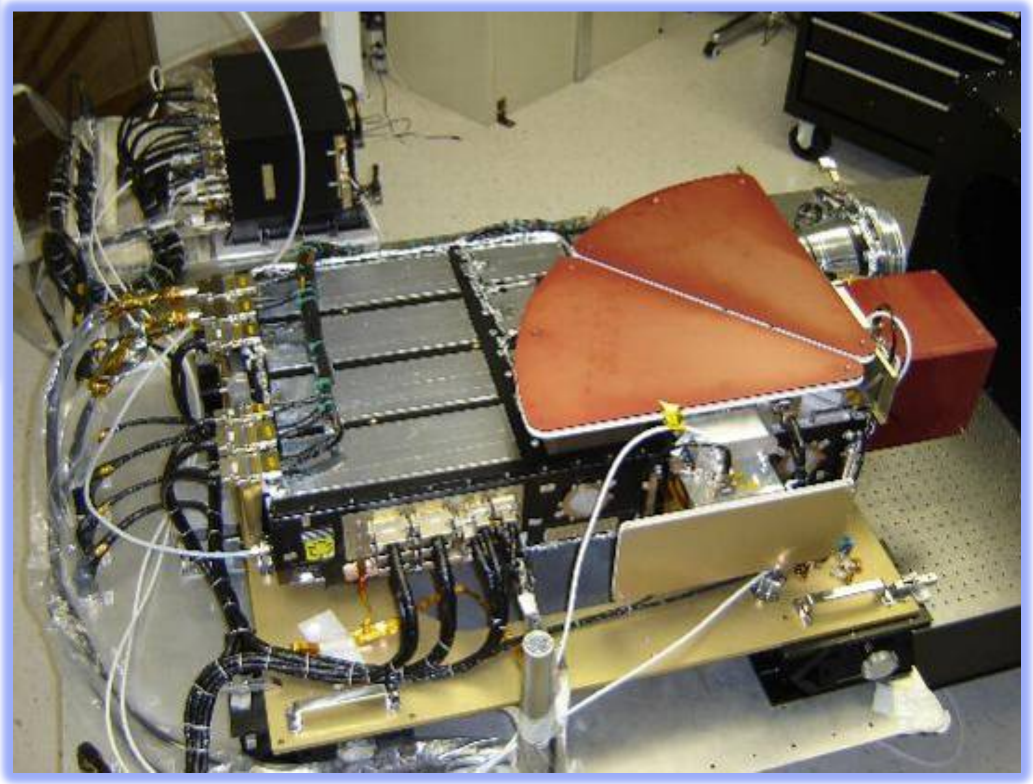
Additional / Backup Information

HMI Flight Instrument



HMI Optics Package (HOP)

HMI Electronics Box (HEB)



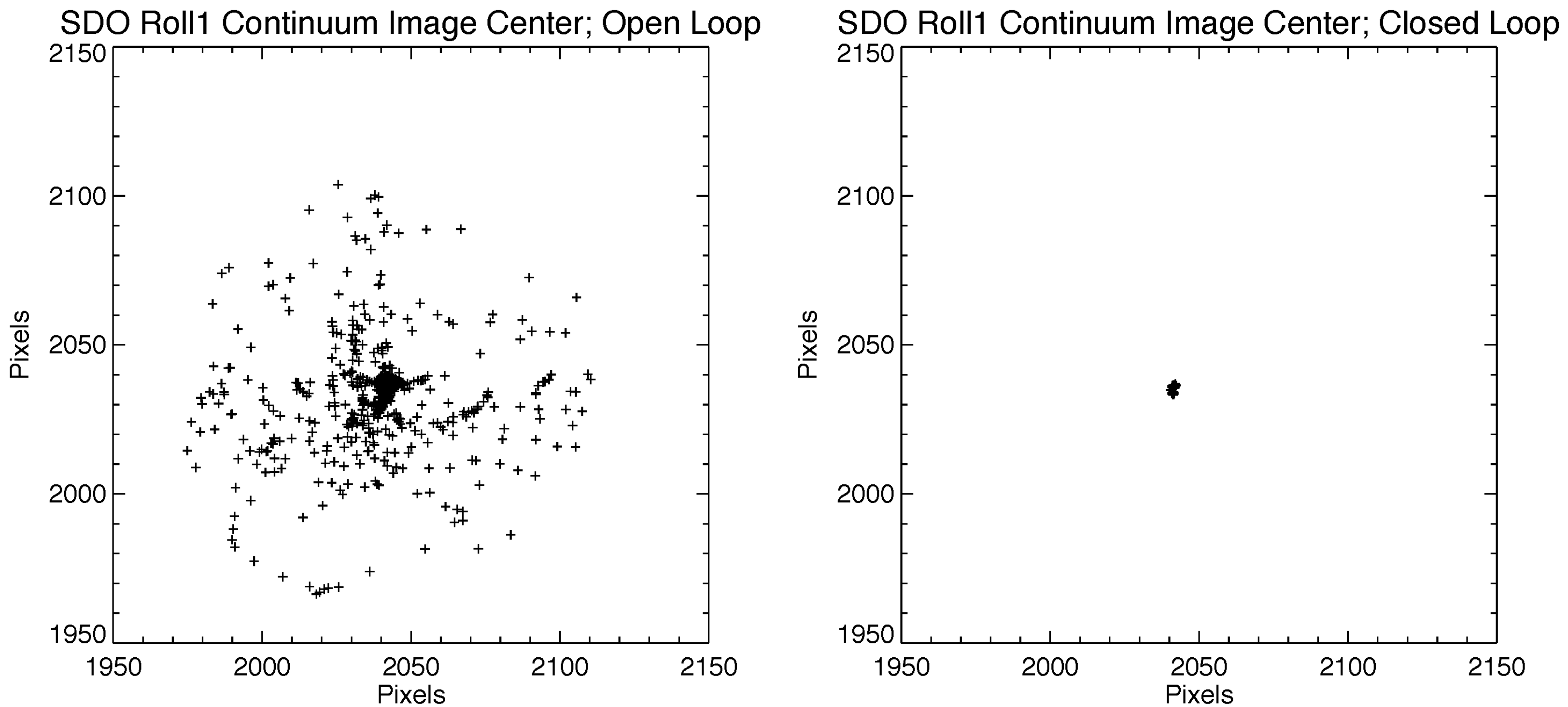
HMI Flight Instrument

SDO Roll Maneuver Dates

Roll #	Seq ID	Start Time (UTC)	End Time (UTC)
1	58377	2010.04.09_06:24:57	2010.04.09_13:10:40
2	58377	2010.04.16_05:37:42	2010.04.16_12:23:25
3	4013	2010.10.12_17:57:12	2010.10.13_00:47:25
4	4033	2011.04.06_05:45:57	2011.04.06_12:36:10
5	4033	2011.10.12_17:52:42	2011.10.13_00:42:10
6	4033	2012.04.04_05:43:42	2012.04.04_12:32:25
7	4033	2012.10.03_18:21:56	2012.10.04_01:12:09
8	4033	2013.04.03_05:36:56	2013.04.03_12:24:54
9	4033	2013.10.02_17:52:41	2013.10.03_00:42:09
10	4033	2014.04.09_05:12:11	2014.04.09_12:00:54

The Seq ID indicates the observing program run by the HMI during the roll maneuver. The primary difference is that the first three rolls only observed line continuum on the side camera.

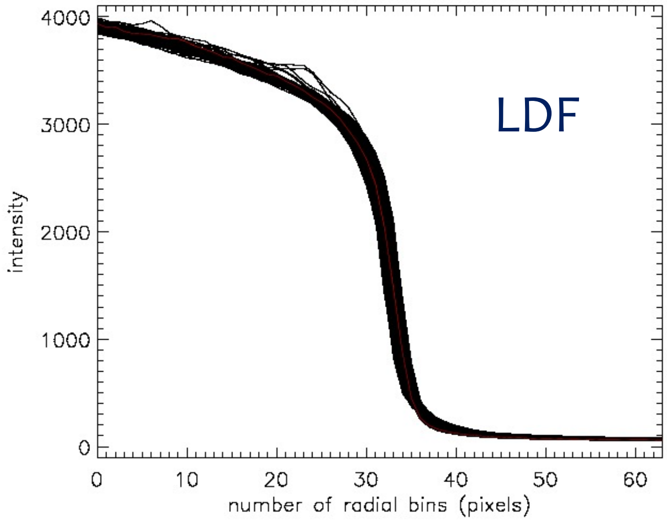
HMI Pointing Stability during Roll Maneuver

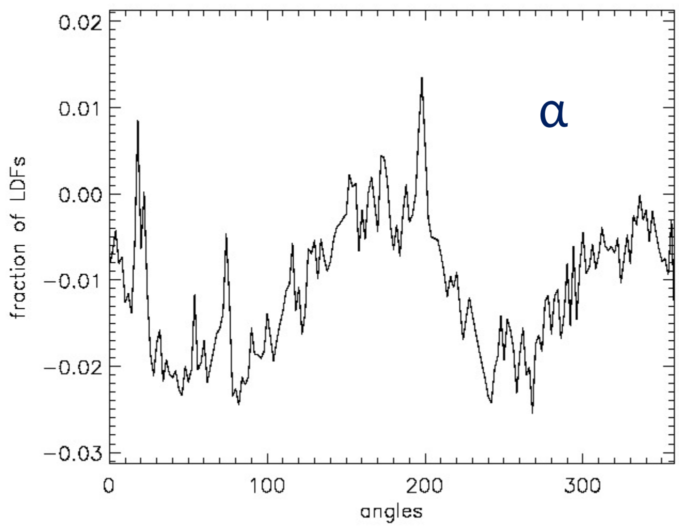


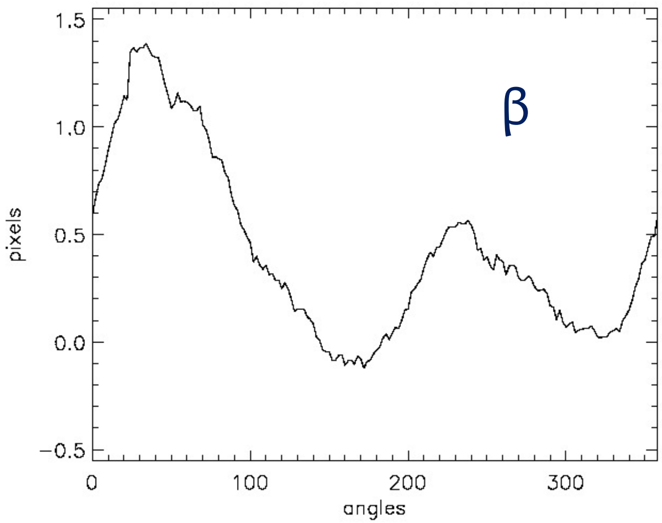
The HMI Image Stabilization loop is opened during the roll slews and closed during the observing dwells. The left plot show the image center for all continuum observations during the roll. The right plot shows the image center location during the observing dwells and has a scatter of +/- 0.2 arcseconds.

Center and Limb Determination

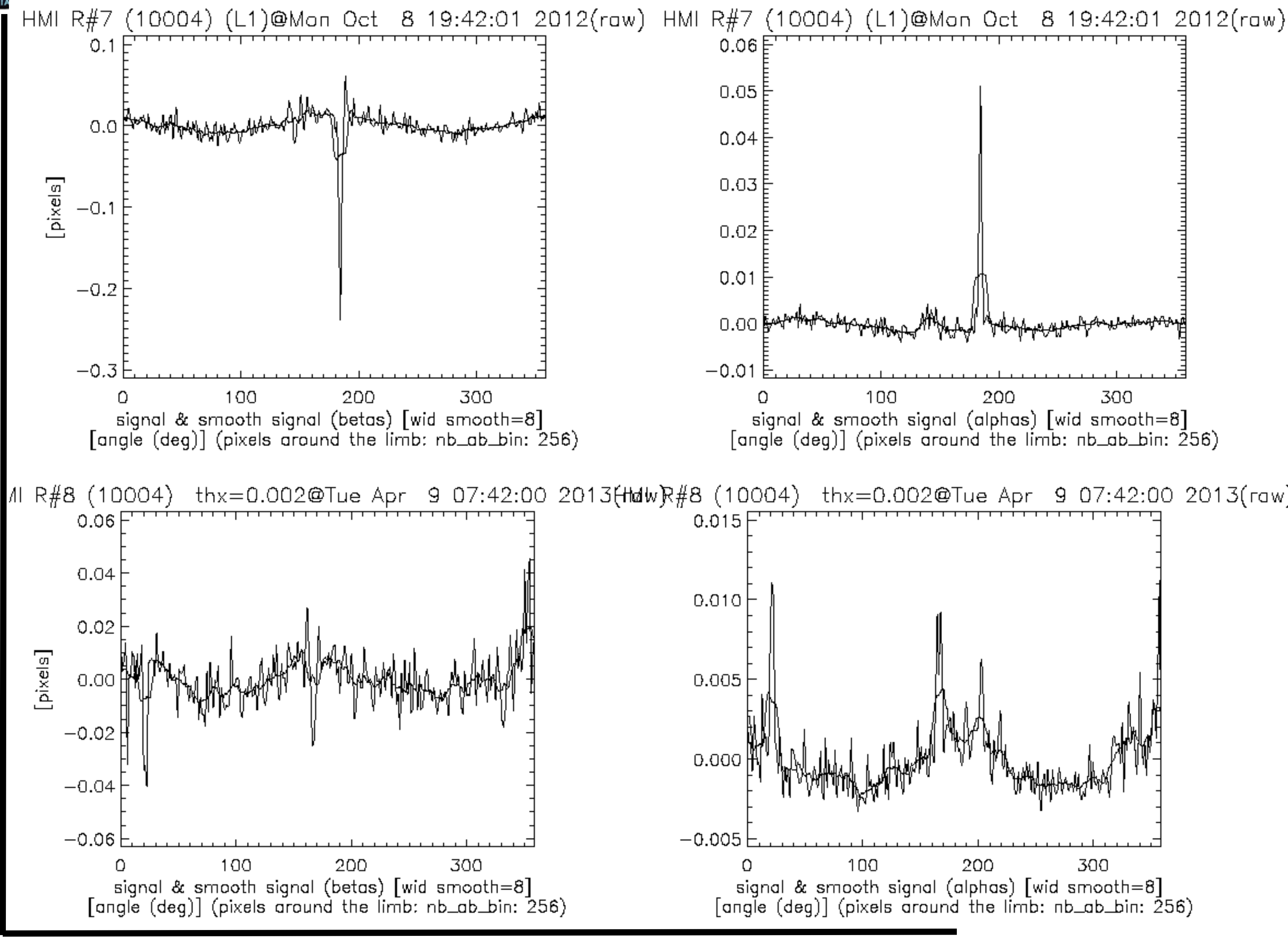
The local limb brightness (α) and displacement (β) are determined at regular intervals around the limb using a Limb Darkening Function (LDF).







Alpha & Beta Fits during Rolls #7 and #8



Solar Shape Determination - Rolls #7 and #8