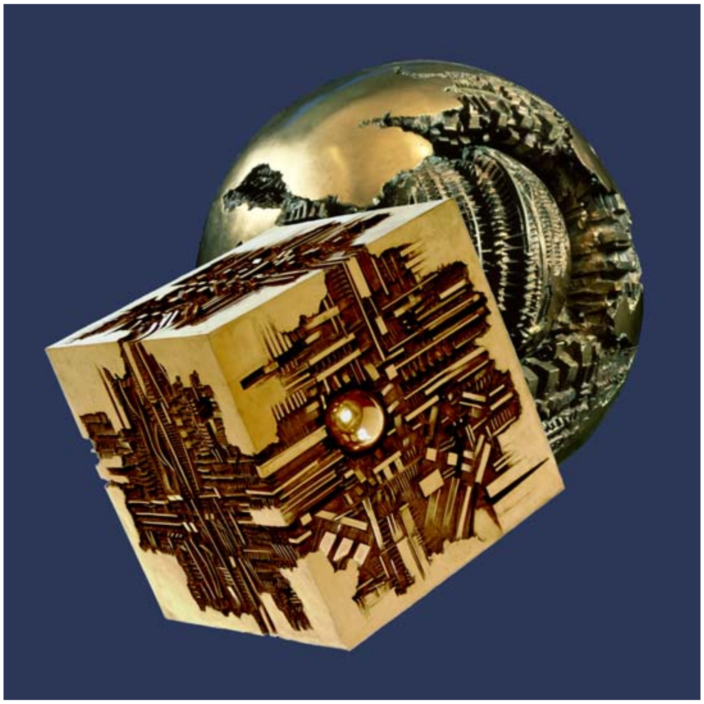
Helioseismic and Magnetic Imager
for
Solar Dynamics Observatory



Instrument Calibration Plan

HMI-S020

PER Version – 13 Dec 2006

Stanford University Hansen Experimental Physics Laboratory
and
Lockheed-Martin Solar and Astrophysics Laboratory

The cover of the NASA 1984 report "Probing the Depth of a Star: The Study of Solar Oscillations from Space" featured Hirschhorn's the Pomodoro Sphere. That report led to the helioseismic study of the global Sun. Pomodoro's Cube at Stanford symbolizes HMI data cubes for investigation of localized regions in the Sun.

Contents

1 Introduction

The purpose of this document is to describe the calibrations which will be performed on the HMI instrument and its various pieces.

It is essential that such calibrations are performed in order to be able to meet even the minimum science requirements and performing a comprehensive set of calibrations will allow us to maximize the overall science return.

Section 2 gives an overview of the various stages of calibrations followed by a section describing some of the equipment and setups used. Section 4 describes the different calibrations to be performed ordered by subject. For each subject the procedures will be described and an outline of the analysis provided.

This plan only covers the calibration of the optical system and closely associated mechanical or electrical systems to the extent that they directly affect the optical performance. In other words calibrations of thermistors etc. will not be captured here.

Many of the calibration procedures described in this document have been used previously on previous experiments such as MDI and Solar-B FPP and are as such not new developments.

This plan does not describe all the details of the calibrations to be performed or of the associated analysis. The former is captured in the associated shop orders and the latter in the reports capturing the results. As such the present document directly drives both the shop orders and the reports.

This document is to a large extend based on the discussions in the Instrument Performance Document (IPD). In particular the requirements are defined there (see Tables 1, 4, 5 and 6).

The calibration of the instrument is also closely related to the Integration and Test (I&T), Alignment and Verification for which there are separate plans. The purpose of the calibration activities is not to provide formal verification of requirements.

In addition to the end-to-end tests described in this document several of the individual optical components (eg. lenses) have been tested. While these measurements will be incorporated as needed, no description of these tests are provided here.

Some of the subsystems (such as the Lyot) as well as several of the more complex calibrations (such as the filter transmission and polarization) have separate plans, and the details will only be summarized here.

After the calibrations have been completed several reports will be written, including

- Overall calibration report
- Detailed reports for each item
- Contributions to the SDO Book

The detailed reports will contain details of the calibrations run, the analysis done and the results obtained. The overall report will summarize the results and reference the detailed reports.

2 Levels of Calibrations

The following subsections describe the different stages of calibrations performed. These efforts mostly consist of measurements that are used for after the fact calibration of the data.

2.1 Component Tests

Some of the quantities needed for the calibration can only, or most conveniently, be measured before final integration of the instrument. The calibrations will thus be performed at different levels of assembly, as appropriate.

Examples of items tested at the parts level include individual waveplates, polarizers, Calcite elements for the Lyot and various powered optics elements. All parts are inspected, measured and photographed to verify that they are undamaged and meet their mechanical specifications. Also the orientation of parts are noted as they are calibrated.

Subassemblies to be tested include the individual Lyot elements.

Assemblies to be tested include the Lyot and the Michelsons.

The tests in this section are generally not described in this calibration plan. Most of them are I&T activities and separate documents describe the other tests.

2.2 Sun Test

The first calibration exercise of the integrated instrument is the so-called Sun Test. The purposes of this include:

- Learn how to operate the HMI optics package.
- Learn how to characterize/calibrate the instrument. In some cases, obtain initial calibration parameters.
- Discover gross errors in design or workmanship of the HMI optics package.
- Determine position of focus to set the final shim on the telescope secondary lens.
- Determine position of waveplates in the polarization selectors to set the final orientation relative to HCM step locations.
- Develop procedures and software for the following calibration activities.

2.3 In-Air Calibration

The first formal calibration activity is the In-Air calibration. The main purposes of this activity includes:

- Obtain calibration data which can not be obtained during the vacuum calibration. This includes certain aspects of the polarization calibrations and image quality measurements requiring the stimulus telescope to be mounted rigidly to the instrument.
- Practice the procedures which will be used during the vacuum calibration.

2.4 Vacuum Calibration

This is the main calibration activity. The noise here will be substantially less than in air.

2.5 Spacecraft Tests

Several calibrations will be repeated once the instrument has been integrated with the spacecraft. The main purpose of these tests is to verify that the calibration has not changed.

Since these tests are mostly for trending and since no calibrations depend on data taken during these tests, they are not discussed further in this document. Instead they are described in the CPT and SPT plans.

2.6 On-Orbit Commissioning

Many of the calibrations will be repeated on-orbit. In addition some calibrations are only possible or most conveniently performed after launch. This includes aspects of the polarization calibration and the distortion.

In this document only those calibrations which depend on being on orbit will be discussed in detail. Other calibrations performed at this level are identical to those done in the vacuum calibration.

The overall plan for calibrations included in the commissioning is part of the In-Flight Checkout Plan.

2.7 On-orbit Periodic

Several calibration procedures will be repeated at varying intervals during the mission. The main purpose is to check for any drifts and to update various calibration tables to compensate for any changes.

The frequency of these range all the way from daily to once or twice during the mission. Most of the calibrations are similar to those described for the ground calibrations of the integrated instrument.

As we gain experience with the instrument on orbit procedures may be added or deleted and the exact frequency of the various tests will be determined.

3 Equipment and Setups

The majority of the equipment is described in the I&T plan and will not be described here.

3.1 Polarization Calibration Unit

For several of the calibrations the so-called Polarization Calibration Unit (PCU) made at High Altitude Observatory (HAO) is used. The basic design of the PCU is shown in Figures 1 and 2 and is described in more detail in HMI01560. Basically the PCU consists of a pair of linear and rotary stages, the first containing a polarizer and the second a retarder with a retardance of roughly 1/4λ. By moving the stages various input polarizations can be generated.

In addition to this the PCU can also be used to stop down the aperture by inserting an aperture plate instead of the polarizer.

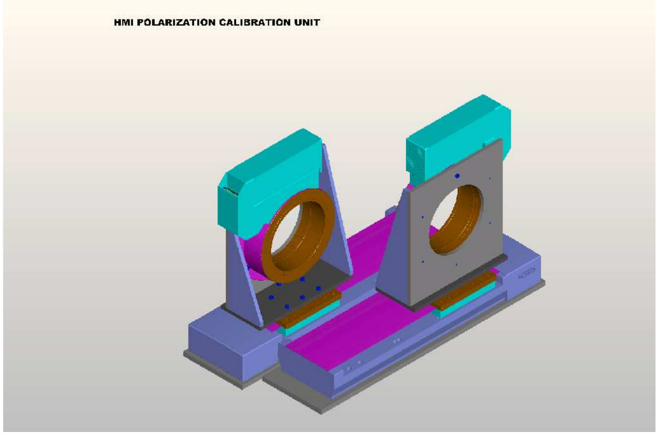


Figure 1: PCU without covers showing the linear and rotary stages.

3.2 In-Air Configurations

Several different setups will be used for calibrating the integrated instrument in air, including

- Standard setup with sunlight shown in Figure 3. This is used for the majority of tests using sunlight.
- Standard setup with stimulus telescope. See Figure 4.
- Mechanically stable setup shown in Figure 5. This is mostly used for image quality and motion test where it is essential that the amount of jitter is minimized.
- 90 degrees setup shown in Figure 6. This is used for front window heating tests.

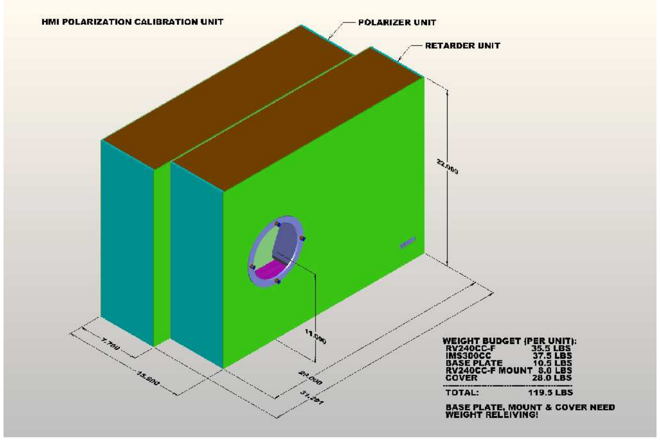


Figure 2: PCU with covers installed.

Note that the light source can be either a lamp fed through a fiber, sunlight fed through a fiber or laser light. Only the lamp option has been illustrated in the figures.

3.3 Vacuum Setup

The main difference here is that the instrument is in a vacuum tank and that the air-to-vac corrector is thus not needed. The basic setup is shown figure 7. This configuration may also be used with sunlight or put in the 90 degree configuration.

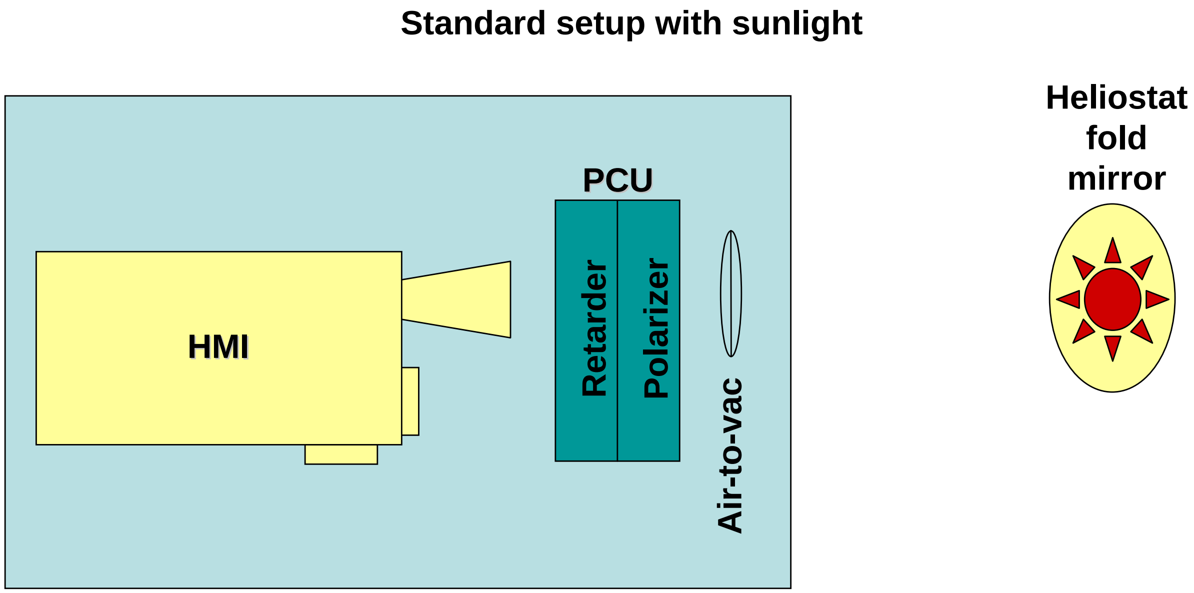


Figure 3: Standard calibration setup with sunlight.

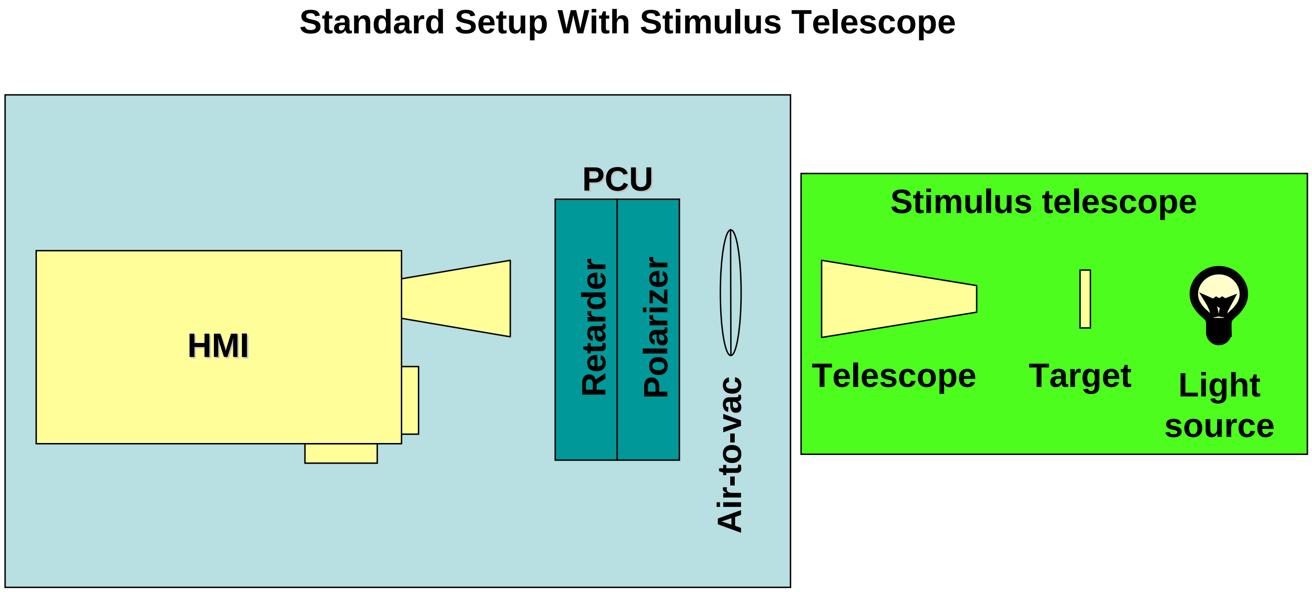


Figure 4: Standard calibration setup with stimulus telescope.

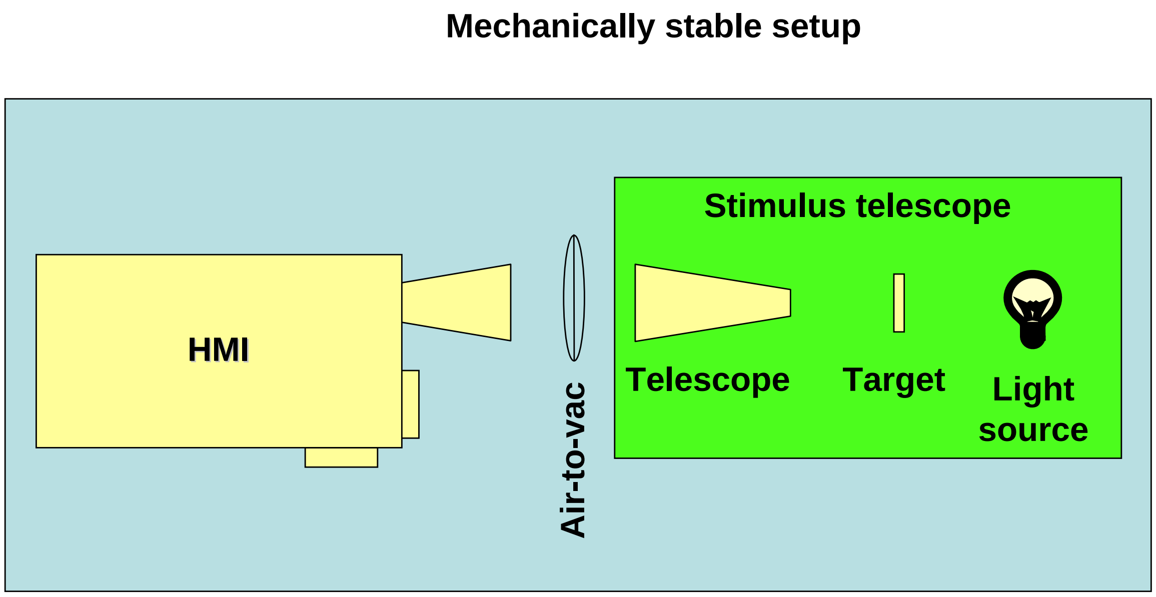


Figure 5: Mechanically stable setup.

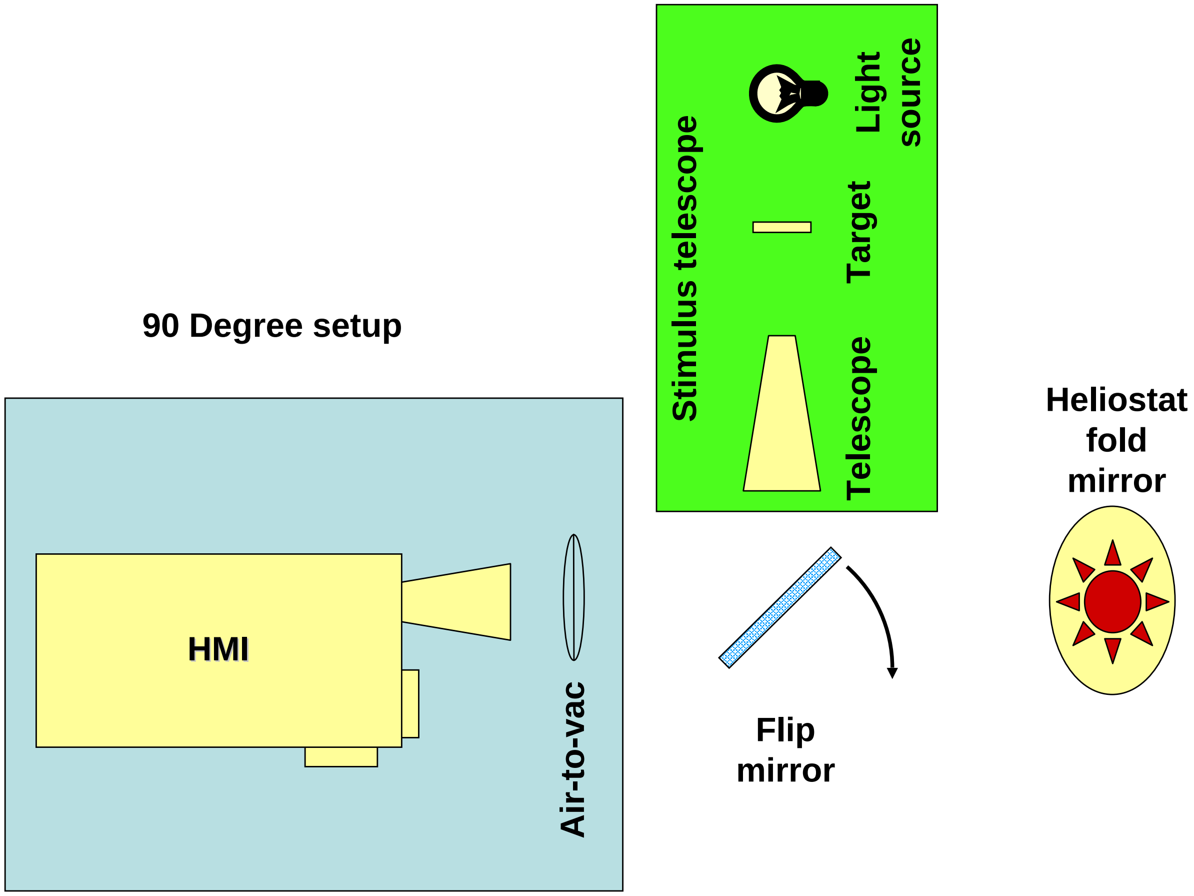


Figure 6: Setup for front window heating tests. The equivalent setup with sunlight has not been shown.

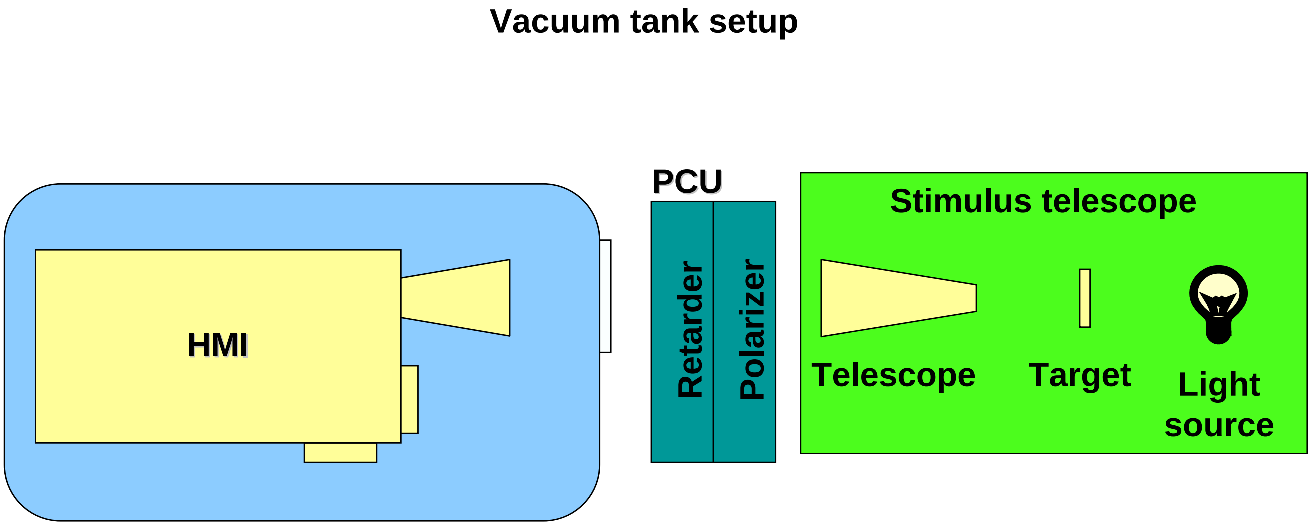


Figure 7: Vacuum tank setup. The equivalent setup with sunlight has not been shown.

4 Calibration Procedures

In this section the calibrations to be performed are described. The different aspects of the calibration have been ordered by subject.

Unless explicitly stated all calibrations are done in air and in vacuum. The setup is described for each item with particular emphasis on calibrations which have particular constraints.

A summary of the tests done at various levels is shown in Figure 8. Note that in some cases calibrations are shown to be performed at different times. In some cases only one of these are required. Also note that as experience with various setups is gained some of them may be added or deleted at various stages. Finally note that many details described in this section have been left out of the calibration matrix.

4.1 Image Quality

These calibrations cover a variety of issues regarding the optical performance and will be performed on both cameras.

4.1.1 Image scale, camera co-alignment and absolute roll.

The purpose is to determine the image scale as a function of focus position.

Solar images from the ground. This is probably the easiest and most accurate measurement on the ground. The apparent solar diameter in pixels is estimated from an image and the apparent solar diameter in arcseconds is determined from an ephemeris.

Stimulus telescope and theodolite. The image scale can also be determined by measuring the alignment leg offset using a theodolite and comparing that to the shift in pixels of a target in the stimulus telescope. This method is probably less accurate, but avoids uncertainties associated with the heliostat.

On-orbit. This is similar to using the solar images on the ground and will be done continuously to monitor aging effects, in particular those affecting the thermal properties.

Due to the uncertainty in the physical radius of the Sun the most accurate measurement of the absolute image scale will be from planetary transits and this will be done whenever possible. To do this regular images are taken during the transit. The only such transit during the prime mission is a Venus transit in 2012.

Considerations include not using data where the thermal environment has changed too much due to the decreased level of sunlight during solar eclipses. This effectively limits the calibrations using the moon to the time around first contact.

The analysis consists of measuring the position of the object as a function of time and correlating this with an ephemeris.

Calmode image scale. This will also be determined by measuring the diameter of the image of the aperture stop.

Co-alignment. This activity determines the offset and roll difference between the two optical paths. This is done by mounting a high contrast fine structure target in the stimulus telescope and correlating sub-areas of the image. The plan is to use the random noise target. Some of the details of the correlations are described under distortion.

Absolute roll. Venus and Mercury transits and solar eclipses present the only way to accurately estimate the absolute roll angle of the instrument.

Considerations are similar to those for the images scale above.

The absolute roll will, of course, also be estimated on the ground to the accuracy possible.

Thermal effects. The main effect to check for here is any change in the overall instrument pointing or the offset between the CCDs. This can be done by

Test	Group	Property	Sun Tests	In Air	In Vac	Light Source	Rigid	PCU config
1	Image quality	Distortion	Yes	Yes	Yes	Lamp	(Yes)	None
2		Image scale	Yes	Yes	Yes	Sun+lamp	No	None
3		MTF	Yes	Yes	(No)	Lamp	Yes	None
4		Focus and field curvature	Yes	Yes	Yes	Lamp	(Yes)	None
5		Camera co alignement	No	Yes	Yes	Lamp	No	None
6		Camera relative focus	No	Yes	Yes	Lamp	(Yes)	None
7		Ghost images	No	Test	Yes	Laser+Sun	No	None
8		Scattered light	No	Test	Yes	All	No	Hole
9		Roll	No	Test	No	Lamp	No	None
10	CCD and Camera	Noise	No	No	Yes	None	No	None
11		Flat field	Yes	Yes	Yes	Lamp+Sun	No	None
12		Linearity	Yes	Yes	Yes	Lamp	No	None
13		Quadrant crosstalk	No	Test	Yes	Laser+lamp	No	Hole
14	Contamination		Yes	Yes	Yes	All	No	Hole
15	Vignetting		Yes	Yes	Yes	All	No	Hole
16	Image motions	Offset and distortion	Yes	Yes	(No)	Lamp	Yes	None
17	Filter transmission	Wavelength and spatial dependence	Yes	Yes	Yes	All	No	None
18		Angular dependence	Yes	Yes	Yes	Laser+Sun	No	Hole
19		Thermal	No	No	Yes	All	No	None
20		Turn-on transients	No	No	Yes	Sun	No	None
21		Throughput	Yes	Yes	Yes	Sun	No	None
22	Polarization	Various	Yes	Yes	Part	Lamp+Sun	(Yes)	Pol
23	Observables performance	Doppler	No	Yes	Yes	Sun	No	None
24		Line of sight	No	Yes	Yes	Sun	No	None
25		Vector	No	Yes	Yes	Sun	No	None
26	Thermal effects	Pointing	No	Test	Yes	Lamp	(Yes)	None
27		Focus	No	Yes	Yes	Lamp+Sun	(Yes)	None
28	ISS	Range and stability	No	Yes	Yes	Lamp	No	None
29	Alignment legs	Range and step size	Yes	Yes	Yes	Lamp	No	None
30		Repeatability	Yes	Yes	Yes	Lamp	No	None

Figure 8: Calibration matrix. ”Yes” means that something can be done at that level, ”(Yes)” that the results benefit, ”Part” that partial tests are done, ”Test” that the procedure can be tested at this level (and gross errors in some cases detected), ”No” that a calibration is not doable or interesting at that level and ”(No)” that it is likely not doable. ”Rigid” indicates the stable configuration shown in Figure 5.

changing the instrument heater setpoints and using the stimulus telescope. This may need to be done in vacuum in order to be able to control the temperatures.

4.1.2 Distortion

The purpose of this set of calibrations is to determine the optical distortion of the instrument such that it can be corrected.

A number of methods are used for determining the distortion.

Direct measurement. With this method a well characterized target is placed in the focus of the stimulus telescope and the resulting image on the detector is analyzed.

The plan is to use a set of Ronchi rulings rotated to 0, 90, 180 and 270 degrees. Important considerations in the setup include having the target properly focused, mounting the targets perpendicular to the stimulus telescope optical axis and knowing where the stimulus telescope optical axis is located on the image.

Analysis includes measuring the positions of the lines, correcting for the stimulus telescope distortion and fitting the results to a low order polynomial:

$$\Delta x = \sum_{s+t \leq N} \alpha_{st} x^s y^t \tag{1}$$

$$\Delta y = \sum_{s+t \leq N} \beta_{st} x^s y^t \tag{2}$$

where N is the order of the distortion (N=3 is expected to be adequate). Note that the terms with $s+t \leq 1$ (representing the image scale, image center, ellipticity and roll) are not determined here. Some of these (image scale) are determined elsewhere in the ground tests while others will be done on orbit.

Offset images. In this method a high contrast fine structure target is mounted in the stimulus telescope, images are taken at various alignment leg positions and the images analyzed to determine the distortion.

The plan is to use two targets: A random noise target and a grid. Since this method does not depend on knowing the absolute properties of the stimulus telescope and the target it is much less sensitive to the stimulus setup.

Analysis consists of cross-correlating small areas of the images and fitting the resulting shifts to the equations (1 and 2) describing the distortion.

On orbit rolls and offsets. Several of the terms in the equation describing the distortion are difficult to measure on the ground. In particular this includes the roll, image scale and ellipticity of the image.

The ellipticity terms can easily be measured on orbit by rolling the spacecraft around the spacecraft-Sun axis and measuring the distortion of the solar limb.

By a combination of rolls and offsets (using the spacecraft or the alignment legs) it is also possible to determine other terms in the distortion by tracking the limb and supergranulation (as demonstrated with MDI).

The plan is to do such calibrations on a regular but infrequent basis.

4.1.3 Focus and field curvature

On the ground the absolute focus can be measured in two different ways:

Focus with stimulus telescope. To do this the stimulus telescope is autocollimated by placing a flat mirror in front of the stimulus telescope and looking through a beamsplitter placed before the target. Important considerations include ensuring that only a narrow wavelength range around the target wavelength is used.

For the actual focus check the air-to-vac corrector lens must be in the beam. A high contrast, fine structure target is placed in the stimulus telescope focus and images taken at each focus position. Plan is to use a random noise target, a star array target and a selection of Ronchi rulings.

Important considerations include autocollimating using the correct wavelength (by using a narrow band filter), ensuring that the air-to-vac corrector spacing is correct and noting environmental conditions.

To determine the focus the amount of spatial power is determined as a function of focus setting and the position of the maximum is determined. This number is then corrected for any differences between the environmental conditions assumed for the air-to-vac setting and those actually present.

Given the poorly corrected image in the stimulus telescope (see below) only the center of the image (where the autocollimation is performed) should be used.

Focus with heliostat. To do this images are taken at different focus positions and the sharpness of the solar limb is measured. Again the air-to-vac corrector needs to be installed.

Important considerations include ensuring that the air-to-vac corrector spacing is correct and noting environmental conditions. It is also essential to ensure that the heliostat is not introducing any unknown focus offset. To ensure this a comprehensive series of thermal tests are planned.

Field curvature with stimulus telescope. To determine the field curvature the focus position is determined as a function of position in the image.

Important considerations include those above, as well as ensuring that the stimulus telescope targets are mounted perpendicular to the optical axis of the stimulus telescope. Given that only the focus variations are to be determined here, the environmental conditions are of less concern.

The analysis is similar to the focus analysis above. To disentangle the stimulus telescope field curvature from that of the instrument two methods will be used. One is to subtract a model based on a ray trace, the other is to use offset images (see the distortion discussion). This calibration is done on both cameras.

Relative focus. The relative focus of the two CCD cameras is fairly straightforward to measure by doing a field curvature measurement, as described above, with both cameras and subtracting the results.

Given that the data will be taken at the same time the environmental conditions and stimulus telescope setup are of less concern.

Thermal effects - front window and primary. As mentioned earlier one of the main concerns with thermal effects is that of focus shifts. While this is to a large extent an I&T effort (since it affects the setting of the final focus of the instrument) it has a lot in common with the calibrations and these are the main items in this test.

First of all the temperature of the front window has to be measured, as a function of position, with and without sunlight. This then needs to be correlated with a thermal model of the window. This should preferably be done in vacuum (due to concerns with convective cooling in air), but an in air test may be adequate if thermal imaging is not possible through the vacuum window. Considerations include measuring the intensity of the incident sunlight and taking enough measurements to estimate the relevant timescales.

Second, the focus change associated with the thermal gradients needs to be measured. To do this the stimulus telescope is set up at right angles to the boresight (see Figure 6) and a mirror is used to quickly change between the heliostat and stimulus telescope. The test starts out with a focus measurement with the stimulus telescope before exposure with sunlight, letting the window reach equilibrium and switching back to the stimulus telescope to take focus measurements while the front window is cooling down. Again vacuum is preferable. Considerations are similar to those above.

Third, the effect of the front window heaters have to be characterized in terms of induced temperature gradient and focus change. This can be done with the stimulus telescope as above.

Fourth, the degradation of the front window with time has to be modeled.

Finally all these have to be added up to find the best focus setting.

Thermal effects - optics package. Any change in the absolute and relative focus of the cameras as a function of optics package temperature also need to be measured.

4.1.4 MTF

Absolute MTF. The MTF is measured using targets with accurately know properties in the stimulus telescope. In particular we will use Ronchi rulings and star targets.

Important considerations include ensuring that there are no other sources of image degradation. Jitter is a particular concern and the setup shown in Figure 5 is used. It is also important to ensure that the illumination of the aperture is uniform at each field point.

Analysis consists of measuring the contrast of the targets as a function of spatial position and focus and comparing that to what is expected from a ray trace.

Relative MTF. We need to determine the MTF differences between the two telescopes as a function of spatial positions and focus position in order to determine if it is possible to combine the data from the two cameras.

To do this a random dot target will be imaged as a function of focus position with both cameras. The data taken will be the same or similar to that used for focus and distortion.

Considerations include ensuring that there is very low jitter.

The analysis is beyond the scope of this document.

This calibration will need to be repeated on-orbit at a regular basis.

4.1.5 Ghosts and scattered light

The purpose of these activities is to determine if ghosts or diffuse scattered light appear due to reflections off various surfaces in the instrument. Procedures to look for electronic crosstalk between cameras are described in Section 4.2.

Optical elements and mounts. These tests are performed by using a localized bright source and looking for increased light levels in other places on the CCDs. These activities are best done in vacuum with a cold CCD due to the dark current masking any faint ghosts in air.

Considerations include ensuring that the field of view is well covered. The data should be taken in both obsmode (using a field stop and moving a laser) and calmode (using the PCU aperture plate and moving the laser). Much of the data taken for this purpose will be identical to that taken to look for contamination described later.

Analysis consists of examining the dark subtracted images to look for increased light. If any significant excess light is found more sophisticated procedures and/or analysis will be needed to characterize the problem and/or pinpoint the source.

Inter camera ghosts. Determine if there are any ghost reflections from one camera to the other when both shutters are opened simultaneously.

The procedures are similar to those described above, but involve examining the difference between images taken with one camera with and without the other shutter open.

4.2 CCD and Camera

Most of the CCD and camera tests are described in separate documents.

The important quantities to measure include:

Bias, gain, linearity and CTE. These need to be measured as a function of temperature and any relevant camera settings. Similarly any problems with the CTE, droop etc. needs to be measured accurately.

Gain stability. This issue has been discussed earlier in Section 4.5.6

Flat field and other cosmetics. The flat field can be determined in several ways, each of which has distinct advantages and disadvantages. These methods include using the built-in LED, using offset images (eg. Kuhn, Lin & Loranz, 1993, PASP, 103, p. 1097-1108), using calmode images and determining it directly from the images (averaging and exploiting the solar rotation).

Quadrant crosstalk. Given the proximity of the cables from different amplifiers and common electronics there is a potential for electronic crosstalk. The presence of such crosstalk is determined in a matter similar to that for ghost images. To distinguish the two the CCDs can be read out using different combinations of amplifiers.

4.3 Contamination and Vignetting

4.3.1 Contamination - general.

An efficient way to find contamination is to shine a narrow beam through the instrument and use the parallax to determine the location of each feature. The narrow beam will be generated several ways.

Aperture stop. The PCU polarizer can be replaced by an aperture plate, which can then be moved around to fill the aperture. Data are taken in obsmode. Calmode images are used to determine the exact position of the aperture stop. Sunlight and stimulus telescope can be used.

The stimulus telescope is most efficient since it overfills the field. Sunlight (or offpointing the stimulus telescope) can be used to distinguish stimulus telescope contamination from that in the instrument.

Analysis consists of determining the position of the aperture stop and shifting the obsmode images by an amount proportional to this. By varying the proportionality constant a fly-through of the instrument can be generated.

Field Stop. Here a small field stop is moved around in the stimulus telescope field of view. Otherwise the procedure is similar to the above exchanging obsmode and calmode. Using calmode images makes it possible to find contamination close to the aperture.

Laser. A laser can also be used to generate the narrow beam in either obsmode or calmode. Advantages include that more of the optical path can be mapped out. Disadvantages include the presence of interference fringes and speckles.

4.3.2 Contamination on waveplates and focus blocks.

Contamination can also be present on the movable optics. To find this a narrow beam is generated by the methods described above and the mechanisms moved. A smaller set of positions is used here since the position of the contamination is given by the item being moved.

4.3.3 Vignetting - general.

Vignetting can be found using the method and data described under contamination. However, more care needs to be taken to avoid effects caused by the stimulus telescope to HMI distance and non uniformities in the stimulus telescope illumination. For this reason sunlight is the preferred light source. The field is then filled by offpointing the heliostat.

4.3.4 Vignetting - path differences.

Vignetting caused by objects after the BDS beamsplitter can be found by examining the difference between images taken with the two cameras. This has the advantage of canceling out any stimulus telescope artifacts.

4.4 Image Motions

Image motions cover both solid offsets of the images and distortions. While some of these motions are corrected by the ISS others are not.

To measure the image motions a high contrast fine structure target (random dots) is placed in the stimulus telescope and the ISS turned off. Each focus block is then placed in the beam and any motions measured by cross correlating with the original image. For the Hollow Core Motor test the image is kept at a fixed focus and each HCM is rotated through several angles.

Considerations include ensuring that the stimulus telescope does not move. This is achieved using the configuration where the stimulus telescope is mounted on the same (floated) optical table as the instrument. Also, the target used for the focus block tests must show structure when significantly out of focus.

It is also desirable to do this test with the ISS on since this will take out any jitter and allow the distortions to be measured more accurately.

These calibrations are repeated on orbit since the jitter sources are different.

4.5 Filter Transmission

The calibration of the filter system is quite complex and a separate document (HMI-S029) describes the details, here only a brief summary is provided. Separate documents describe the measurements done on items before integrating them in the instrument.

4.5.1 Wavelength Dependence

To get the overall wavelength dependence a tunable laser is set to a number of wavelengths across the transmission range of the blocker and the light fed into the stimulus telescope. The tuning motors are then co-tuned across their full range. This is done in both obsmode and calmode.

Considerations include ensuring that the angular distribution of the beam hitting the CCD is well understood and in most cases match that of the Sun. In obsmode this means ensuring a uniform illumination of the aperture at all field positions. In calmode the field should be illuminated like the Sun, in particular a field stop must be used. It is also essential to monitor the intensity and wavelength of the laser and ensure that the polarization and spatial dependence do not change as a function of wavelength.

Sunlight also help to set the absolute wavelength scale and avoids problems with speckling inherent to the laser tests.

Using the stimulus telescope with a lamp source helps looking for fringes.

4.5.2 Spatial Dependence

This involves determining the phase and contrast of the elements as a function of spatial position on the CCD. To do this a similar setup to that used for the overall wavelength dependence above is used. However, to do this test the tuning motors are run through a so-called detune sequence in which each motor is moved over its entire range independently of the others. Again this is done in both obsmode and calmode.

4.5.3 Angular Dependence

This involves determining the dependence of the filter transmission as a function of the angle of incidence onto the CCD. Again this is done by taking detunes at one or a few wavelengths.

To do this on obsmode the PCU aperture stop is used for both laser and sunlight. In calmode the laser spot is moved in the stimulus telescope field or a field stop is used.

4.5.4 Artifacts from moving elements

This mainly involves taking data at different focus positions, but the polarization selectors also need to be tested. All light sources will be used.

4.5.5 Temperature Dependence

Front window. Since the front window will experience significant temperature changes both due to eclipses and other orbital effects and due to degradation with time, it is particularly important to determine the temperature dependence of the transmission with fringes being of particular concern.

To do this detunes are taken at different front window temperatures. Calmode images will directly image the front window and are thus most important, but obsmode images are also useful to determine how the variations average out.

Particular considerations include ensuring that the laser wavelength is the same during these tests.

Using Sun and lamp light is particular useful for tracking fringes.

Oven components. While the components in the oven are temperature compensated some amount of residual variations will be present.

One test involves setting the oven to a number of setpoints and measuring the transmission as described earlier. For absolute variations sunlight is the best source due to the inherent stability (after orbital corrections). For spatial dependences the laser works well. For blocker fringes lamplight is likely to work best.

While the elements are temperature compensated this assumes that the temperature is spatially constant. An area of concern is thus that temperature transients in the oven will introduce spatial gradients. Thus it is desirable to take data while the oven is stabilizing to a new setpoint. This will also help establishing the temperature constant of the various components.

A problem seen with MDI is that small transients are observed when the normal sequence is restarted after a significant pause. Attempts to measure this will be made using sunlight.

This includes the front window, the blocker, the Lyot and the Michelsons.

4.5.6 Shutter and Hollow Core Motor Repeatability

These activities are essentially I&T activities, but are briefly described here.

Shutters. This actually covers both the accuracy of the knowledge of the shutter opening time and that of the gain stability of the CCDs and cameras.

The best way to measure this in the integrated instrument is to observe a stable light source, such as the Sun, and see if there is any excess noise in the intensity. To reduce the effect of the source variations it is beneficial to open the two shutters simultaneously and compare the results. Similarly looking for variations between quadrants can further reduce the effects of light source variations. These latter methods, however, do assume that the noise sources are uncorrelated between different shutters, cameras and readout chains, which may not be the case.

Particular concerns include making sure that the cameras are cold to avoid contributions from any variations in the CCD integration time. It is, of course, important to avoid moving any other mechanisms.

HCMs. Another challenging problem is that of the repeatability of the hollow core motors. This has been measured standalone, but it is also desirable to be able to measure it in the integrated instrument. To do this a measurement similar to that for the shutter variations are done, but this time stepping back and forth in wavelength. Any noise beyond that seen in the shutter test indicates HCM related noise.

4.5.7 Overall throughput

This can be measured by measuring the solar image intensity at the CCD as a function of zenith angle and extrapolate to zero air mass. To do this the intensity outside and inside after the heliostat mirrors are measured and detunes (or cotunes) are taken several times during a day.

Considerations include using clear days and taking data several times during a clear day from early morning to late afternoon to check for long term transparency variations.

4.6 Polarization

The polarization calibrations are among the most complicated for the instrument and more detailed descriptions are contained in a separate document (HMI-S030).

The optics responsible for the polarization properties include the front window, primary lens, secondary lens, the three polarization selector waveplates, the focus blocks, the ISS mirror, the ISS beamsplitter and the polarizer following that.

4.6.1 Overall polarization

Details of the overall polarization calibration are provided in HMI-S030. This subsection summarizes the procedures.

Overall goal. The primary goal of the polarization calibration is to enable us to determine the polarization state of the incoming light as a function of spatial position in the image to the accuracy given in the IPD Section 2.1.5. This is done by determining the polarization state detected as a function of spatial position in the image and the settings of the polarization selector waveplates and using this information to calibrate the data.

A second goal is to find a setting of the polarization selector waveplates which allows circular polarization to be detected with less than 5% leakage from linear polarization using only two measurements (see IPD Section 2.1.6).

PCU. As described in section 3.1 the PCU contains a polarizer followed by a waveplate with a nominal retardance of 0.25λ. Both of these elements can be inserted or removed from the beam and rotated by arbitrary angles to provide a large selection of input polarizations to the instrument.

The angular position at which the PCU polarizer transmits horizontal polarization has been determined by HAO and defines the coordinate system for the system.

The other properties of the PCU optics (such as transmissions and retardance and angular orientation of the waveplate) are determined as part of the calibration described below.

Test sequences. In order to determine the properties of the instrument, PCU and light source a number of sequences have been developed. These sequences consist of images taken with various configurations of the PCU and various settings of the polarization selectors.

Analysis. To determine the parameters a non linear least squares fit is performed at each position in a binned version of the images obtained with the sequences described above. The parameters determined include the intensity and polarization of the light source, the properties of the PCU polarizer and waveplate, the properties of the telescope (front window, primary and secondary lenses) and the retardances and mounting angles of the polarization selectors.

Extensive testing of various sequences and analysis algorithms was done prior to running these algorithms and improvements made based on the results and the results obtained during the Sun test.

Removal of degeneracies. A difficulty of the polarization calibration is that a number of parameters are nearly degenerate. In particular it may be shown that the mounting angles of the waveplate are degenerate if the retardances are at their nominal values.

To resolve this degeneracy a set of data were taken with none and only some of the polarization selector waveplates present.

While not important for the calibration of the instrument this test also determines the angle of polarization picked up by the ISS mirror and beamsplitter combination.

4.6.2 Focus block birefringence

Mounting stresses in the focus blocks can introduce birefringence which would cause the polarization data to be focus dependent.

To determine if any such birefringence is present a set of input polarizations are generated by the PCU and a standard polarization sequence taken at each focus position. These data are then analyzed to determine if there are significant differences.

4.6.3 Thermal effects

Just as mounting stresses can introduce birefringence, temperature induced stresses can introduce birefringence. This is a particular concern for the front window which experiences large temperature variations.

To look for such variations a test similar to that done with each focus block in the beam is done at different front window temperatures.

4.6.4 HCM repeatability

The repeatability of the polarization selector motors can be measured in a manner similar to that used for the wavelength selectors in Section 4.5.6 by using a strongly polarized input signal and having the polarization selectors alternate between positions.

4.6.5 On orbit calibration

It turns out to be extremely difficult to determine a number of the necessary parameters (those describing the leakage of I into (Q,U,V)) from ground based measurements, but quite easy to determine them from on orbit measurements. The determination of these parameters are thus deferred until the commissioning.

4.7 Observables

As an end-to-end test a set of real observing sequences are run observing the Sun.

While the observing conditions (seeing in particular) are such that we will not get high quality data, running the observing sequences still serve several purposes.

- Verify calibrations end-to-end
- Provide test data for front end processing
- Provide test data for analysis software development

Since the current baseline sequence interleaves the two cameras with Doppler and line-of-sight magnetic on one and vector magnetic on the other this is the prime sequence to test. However, sequences where images are combined should also be run as should sequences with different cadences and different vector field cadences.

Data should be taken in air and in vacuum and with the ISS on. For the vacuum test it is important to have calibrated the polarization performance. It is also highly desirable to have data from other instruments, such as MDI, GONG, ASP, SOLIS and Hinode.

Doppler Sufficient data should be obtained to make a ring diagram with clearly visible rings with at least one and preferably all standard framelists.

Line-of-Sight Magnetic Enough data should be taken to make few magnetograms. Preferably this should be run on a couple of different days and with a sunspot if at all possible. Having a sunspot will also allow magnetic effects on the Doppler data to be investigated.

Vector Magnetic Enough data should be taken in each of the three main modes (3 cycle cadence, 2 cycle cadence and combined cameras) to allow for a few 10 minute averages to be made. Preferably this should be run on a couple of different days and with a sunspot if at all possible.

Miscellaneous This includes observables such as intensity and linedepth and can be derived from the Doppler data.

4.8 Thermal Effects

These are discussed under the individual subsections.

4.9 Image Stabilization System

The details of the calibration of the ISS are described in separate documents.

The most important quantity to measure is the amount of jitter attenuation as a function of frequency. This can be measured by introducing jitter in the stimulus telescope. Other aspects include measuring the linearity range of the limb sensors and the total range.

4.10 Alignment Mechanism

Step size. This is measured by crosscorrelating images taken at different leg positions. This can be done with the data taken for distortion.

Range. Here the legs are moved to the end of their range and the offset measured.

Pointing equation. Here the offsets at different leg positions are fitted to a low order polynomial.

Repeatability. To do this the legs are moved back and forth by varying amounts and the images cross-correlated to determine shifts.