The Helioseismic and Magnetic Imager Instrument Design and Calibration

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Abstract XXX Fix author list. Emails. Add Edward, Kirkpatrick, Torgerson, Rairden? The Helioseismic and Magnetic Imager (HMI) investigation (Scherrer and Schou, 2010) will study the solar interior using helioseismic techniques as well as the magnetic fields near the surface. The HMI instrument is part of the Solar Dynamics Observatory (SDO), which was launched on Feb. 11, 2010. The instrument is designed to measure the Doppler shift, intensity and vector magnetic field at the solar photosphere using the 617.3nm FeI absorption line. The instrument consists of a front window filter, a telescope, a set of waveplates for polarimetry, an image stabilization system, a Fabry-Perot filter, a five stage Lyot filter with one tunable element, two wide-field tunable Michelson interferometers, a pair of 4096\textsuperscript{2} pixel cameras with independent shutters, and associated electronics. Each camera will take an image roughly every 4s giving an overall cadence of 45s to 50s for the Doppler, intensity and line-of-sight magnetic field measurements and a somewhat slower cadence for the full vector magnetic field. The present paper describes the design of the HMI instrument and provides an overview of the calibration efforts. Overviews of the investigation, details of the calibrations, data handling and the science analysis are provided elsewhere.

Keywords: Solar Dynamics Observatory; Helioseismology, Observations; Instrumentation and Data Management; Magnetic fields, Photosphere

1. Introduction

XXX Instrument description, calibration, overview, setup, conclusion

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The Helioseismic and Magnetic Imager (HMI) instrument is built as part of the HMI investigation (Scherrer and Schou, 2010) and is designed to measure the Doppler shift, intensity and vector magnetic field at the solar photosphere using the 617.3nm FeI absorption line (Norton et al., 2006).

XXX Filtergraph. Filtergrams converted to observables on ground.

To a significant extent the instrument designed is based on the design of the highly successful MDI instrument (Scherrer et al., 1995) with a few significant improvements. Among these improvements are two cameras instead of one, better spatial resolution and coverage, the capability to observe the full Stokes vector, that the data are downlinked without significant processing and a significant level of redundancy.

XXX Add section #s. Below we start with a description of the various components of the instrument (Section 2). This is followed by an overview of the calibration in Section 3 and a conclusion in Section 4. Rather than describing all the instrument details and calibrations in one paper, a number of other papers describe the main components of the calibration efforts. Wachter et al. (2010) describes the image quality and CCD performance. Couvidat et al. (2010) the filter performance and Schou et al. (2010) the polarization properties. In all cases we have restricted ourselves to ground based results.

2. Instrument Description

A cartoon of the optical path of HMI is shown in Figure 1. Sunlight travels through the instrument from the front window at the upper right to the cameras at the lower right of the cartoon. A raytrace is shown in Figure 2. A prescription of the optical components can be found in Appendix A.

The front window is a 50Å bandpass filter that reflects most of the incident sunlight. It is followed by a 14 cm diameter refracting telescope consisting of a primary and secondary lens.

Two focus/calibration mechanisms, three polarization selection mechanisms and the image stabilization system tip-tilt mirror are located between the telescope and the polarizing beamsplitter feeding the tunable filter. The filter is mounted in a precisely temperature-controlled oven, containing the following elements:

- A telecentric lens
- A blocking filter
- A Lyot filter with a single tunable element
- A beam control lens
- Two tunable Michelson interferometers
- Reimaging optics.

Following the oven is a beam splitter, which feeds two identical shutters mounted at a pupil image and the CCD camera assemblies.

There are two mechanisms external to the optics package: a front door, which protects the front window during launch, and an alignment mechanism used to adjust the optics package pointing.

In the following subsections the different subsystems are described in more detail.
Figure 1. Cartoon of the HMI optical layout with various elements annotated. XXX Also annotate primary, secondary, limb sensor, LED?
2.1. Imaging Optics

The main telescope is a two element refracting telescope with a 140mm clear aperture. The primary is a convex asphere/convex lens while the secondary (Barlow) lens is bi-concave. The primary and secondary lenses are connected with a low coefficient of thermal expansion metering tube to maintain focus.

These are some of the key numbers for the optical system: XXX Probably make table.

2.1.1. Primary:

- Effective focal length: 585mm
- Focal ratio: f/4.18
- Image size: 5.45mm
- Path length: 615mm

2.1.2. Telescope:

- Effective focal length: 2468mm
- Focal ratio: f/17.65
- Image size: 23.0mm
- Angular magnification: 5.43XXX ?.XXX
- Path length: 909mm

2.1.3. Final:

- Effective focal length: 4953mm
- Focal ratio: f/35.4
- Image size: 46.1mm
- Angular magnification: 8.24
- Path length: 2218mm

Path lengths are from the front of the filter. Image diameters are for a mean solar radius of 960". Several of the numbers are, of course, trivial to derive from others. All lens surfaces other than the front of the primary are spherical.

Focal ratios (in vacuum) through the Lyot is f/18.3 and through the Michelsons f/21.7. The primary to secondary magnification is thus 2.01 of which a factor of 1.63 is done by the reimaging lenses.

The telephoto ratios of the telescope and the entire system are 2.72 and 2.23, respectively, measuring from the front face of the front filter.

The HMI calibration and focus adjustment system consists of two calibration/focus wheels (see Section 2.5.2) each of which contain 4 optical flats of varying thickness (including zero) in four positions to provide focus adjustment. By making the (identical) steps in optical thickness in the one wheel 4 times larger than the steps in the other wheel, it is possible to select one of 16 uniformly spaced focus steps of roughly 1mm at the focal plane, corresponding to 2/3 of a depth of focus. XXX I think. Besides allowing best focus to be set on orbit, this capability also provides a highly repeatable
Figure 2. Raytrace of HMI, excluding the path to the limb sensor. The CCD detectors are above the plane of the plot. Different colors indicate different places on the solar image. **XXX Where?** See Figure 1 for identification of the elements.

Figure 3. Raytrace with imaging mode rays shown in blue and calmode rays shown in red. Only the part of the optical system from the secondary lens to the telecentric lens is shown. **XXX Watch colors. XXX Copy to polarization paper?**

means for measuring the instrument focus and assessing image quality through phase diversity analysis.

In calibration mode, a lens in the fifth position of each wheel images the entrance pupil onto the focal plane to provide uniformly integrated sunlight. This is illustrated in Figure 3. Calibration mode images are used to provide Doppler calibrations, monitor the instrument transmission and assess variations in the detector flatfield. The calibration mode image has a diameter of 50.1mm, which is large enough to cover the largest solar image seen.

The light is folded by the ISS mirror and then split by a polarizing beamsplitter to send the s-component light to the filters while passing the orthogonal light onto the limb sensor. The limb sensor receive the full bandwidth through the front window, while light for the rest of the instrument continues through a blocking filter located just inside the oven.
A telecentric lens at the entrance of the filter oven produces a collimated beam for the Lyot filter. This ensures that the angular distribution of light passing through the Lyot filter is identical for each image point, minimizing the variation of the central wavelength across the image as well as the contrast loss.

At the exit of the Lyot filter a beam control lens minimizes the clear aperture requirements for the Michelsons by making the extreme rays parallel. This means that the beam is not telecentric through the Michelson interferometers, however, this only causes an insignificant degradation of their contrasts.

At the exit of the oven, a pair of lenses reimages the primary focus onto the detectors. A beamsplitter evenly divides the light between the two camera paths with folding mirrors used to provide convenient placement of the cameras. In order to avoid that non uniform movement of the shutter blades result in exposure gradients across the images the shutters are placed at a pupil image.

XXX Consequences?
The unused port of the beamsplitter has a light trap. For the purpose of having a light source to test the cameras when there is no external light source, an LED was added to this port.

XXX Discuss assorted 1/4 waveplates to minimize reflections?

2.2. Polarization Selectors

The polarization selectors rotate optical retarders to convert the desired incoming polarization into the fixed linear polarization picked up by the polarizing beamsplitter. Each retarder is mounted in a Hollow Core Motor (HCM) which allows them to be rotated to any of 240 uniformly spaced angles (see Section 2.5.1). The nominal retardances of the waveplates are 10.5, 10.25 and 10.5 waves, in the order encountered. This design has a 3 for 2 redundancy, meaning that any one of the three waveplates can be left in any position, while preserving the ability to measure all polarization states. High order waveplates were chosen for mechanical convenience, but this does have implications for the polarization performance, as discussed in Schou et al. (2010).

2.3. Filters

XXX Refer to Couvidat paper.

The HMI filter system consists of the front window, a blocker filter, a Lyot filter with a single tunable element, and two tunable Michelson interferometers. Both the Lyot filter and the Michelson have temperature compensating designs, and all the filters, except the front window, are mounted in an oven stable to ±0.1C. XXX What is spec and what is performance? Much better? The filter system enables narrow-band filtergrams to be made across the Fe I 6173Å line by co-tuning one Lyot tunable element and both Michelson interferometers. The combined filter bandpass is 76mÅ FWHM (nominally at center tuning) with a tunable range of 690mÅ. Details of the filters are given in Couvidat et al. (2010) and summarized below in the order encountered by the light.

2.3.1. Front Window

The front window, the main purpose of which is to limit the heat input to the instrument, is a 50Å bandpass filter. In the order in which the light travels it consists of 6mm of
BK7G18 clear glass, 3mm of GG495 green glass, a bandpass coating, an infrared rejection coating, and another 6mm of BK7G18 glass. The radiation hard BK7G18 glass, among other things, serves as a radiation shield to the non radiation hard GG495 glass. The GG495 glass serves important purposes. One is to block the blue and ultraviolet light from reaching the bandpass filter, which is sensitive to those wavelengths. Another is to cause the window to absorb a small amount of light, thereby limiting the center to edge temperature gradient.

Due to manufacturing problems there was a significant wavefront error internal to this design and as a result a compensating error was polished into the surface of the front window. This is further discussed in Wachter et al. (2010).

XXX Mention expected darkening and temperature increase.

2.3.2. Blocking Filter

The blocking filter is a three-period all-dielectric interference filter with a FWHM bandpass of 8Å. The main purposes of the blocker are to reject the unwanted orders of the following filters and to limit the heat input into the oven.

2.3.3. Lyot Filter

The wide-field, temperature-compensated Lyot filter uses the same basic design as the MDI (Scherrer et al., 1995) filter with the addition of a fifth tuned element and without doubled elements. By pairing KDP or ADP elements with the calcite elements, the temperature sensitivity in the calcite is compensated by an opposite change in the KDP/ADP. The five-element Lyot filter has a 1:2:4:8:16 (not in actual order) design. The filter final (narrowest) element of the Lyot filter is tuned by a rotating half wave plate mounted in a HCM identical to those used for the polarization selectors. It is worth noting that the Lyot tuner is not redundant. XXX And? This is unlike the MDI filter where some of the elements were doubled in order to reduce unwanted sidelobes in the untuned part. The FWHM width of the untuned part is 612mÅ, nominally. The Lyot components are held in optical contact by optical grease to avoid stressing the elements with changing temperature, and are keyed to hold the elements in proper relative alignment.

Due to a drawing error the exit of the Lyot holder has a clear aperture only marginally larger than the solar image. This results in some vignetting if the image is not accurately centered on the center of the obstruction.

XXX Mention earlier misassembled Lyot?

2.3.4. Michelson Interferometers

The final filters are two wide-field, tunable solid Michelson interferometers with a clear apertures of 32 mm and nominal free spectral ranges of 172mÅ and 345mÅ (86mÅ and 172mÅ FWHM bandpasses respectively). The design incorporates a polarizing beamsplitter with a vacuum leg and a solid glass leg. The vacuum leg is maintained with temperature compensating standoffs made of calcium fluoride.

Tuning of the two Michelsons is accomplished by rotating a combination of a half wave plate, a polarizer and a half wave plate, each of which are mounted in a HCM
identical to those used for the polarization selectors. Unlike the Lyot tuner, this design has a full 3 for 2 redundancy meaning that any one of the three mechanisms can fail in any position without impacting the ability to tune either Michelson.

Figure 4 shows the ideal transmission profiles of the resulting filter. Details of the actual performance are given in Couvidat et al. (2010)

**XXX Mention drifts?**

In summary the nominal filter FWHMs are, in the order in which the light travels:

- Front window: 50 Å
- Blocking filter: 8 Å
- Lyot element #2: 690mÅ
- Lyot element #3: 1379mÅ
- Lyot element #4: 2758mÅ
- Lyot element #5: 5516mÅ
- Lyot element #1: 344mÅ(tuned)
- Wide Michelson: 172mÅ(tuned)
- Narrow Michelson: 86mÅ(tuned)
- Width of untuned part: 612mÅ
- Final width: 76mÅ

### 2.4. Image Stabilization System

**XXX This section needs reorganization.**

The HMI Image Stabilization System (ISS) is a closed loop system with a tip-tilt mirror to remove jitter measured at a primary image within HMI.

The ISS uses the light rejected by the polarization selection beamsplitter to image the Sun onto four orthogonal detectors at the guiding image focal plane. Each detector consists of a redundant photodiode pair. The electronic limb sensor photodiode preamplifier has two gains, test mode and Sun mode, and selectable prime or redundant photodiodes.

The mirror uses low voltage piezoelectric transducer (PZT) actuators to remove errors in the observed limb position, derived as the difference between the intensity reaching opposite photodiodes. The mirror design has a first resonance of \( \approx 800 \, \text{Hz} \), which is much higher than the structural mode of the HMI optics package, and which enables a simple analog control system.

The range of the tilt mirror is approximately \( \pm 15 \) by \( \pm 18 \) arc-second.

The servo gains and other parameters are adjustable by ground commands. In particular, offsets can be added to the X and Y axis error signals to change the nominal pointing while maintaining lock. Individual PZT actuator offsets can be specified to fix the nominal position of the mirror anywhere in its range during open loop operation or during calibrations.

**XXX Show performance later.**

The error and mirror signals are continually sampled, and down-linked to monitor jitter and drift. For calibration purposes, these signals can be sampled at a rate of up to 512Hz.

### 2.5. Mechanisms etc.

**XXX Show some pictures?** The instrument contains a number of different types of mechanisms, each of which are described below. In most cases the details of their operation are of little consequence to the scientific operation of the instrument, in other cases
they have important implications. The mechanisms are controlled by FPGAs (Field Programmable Gate Arrays) commanded by the flight software.

2.5.1. Hollow Core Motors

The HCMs are used to rotate the polarization selectors and wavelength tuning optics. Each motor has an encoder with 240 positions. To move from one position to another the motor is first commanded to move in the desired direction. Once the encoder indicates that a particular position has been reached, the FPGA waits a programmable time after which the motor windings are shorted out, causing the motor to brake and stopping some distance away. By selecting an appropriate encoder position and delay time, the motors can be made to stop at any desired position (there is very little detent in the motors). However, in order to be able to control the stopping positions more accurately, only positions at the places where the encoder changes are used. This is further discussed in Section 2.9.5.

The spin time of a HCM is around 1s. By always going in the shortest direction it is thus possible to change between arbitrary positions in less than about 500ms.

2.5.2. Filter wheels

The filter wheels are very similar to the HCMs, except that the optics are placed around the rotation axis in a wheel, rather than on axis. While the can, in principle, be positioned at any one of 180 positions, only the 5 positions for which the optics are centered are used. The filter wheels also take about 1s to rotate and since the longest distance necessary to move is 0.4 revolutions, the maximum move time is 400ms.

2.5.3. Shutters

The shutters are very similar to those on MDI and SXI, and provide relative exposure measurement with a resolution of 1µs. The combination of knowing the actual exposure times combined with downlinking all the images means that it is possible to correct for any exposure variations and thus that variations more than an order of magnitude larger than those seen on MDI after 60 million operations on orbit will cause no detrimental effects. XXX Combine with earlier comments on shutter?

In normal operation the shutters can be commanded to expose the CCDs from about 35ms to just over 16s.

2.5.4. Alignment mechanism

The HMI alignment mechanism has two legs each of which can adjust the optics package pointing in steps of 0.32 arcsec at a rate of 8 steps per second. XXX Verify. The directions of image motion caused by the two legs are roughly orthogonal and correspond to diagonal motions in the CCD image. The legs do not have a built-in encoder and rather rely on a hardware center indicator and a software counter. There are also end of range indicators, which if tripped will cause the FPGA to stop moving the leg. Since going to the physical end of motion is risky and the indicator can’t be relied on, the flight software limits the motion to ±1500 steps or about ±480 arcsec.

It is expected that the alignment legs will have to be used every couple of weeks to keep the solar image centered in the ISS dynamic range.
2.5.5. *Front door*

The front door has two independent mechanisms, each of which can open the door regardless of the position of the other mechanism, thus providing redundancy. To close the door both mechanisms must be in the closed position, but since it is only planned to operate (open) the door once on orbit, there is no need for this to be redundant. Each of the door mechanisms have switches detecting that they are fully closed or fully open.

2.5.6. *Heaters*

XXX These are not really mechanisms, but they kind of fit into this section.

There are three different types of heaters used on the instrument, all of which are redundant.

Survival heaters used to keep the instrument warm enough not to damage it when the instrument is not powered or in case of instrument failures. These heaters are powered directly by the spacecraft (bypassing the instrument electronics) and are controlled by built-in thermostats.

Operational heaters are used to maintain the instrument at the desired operating temperature. There are seven such heaters on the instrument. Their operation is further discussed in Section 2.9.4.

XXX Show positions? What about thermistor positions?

Decontamination heaters are used to warm up the CCDs to prevent them from accumulating condensable materials outgassing from the rest of the instrument after launch. These are mounted on the back of the CCDs and are thermostatically controlled. They can be individually enabled and disabled by the instrument. If needed, they can also be used to drive off any condensed material later in the mission or to anneal the CCDs.

2.5.7. *Filter oven*

Finally the most temperature sensitive elements of the filters are placed in a filter oven. This oven uses an analog proportional heater control system to maintain a temperature stable to XXXC. The oven includes a multi stage thermal isolation system to ensure that the time scale of any residual filter temperature variations is extremely long. The oven control electronics and heaters are redundant.

2.6. **CCDs**

2.7. **Cameras**

The HMI instrument contains two identical CCD detectors, with a 4096\(^2\) pixel format, made by E2V. The CCDs are front-illuminated with 12\(\mu\)m pixels and will have a full well capacity of >125000 electrons.

To achieve the readout in less than 3 seconds, they have a readout rate of 2 Mpx/s through each of four quadrant readout ports.

2.8. **Data Processing Electronics**

The data from the CCDs are downlinked without any processing other than a hardware compression and encoding. The different components of the electronics are described below.
2.8.1. **CIF**

XXX One per camera. Two buffers.

2.8.2. **DCHRI**

XXX Compression, cropping, lookup, redundancy. XXX Redundant. Both CIFS to both DCHRI. Almost full rate through one.

2.9. **Flight software**

XXX **Sequencer, commanding, thermal, HK telemetry, HCM algorithm.**

The flight software (FSW) consists of several different modules. Some of these, like those related to loading other modules, while important, have little direct interaction with the scientifically important aspects of the instrument, while others, like the sequencer are important for understanding the instrument capabilities.

Below several of the scientifically important parts of the FSW are described.

2.9.1. **Overall control**

The core of the FSW is a kernel running under a real time operating system. It is read from ROM at startup and is responsible for loading other modules and allocating CPU time for their execution.

Ordinarily the instrument is booted and loads the various modules from EEPROM into RAM. While not planned for routine use, it is possible to reload these parts of the software to the EEPROM. It is also possible to load new FSW directly to the RAM for testing or in case the EEPROM becomes non-functional.

In addition the the flight software itself it is possible to load tables to memory for use by other modules, as described below.

2.9.2. **Commanding Interface**

XXX **Basic capability, individual commands, scripts, etc.**

The FSW has the capability to receive and execute a large number of commands to load software and tables, control various subsystems like mechanisms and heaters, configure various onboard control systems, initiate downloading of diagnostics data and so forth.

It is also possible to execute simple onboard scripts. Typical examples of such scripts include ones to the change settings when entering or exiting eclipses.

2.9.3. **Housekeeping**

The instrument provides a large variety of data in the housekeeping data stream. This includes such items as temperatures, voltages, currents, limb sensor voltages, states of subsystems, mechanism positions, command counts and so forth. These are generally downlinked every 4 or 8s.

In addition the housekeeping values relevant to each image are downlinked as a so-called image status packet with the image data as well as in the regular housekeeping data stream.
It is also possible to sample a selection of data points at rates from 128Hz to 512Hz. This is typically used for sampling the image stabilization system telemetry, but may also be used for such items as motor currents.

Finally the instrument has a number of sensor connected directly to the spacecraft for health and safety monitoring when the instrument is not operating.

2.9.4. Thermal control

Each of the instrument operational heaters are controlled by the FSW. In addition to being left permanently on or off the FSW can run them at various duty cycles using a pulse width modulation scheme in which they are on for \( N \) time increments out of \( M \), \( M \leq 100 \) and the time increments are fixed at 1/8s.

The FSW also provides a crude temperature control of the instrument, based on three temperature settings: deadband low, target and deadband high and two duty cycles, deadband and cold (different \( N \), but same \( M \)). At any given time the heater is in one of three states. Rising in which the cold duty cycle is applied. This changes to maintaining when the target temperature is reached. In the maintaining state the deadband duty cycle is applied. If the temperature drops below the deadband low the state changes to rising. If the temperature rises above the deadband high the state is changed to dropping. In the dropping state the duty cycle is 0 and the state changes to maintaining if the temperature drops to the target.

The consequence of this control algorithm is that one has to either accept that the temperature drifts with the environment or that the temperatures are cycling in a more or less periodic manner.

2.9.5. Mechanism control

All the various mechanisms are also controlled by the FSW.

The front door and alignment mechanisms are simple stepper motors and as such require little control. For the alignment mechanism the FSW can seek for the zero crossing and, since there is no encoder, keeps a count of steps taken. As mentioned earlier it also limits the allowed positions to \( \pm 1500 \).

The focus mechanisms and shutters also require little control.

The HCMs are substantially more complicated. While they can also be operated by simple commanding, two other features are implemented in the FSW. First, in order to minimize the time to perform a move, the FSW can decide which direction is the shortest and use that.

Second, since the stopping positions are inherently sensitive to such parameters as voltages and temperatures, which are in turn variable, an adjustment algorithm has been implemented. As discussed in Section 2.5.1 the HCMs use an adjustable delay to fine tune the stopping position and has an encoder which can tell whether the motion over or under shot the position. The adjustment algorithm uses this information to change the delay times up and down slightly to always end up near the desired position, regardless of temperature or voltage variations. Since the optimal delay depends on move distance and to a lesser extent on the starting position, a separate delay is kept for each (motor, start position, stop position).
2.9.6. Sequencer

XXX Describe top level capabilities of the sequencer. XXX Example in appendix? XXX Need to discuss filtergrams somewhere. This is a filtergraph.

The part of the FSW most directly affecting the operation of the instrument from a scientific point of view is probably the sequencer. The sequencer is responsible for taking the images at the correct times and with the correct settings, as well as for executing calibrations at scheduled times.

The sequencer has two main levels of control. The top level determines when to execute which set of observations (framelist) to execute at any given time, while the lower level schedules the individual frames.

At the top level the sequencer uses a prioritized list to determine which framelist to execute next. By carefully selecting these priorities and the desired execution times for the different framelists it is possible to interrupt the regular observables framelist to run a calibration sequence or to run different sequences depending on the time of day, for example.

The main control of which images are take is done by using so-called framelists. These contain, among other things, a list of relative times to take the images, the wavelength, polarization, focus, expose time, camera, and compression settings of the images. At any given time only one framelist is executing. An example of a framelist and more information about what they contain are given in Appendix B.

Once the framelist has started the times for each of the images to be taken can be calculated from the start time and the relative times specified in the framelist. From these times the times of execution of the different events needed to take an image can in turn be calculated. This is a list of the main 4 events events scheduled during the taking of an image. The relative times of these are set by ground commandable registers.

- Mech Move: This is the time at which the polarization selectors, wavelength selectors and focus wheels start moving.
- Clear: This is the time at which the camera starts clearing the CCD and thereby initiates the image taking. See Section 2.7 for details.
- Shutter Open: This is the time at which the shutter opens.
- Readout: This is the time at which the readout of the image from the cameras to the CIF is initiated.

The events for the two cameras are independent, however a warning is issued if incompatible events overlap. Eg. if a HCM or filter wheel is moving between the start of the shutter move and the start of the readout.

3. Calibration

Since HMI operates in the optical it is possibly to do a wide variety of end-to-end calibrations. Below we start by describing the basic setups used for the calibration followed by a summary of the results obtained. As mentioned earlier details of the calibrations are described in separate papers, in particular Wachter et al. (2010) for image quality and CCD performance, Couvidat et al. (2010) for filter performance and Schou et al. (2010) for polarization properties.
3.1. Calibration Setups

Two basic setups have been used for the majority of the calibrations.

The most used setup involves using the so-called Stimulus Telescope. This is a reverse of the telescope part of HMI, using primary and secondary lenses manufactured to the same specifications as the flight optics. A side-effect of this is that there is significant field curvature in the stimulus telescope.

The Stimulus Telescope can be fed with either white light from a stabilized lamp or laser light. The lamp light is fed into a fiber bundle (thereby scrambling the light) which is then imaged onto the pupil using a condensor lens. This ensures a uniform illumination of both the image and pupil. At the focus of the stimulus telescope it is possible to mount a number of different targets, most of which are made with a metal film deposited on a glass slide. The stimulus telescope can be auto-collimated using a large optical flat.

In case of laser light the same basic setup is used except that the laser, which is fed through an optical fiber from another room, is typically illuminating a rotating diffuser.

The other main setup used is a heliostat which is able to track the Sun and bring sunlight from the top of the building through a tube to a fold mirror in front of the instrument.

The Stimulus Telescope, as used for image quality measurements, is described in more detail in Wachter et al. (2010). Uses for filter characterization are described in Couvidat et al. (2010) as is the use of the heliostat. The uses for polarization purposes is generally similar to that for image quality, with the addition of a so-called Polarization Calibration Unit, (described in Schou et al. (2010)) added between the stimulus telescope and HMI.

In addition to the two different setups, two different environments were used. In one case the instrument is in a vacuum tank with an optical quality window. This allows for the CCDs to be cold and thus low noise, but introduces the unknown properties of the window. In the other case the instrument is in air. This results in a significant and often variable amount of dark current. Another side effect is that the presence of air in the instrument changes the focus dramatically. To compensate for this a so-called air-to-vac corrector (consisting of a plano-concave and plano-convex lens pair with identical radius of curvature and spaced by an adjustable amount) can be placed between the stimulus telescope and the instrument. Alternatively, the targets in the stimulus telescope can be moved away from the position determined by the auto-collimation.

Another variable introduced is that the instrument was rolled 90° between the setup at LMSAL and that used at GSFC and ASO.

Finally it should be noticed that some of the calibrations have been deterred to on-orbit due to practical reasons.

3.2. Image Quality

Details of the image quality calibration setup, procedures and results are given in Wachter et al. (2010). Some of the main results are given below.

The Strehl ratio is expected to be $0.80 \pm 0.02$ or better, the uncertainty being due to difficulties with compensating for the test setup.
After polishing out the wavefront error in the front window, thereby substantially improving the MTF (see Wachter et al. (2010) for details), no measurable changes of the MTF have been observed during the CPTs and other optical performance tests.

The optical distortion has been modeled by a low-order polynomial and is as large as two pixels at the edge of the field of view. Residuals are of the order of a few hundreds of a pixel, and are dominated by irregularities in the CCD lattice.

Residual image motions of up to half a pixel are caused by the HCMs. These motions have been consistently observed, and can be corrected for in the observables calculations.

There are some variations in the best focus across the field of view, which can be expressed in a field curvature (0.4 mm focal plane variation from center to edge), and a field tilt (up to 0.5 mm focal plane variation from edge to edge). Given that the focus steps are 1 mm, corresponding to less than a depth of focus, this additional variation does not degrade the imaging quality significantly.

The best focus position has been positioned in the middle of the available focus range (Focus position 9 in a range from 1 through 16), with a tendency towards a higher focus position, because the heaters at the edge of the front window are only able to bring the best focus to a lower position.

The two HMI cameras are aligned (with a residual shift of less than 10 pixels), and the shift and the rotation (0.08 degrees) have been monitored. During the calibration period, the cameras have shifted slightly (by a couple of pixels) relative to each other, possibly due to changing mechanical stresses in the instrument. This, however, is not a concern, because the shifts are small and can be constantly monitored by tracking the solar limb or correlating the images.

The flat field shows the expected structure originating in the design of the CCD, contamination in the optics, and large scale optical variations. The internal vignetting (see Section 2.3.3) results in a sharp drop off in the flat field at the outer edge of the field of view. The large scale flat field could be determined with an accuracy of 0.2%. Drifts observed in the small scale flat field are believed to be caused by outgassing material condensing on the CCDs when cold. Due to the lengthy outgassing period in space, during which the CCD is kept warmer than the rest of the instrument and the ability to drive any condensed material off by warming the CCD, this is expected to be negligible in space. A small-scale flat field monitoring mechanism is installed to keep the flat field up to date at the aforementioned level of accuracy (see Wachter and Schou (2009)).

3.3. Wavelength Dependence

The instrument also underwent a significant calibration effort in the area of filter performance. This is described in detail in Couvidat et al. (2010) and summarized below.

Each observable sequence that will be taken by HMI to measure the Doppler velocity and full magnetic-field vector at the solar surface, consists of a series of filtergrams: images taken at a specific tuning position (i.e. with a specific HMI filter) and at a specific polarization. The current plan is to use six tuning positions, roughly spanning the range $[-172.5, +172.5]$ mÅ around the target wavelength 617.3 nm. In order to accurately derive the Doppler velocities and vector magnetic fields from these filtergrams, a thorough knowledge of the six filter transmission profiles is needed. Therefore, we need to know the transmission profiles of all the components of the HMI optical-filter system, described in Section 2.3. This is the purpose of the wavelength dependence calibration.
The five stages of the Lyot filter and the two Michelson interferometers, have transmission profiles that can be fully characterized, in a first approximation, by only three parameters: their Full Spectral Range (FSR), their relative phases, and their contrasts (ranging from 0 to 1). Both the phases and contrasts vary across the element aperture, and therefore are to be given as 2D maps. The FSRs of the elements are, to a very good approximation, equal to twice their FWHMs. To access these FSRs, phases, and contrasts of the optical-filter elements, we mainly recourse to detune sequences. A detune sequence is a sequence of HMI images (typically 27- or 31-position long) for which the tuning selectors are such that the peaks of maximum transmission of the tunable elements do not necessarily coincide. The primary detune sequence used three different positions for each waveplate tuning HCM, corresponding to tuning phases of 0°, 120°, and 240°, for a total of $3^3 = 27$ positions. The other sequence has 31 images: the 27 positions of the previous sequence, and adds four positions testing the tuning polarizer HCM.

A 27-position sequence with a laser as light source, gives us access to the phase and contrast maps of the three tunable elements. We obtain these maps both in Obsmode and Calmode. Detune sequences taken at different laser wavelengths give us access to the FSRs of the tunable elements, and also the phase and contrast maps of the non-tunable elements (Lyot elements E2 to E5). The FSRs of the non-tunable elements, and the transmission profiles of the front window and blocking filters, have to be measured separately while these parts are outside the instrument. Taking detune sequences in sunlight (using a heliostat) allows a determination of the phases of the tunable elements. In sunlight, we cannot access the contrasts of these elements, only their phases, and we can only get the phases in Calmode. We fit for the phases of the tunable elements as well as the parameters defining the Fe I solar line (here conveniently approximated by a Gaussian profile). Numerous detune sequences taken on the ground showed the high quality of the HMI optical-filter elements. The phase ranges of the three tunable elements are relatively small (less than 20°), and their contrasts are very high (> 0.95 on average), especially compared to the Michelson interferometers of the MDI instrument. Their FSRs are well within specifications. It is noteworthy that the phase maps of the tunable elements are slightly different in Obsmode and Calmode (especially for E1), for reasons that are not fully understood. **XXX Somehow explained by angular dependence?**

Similarly, there seems to be a small difference for the phases of the narrow-band Michelson between phase maps obtained from detune sequences taken by the front and side cameras. The overall transmission profile of the non-tunable elements seems to be, on average, centered at +18 mÅ from the target wavelength, with a FWHM of 624.5 mÅ for the main peak. There are two small main sidelobes at about −1 and +1 mÅ.

The blocking filter and front window are composed of different glass blocks which, unfortunately, act as weak Fabry-Perot interferometers because of partial reflections at the glass interfaces, and produce a fringe pattern visible on the filtergrams and on the phase and contrast maps of the filter elements. This fringe pattern needs to be characterized. A way of doing so is by using white light (from a lamp) and by taking detune sequences in Calmode and Obsmode. The transmission profile of the non-tunable part of the HMI optical filter can be expanded into a Fourier series. The first seven Fourier coefficients are accessible through this analysis. The Fourier-coefficient maps at these different spatial frequencies clearly show the different fringe patterns and help us localize the origin of these patterns. A major issue is that the phases of these patterns
depend on the temperature of the front window and blocking filter. That means that these fringes will not be stable for a few hours after each eclipse that will affect SDO due to its geosynchronous orbit.

The presence of the blocking filter and front window also means that in white light, each detune or cotune-sequence position does not transmit exactly the same amount of light (the integral value of the corresponding transmission profile varies). This is called an I-ripple. Taking detune sequences in white light allows us to measure the overall I-ripple of HMI, while taking fine-tuning sequences (in which each element is tuned separately) allows us to measure the individual I-ripples of the tunable elements. The individual I-ripples are all smaller than 1% (relative peak-to-peak variation of transmitted intensity), while the overall I-ripple is slightly below 2%.

The transmission profiles, fringe patterns, and I-ripples may all depend on the angle of incidence of light rays, and on the temperature of the optical-filter elements. Therefore, it is necessary to characterize the angular and temperature dependences. The angular dependence of the tunable elements is obtained in Calmode (respectively Obsmode) from detune sequences taken at different positions of a field stop (respectively aperture stop) with a small hole. The Lyot element E1 is the tunable element with the largest angular dependence, followed by the NB Michelson and the WB Michelson. This was expected, as the angular dependence of a wide-field Lyot element is in $\theta^2$ (where $\theta$ is the angle of incidence) while it is in $\theta^4$ for a wide-field Michelson interferometer. E1 also seems to show a significant amount of azimuthal dependence. The temperature dependence of the tunable elements is satisfactory. Indeed, the wavelength drift is only about 15 mÅ/degrees at $T = 30^\circ$. We also checked that the I-ripple does not vary with temperature, and with a change in the focus block.

Finally, we measured the throughput (ratio of transmitted over input intensity) of HMI, and obtained 1.35% which is on the low side of the expected range, but is adequate for the 45-second cadence of the observable sequence with enough margin to accommodate front window darkening exceeding that seen with MDI.

An example of the resulting six tuning-position transmission profiles is shown on Figure 4, with respect to the Fe I solar line profile at rest and at disk center (provided by R. K. Ulrich).

XXX Discuss mishelson drifts XXX Mention calibration using orbital velocity?

3.4. Polarization

The final major calibration area is polarization. The details of this effort are described in Schou et al. (2010).

The main results is that the polarimetric model indicates that the crosstalk between Q, U and V is less than 1% across the FOV, as required.

Several of the parameters describing the polarimetric model have a significant temperature dependence, but it has also proven possible to model this with sufficient accuracy.

3.5. Miscellaneous

XXX Do ISS, cameras, alignment legs, thermal go here?
Figure 4. Example of HMI tuning-position profiles obtained from the wavelength-dependence calibration procedure. Six tuning positions are shown here with respect to the Fe I solar line at disk center and at rest. The line profile was provided by R. K. Ulrich and obtained at the Mount Wilson Observatory.

3.6. Performance Summary

XXX Needed? Similar to requirements table(s) in IPD?

4. Conclusion

HMI is the greatest instrument ever built!

Appendix

XXX Major events? Known issues with data processing? XXX Dark jitter and removal? Overscan? Broken images?

A. Optical Prescription

XXX Could go to image quality paper. XXX ZEMAX prescription as supplemental material.

B. Sequencer and Framelist Examples

XXX Care for this?

Table B shows an example of a framelist. In order the columns are the following:
Table 1. Example framelist. See text for description.

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- **FID**: This number is simply downlinked with the image and has no effect on the sequencer execution. In the present case it is used to indicate the position in the line and the polarization state. It can also be used to indicate frames intended for calibration only.
- **RelTime**: This is the time of the frame relative to the start time of the sequence.
- **Img**: The type of readout (1, 2 or 4 port), cropping and compression used.
- **PL**: The index of the polarization setting desired.
- **WL**: The index of the wavelength setting desired.
- **CF**: The focus position used. 1-16 indicate normal images. 17 calmode.
- **Exp**: The index of the exposure time desired.
- **Obspath**: The camera used. IMAGE indicates that an exposure is taken. DARK that a dark frame is taken.

Note that most of the settings use an index into another table. This other table then details the settings of the individual mechanisms. In many cases a default value is specified. The corresponding values are kept separately in registers in the FSW. This allows for changing parameters such as the focus position and exposure time without remaking framelines.

It the example shown in Table B WL positions 465, 467, 469, 471, 473, and 475 correspond, in order to I5, I4, I3, I2, I1, and I0, which in turn correspond to increasing wavelength, thereby minimizing the errors in the inferred Doppler velocities.

Similarly PL positions 258 and 259 correspond to LCP and RCP while 250 through 253 are 4 positions allowing for the determination of I, Q, U and V.

As can be seen the framelist loops twice through the wavelengths in order I3, I4, I0, I5, I1, I2. This is done such that the center wavelengths (I2 and I3) are centered on the target times (0s and 45s).

In both halves of the framelist the front camera does LCP and RCP at each wavelength, thereby allowing for the Doppler and LOS field to be obtained. The side camera, on the other hand, does to of the 4 polarizations in the first half and the other in the second half, thereby allowing for a 90s cadence using data from that camera only.

Many other framelines with various tradeoffs are, of course, possible.

### C. Other background material?

#### XXX IPD,...

**Acknowledgements**  The authors thank ... *(note the reduced point size)* XXX Stanford laser, LMSAL engineers, SU staff. The order of the authors beyond the first author was determined by a random number generator. This work was supported by NASA contract NAS5-02139 to Stanford University.

**References**


