Helioseismic and Magnetic Imager
for
Solar Dynamics Observatory

Appendix B
Instrument Performance Document

SU-HMI-S013
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Stanford University Hansen Experimental Physics Laboratory
and
Lockheed-Martin Solar and Astrophysics Laboratory
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1 Introduction

Note that this is a very preliminary version of this document. While some sections contain significant detail others are empty or missing.

The purpose of this document is to capture the derivations of instrumental requirements. It will also be used to guide testing and calibration.

In Section 2 an overview of the HMI including the observables requirements, the observing scheme and an instrument overview is provided. The observables requirements are summarized in Table 1.

In Section 3 the derivations of the requirements on the individual filtergrams from the science requirements are given. The filtergram requirements are summarized in Table 3.

In Section 4 the filtergram requirements are used to derive requirements on the various instrument subsystems. A summary of the subsystem requirements is given in Table 4.

Finally the appendices contain various background materials.

It should be kept in mind that the requirements flow is not as simple as stated above. In reality limitations on the instrument which can realistically be built have to be taken into account. Also, note that this document will evolve as the instrument is designed and built.
2 HMI Overview

2.1 Observables

This section briefly describes the observables produced by HMI and lists the requirements and their origin. The requirements are summarized in Table 1. The following subsections contain comments on some of the requirements. Note that some requirements have been listed as general (e.g. the angular resolution) even if the MRD or the science part of the CSR only specify them for selected observables.

2.1.1 General Requirements

Not only should the cadence be better that a certain number, it should also be fixed and the phase should be constant. In other words, all Dopplergrams should be taken an integer multiple of the cadence apart over the entire mission.

For convenience it is also a requirement that the cadence is an integer number of seconds and divides into 1 day and preferably 1 hour. Possible cadences thus include 50s, 48s, 45s and 40s (could be shorter, but that is probably unrealistic) for the Doppler and line-of-sight magnetic field.

2.1.2 Doppler Velocity

For the purposes of this document the numbers are for quiet Sun unless otherwise noted.

For essentially all scientific analysis, what is needed in terms of the absolute knowledge is the velocity differences across the images. The global zero point is therefore not important. In the following only the relative knowledge of the zero point across the image will be considered.

2.1.3 Line of Sight Magnetic Field

For the purposes of this document, the accuracy and precision with which the field can be measured are defined to be that derived for a pure line of sight field with a 100% filling factor. Unless otherwise noted the numbers refer to quiet Sun.

The results using this definition are very close to those obtained by considering the mean (signed) line of sight field over the area covered by one pixel. Note furthermore that this mean field is identical to the integrated line of sight flux over the pixel divided by the area of the pixel.

It is important to distinguish this from the mean unsigned field, whether line of sight or not, or the field over the part of the pixel given by the filling factor. These quantities are considered under the vector field requirements.

2.1.4 Vector Magnetic Field

Due to the dependence of the noise on the values of the parameters, the precision requirements are stated in terms of the polarimetric precision.

For details on the performance in terms of various variables, please see HMI technical note # TBD.

2.1.5 Continuum Intensity

This section still needs to be written.

2.1.6 Other Observables

This section still needs to be written.

2.1.7 Summary of Observables Requirements

The requirements are summarized in Table 1.
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<th>Requirement</th>
<th>Origin</th>
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<td>General</td>
<td>Pixel size: 0.5”</td>
<td>MRD 1.3.1</td>
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<td></td>
<td>CCD size: $4096^2$</td>
<td>MRD 3.2.2.1</td>
</tr>
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<td></td>
<td>Resolution: 1.5”</td>
<td>MRD 1.3.1</td>
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<td></td>
<td>Resolution: 1.0”</td>
<td>Goal</td>
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<tr>
<td></td>
<td>Field of View: $\pm 1006\text{”}$</td>
<td>Goal</td>
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<tr>
<td></td>
<td>Completeness: 99% for 95% of time</td>
<td>Science req.</td>
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<tr>
<td>Velocity</td>
<td>Cadence: 50s</td>
<td>MRD 1.6.1</td>
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<td></td>
<td>Noise: 25 m/s</td>
<td>MRD 1.5.1</td>
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<td></td>
<td>Noise: 13 m/s</td>
<td>Goal</td>
</tr>
<tr>
<td></td>
<td>Disk averaged noise: 1 m/s</td>
<td>Science req.</td>
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<td>Disk averaged noise: 0.1 m/s</td>
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<td>Absolute knowledge: 10 m/s</td>
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<td>Dynamic range: $\pm 6.5$ m/s</td>
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<td>Goal</td>
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<td>Continuum Intensity</td>
<td>Cadence: 50s</td>
<td>Science req.</td>
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<td></td>
<td>Noise: 0.3%</td>
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<td></td>
<td>Flat field: 0.1%</td>
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<td>Noise: 17G in 50s</td>
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<td>Noise: 10G in 50s</td>
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<td></td>
<td>Zero point: 0.3G</td>
<td>MRD 1.5.2</td>
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<td>Zero point: 0.2G in 50s</td>
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<td>Dynamic range: $\pm 6.5$ m/s</td>
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<td>Dynamic range: $\pm 3$ kG</td>
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<td>Dynamic range: $\pm 4$ kG</td>
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<td>Polarization Accuracy: 0.3% in 10 minutes</td>
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<td></td>
<td>Polarization Accuracy: 0.22% in 10 minutes</td>
<td>Goal</td>
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Table 1: Summary of observables and requirements.
2.2 Observing Scheme

The idea behind the HMI observing scheme is to take a number of filtergrams, downlink these and produce the various observables on the ground. This greatly simplifies the instrument compared to doing onboard calculations, allows for better calibrations and allows for the data to be reprocessed, if needed. However, this approach does imply a high data rate between the spacecraft and the ground.

Each of the filtergrams are characterized by a number of properties:

- Wavelength settings
- Polarization selector settings
- Exposure time
- Timing of filtergram
- Observing mode
- Camera ID
- Compression parameters
- Etc.

Each of these properties are selectable by software and correspond to setting of various mechanisms and flags in the instrument.

The selection of filtergrams to be taken is specified by a so-called framelist. A single framelist is normally repeated indefinitely during normal operations.

Considerations for the optimal framelist, derived from each observable, are described in the various subsections of Section 3. A summary and some possible framelists are given in Section 3.7 and Table 2.
2.3 Instrument Overview

The HMI instrument 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 drawing.

The front window is a multilayer metal dielectric filter that reflects most of the incident sunlight. It is followed by a 14 cm diameter refracting telescope.

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 section consists of the following elements, which are contained in a precisely temperature-controlled enclosure:

- 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 and 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 that adjusts the optics package pointing.

In the following subsections the different subsystems are described in more detail.

2.3.1 Imaging Optics

The primary imaging optics are a refracting telescope with a 14 cm aperture. This gives an image with a diffraction limit of 0.9", defined as the lowest spatial wavelength resulting in a signal at the detector. The primary and secondary lenses are connected with a low coefficient of expansion metering tube to maintain focus.

The total optical path length is 225cm with an effective focal length of 495 cm and a focal ratio at the final image of 34.6.

The HMI calibration configuration and focus adjustment consists of two calibration/focus wheels each of which contain optical flats of varying thickness in four positions to provide focus adjustment in 16 steps. Besides allowing best focus to be set on orbit, this capability also provides a highly repeatable 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 provides an excellent velocity calibration source for the instrument. Calibration mode images are used to provide Doppler calibrations, monitor the instrument transmission and assess variations in the detector flatfield.

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 sensors receive the full 50Å bandwidth, while light for the rest of the instrument continues through the 5Å bandpass 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.

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.

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 conve-
Figure 1: Mechanical layout.
nient placement of the cameras. The shutters are placed near the pupil image.

2.3.2 Polarization Selectors

The polarization selectors rotate optical retarders to convert the desired incoming polarization into vertically polarized (s-component) light. Each retarder is mounted in a Hollow Core Motor (HCM) which allows them to be rotated to any of 240 uniformly spaced angles. Likely retardance values are 1/4, 1/4 and 1/2 or 1/2, 1/4 and 1/2 waves for the three waveplates. This design allows for a 3 for 2 redundancy, meaning that any of the three waveplates can be left in any position, while preserving the ability to measure all polarization states. The final choice of retardances will be based on a trade-off between the wear on the HCMs and any calibration issues.

2.3.3 Filters

The heart of the HMI instrument is the filter system consisting of the front window, a fixed 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 ±0.1°C. The filter system enables narrow-band filtergrams to be made across the Fe I 6173Å line by co-tuning one Lyot tunable element and the Michelson interferometers. The combined filter bandpass is 76mÅ with a tunable range of 690mÅ.

The front window is a 50Å bandpass filter. It is similar to the MDI design that consists of bonded glass optical flats with a multilayer dielectric coating sandwiched in between. The design will be reviewed to ensure that appropriate radiation hardened materials and processes are used in fabrication.

The blocking filter is a three-period all-dielectric interference filter with a bandpass of 8Å. The MDI blocker transmission profile has a ripple of about 1%, which averages out to less than 0.1% over the beam. The temperature sensitivity of the MDI blocker is 0.2Å/C, and current ion-assisted coating technology will provide an order of magnitude lower temperature sensitivity.

The wide-field, temperature-compensated Lyot filter will use the same basic design as the MDI filter with the addition of a fifth tuned element. 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 design, where the filter final (narrowest) element of the Lyot filter is tuned by a rotating half wave plate. The FWHM width of the untuned part is 612mÅ. The Lyot components are held in optical contact by optical grease, and are keyed to hold the elements in proper relative alignment.

The final filters are a pair of wide-field, tunable solid Michelson interferometers with a clear aperture of 40 mm and 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 copper standoffs. Tuning 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. The HCMs are identical to the polarization selector mechanisms with 240 positions. This design has a 3 for 2 redundancy meaning that any one of the three mechanisms can fail without impacting the ability to tune either Michelson.

Figure 2 shows the transmission profiles of the resulting filter.
In summary the filter FWHMs are:

- Front window: 50 Å
- Blocking filter: 5 Å
- Lyot element #1: 5516 Å
- Lyot element #2: 2758 Å
- Lyot element #3: 1379 Å
- Lyot element #4: 690 Å
- Lyot element #5: 345 Å (tuned)
- Wide Michelson: 172 Å
- Narrow Michelson: 86 Å
- Width of untuned part: 612 Å
- Final width: 76 Å

2.3.4 Shutters

The shutters are very similar to those on MDI and SXI, and provide relative exposure measurement with a digitization of 1 μs. Because every HMI image will be downlinked, variations more than an order of magnitude larger than those seen on MDI after 60 million operations on orbit will cause no detrimental effects.

2.3.5 Other Mechanisms

The aperture door and pointing alignment mechanisms are based on MDI designs. The HMI alignment mechanism can adjust the optics package pointing over approximately ±200 arc-seconds, and will be used to center the solar image on the CCD. The front door will only be operated a few times on orbit and the alignment mechanism will be used once a week or less.

2.3.6 Image Stabilization System

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, exactly as is done on MDI.

The ISS uses the image of the solar limb projected 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 piezoelectric transducer (PZT) actuators to remove errors in the observed limb position. The tip-tilt mirror uses the same low voltage PZT’s and drive circuitry as MDI. This mirror design has a first resonance (>500 Hz) much higher than the structural mode of the HMI optics package, enabling a simple analog control system.

The range of the tilt mirror is approximately ±12 by ±18 arc-second.

The servo gains and other parameters are fully 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...
The error and mirror signals are continually sampled, and down-linked to monitor jitter and drift. For special calibrations, these signals can be sampled at a higher rate.

### 2.3.7 CCD and Camera Design

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 operate non-inverted to ensure a full well capacity of $>150k$ electrons with an anticipated readout noise of less than 12 electrons. They will be cooled to below -65C resulting in a 1 nA/cm$^2$ dark current ($0.2$ e- /pixel-sec).

To achieve the readout in less than 3 seconds, they have a readout rate of 2 Mpixels/s through each of four quadrant readout ports. Multiple ASIC and surface-mount electronics packaging technologies minimize the size, mass, and power requirements of the cameras.

The data from the CCDs are downlinked without any processing other than a hardware compression.
3 Derivations of Filtergram Requirements

The purpose of this section is to show how the requirements on the observables in section 2.1 flow to requirements on the individual filtergrams.
3.1 General Requirements

3.1.1 Angular Resolution, pixel size and Field of View

The requirements on angular resolution, pixel size and the Field of View (FOV) largely carry over directly to the filtergrams and thus determine the aperture size and the allowable amount of uncorrected jitter during an exposure.

3.1.2 Flat Field and PSF Knowledge

Since several filtergrams must be combined to generate one observable, it is essential that the images are coaligned or can be shifted to compensate for any misalignment. Also note that, since images with different polarizations need to be added or differenced to make the Doppler- and magnetograms, imperfect shifting of the images will lead to crosstalk between the variables.

A certain amount of shifting is essentially unavoidable since the Sun will rotate by

\[
\Delta x = R \Omega \Delta t = 2000 \text{pixels} \times 2 \pi \times 460 \text{nHz} \times 50 \text{s} = 0.3 \text{pixels}
\]

at the center of the disk in \( \Delta t = 50 \text{ seconds} \).

It is important to note that the shifts caused by the solar rotation are essentially the same during all observations, and is thus fairly easy to correct for compared to random shifts. Ideally all others shifts, especially those that are random, should be insignificant compared to the rotational shifts. Keeping all the other contributions below 0.1 pixels should make them insignificant.

Given that shifts have to be compensated for it is essential that the flat field is well known and that there is little power above the spatial Nyquist frequency. In order to obtain a good flat field small offpoints will have to be performed. The Nyquist criterion is satisfied here given the optical resolution and the pixel size.

The desire to minimize the interpolation errors means that it will be difficult to combine the data from the two cameras. Doing so would require that the offset and relative rotation of the cameras be compensated for. Also the PSF is likely to be slightly different for the two cameras, due to such problems as differences in focus, different optical paths and CCD differences.

Similarly, temporal interpolations of the filtergrams will likely have to be made. While the Nyquist criterion is essentially fulfilled with 50s sampling of each filtergram in the Doppler sequence, it is difficult to fulfill for the vector sequence. The implications and possible solutions to this problem are discussed in Section 3.7.

3.1.3 Data Completeness

Several tens of filtergrams are needed to construct one observable and since we want to avoid gap filling of individual filtergrams, the requirements on the filtergrams are stringent. Using a conservative number of 100 filtergrams means that a completeness of the observables of 99% translate into 99.99% completeness of the filtergrams.

The 95% requirement carries over directly.
3.2 Doppler Requirements

3.2.1 Cadence

The Dopplergram cadence requirement translates directly into a requirement on the length of the corresponding framelist.

3.2.2 Noise

The noise requirement translates into a combination of requirements on the noise in the filtergrams, the filter widths and the cleanliness of the filter passband.

To arrive at the proposed set of filter properties and to estimate the resulting performance a series of simulations have been performed. Details are given in Appendix A.2 and A.1 and some of the results are summarized in Figure 3.

Briefly, a number of methods exist for estimating the velocity given the filtergrams. The, perhaps, simplest method is what has become known as an MDI-like algorithm. Here, the velocity is estimated as

\[ V = f \left( \frac{\sum_i s_i I_i}{\sum_i c_i I_i} \right), \]  

where \( f \) is a suitably chosen function, \( s_i \) and \( c_i \) are suitable constants and \( I_i \) are the observed intensities. In practice \( f \) tends to be similar to an arctan function and may take the sign of the numerator and denominator into account. Similarly \( s_i \) and \( c_i \) are close to sine and cosine functions.

Depending on the number of wavelengths used, this method may be generalized to use more than one of the above functions etc. and make a weighted average of the resulting velocities.

In practice, filtergrams are taken in both LCP and RCP and must be combined. This could, in principle, be done either by averaging the LCP and RCP filtergrams or by averaging the derived velocities. Since the former option would cause the spectral line to be broadened, with resulting loss of sensitivity, the latter method is used

\[ V = (V_{\text{LCP}} + V_{\text{RCP}})/2. \]  

However, the above method does not make optimal use of the information, in particular when the fields become strong. An alternative method is to do a simultaneous fit of both \( V_{\text{LCP}} \) and \( V_{\text{RCP}} \) as well as the various line parameters. Results of this method are also shown in Figure 3. As can be seen the improvement is modest at low velocities and field strengths, but significant at higher velocities and field strengths, where one of the components has been shifted so far that it is difficult to estimate the line parameters.

As seen from Figure 3 the noise is of the order 13 m/s within the dynamic range using an intensity noise of 0.28%. The MRD specification of 25m/s similarly corresponds to 0.55%.

The noise requirements also imply requirements on the filter profiles. In particular the passbands should be narrow and the profiles should be free of significant sidelobes. This is discussed further in A.1.
3.2.3 Dynamic Range

As can be seen from Figure 3 the dynamic range is of the order ±5.0 km/s to ±6.0 km/s, depending on the algorithm used.

For each additional tuning position used, beyond the 5 used to make Figure 3, the dynamic range increases by roughly ±1.7 km/s.

Note that Figure 3 was made using tuning positions spaced by 0.4 times the full spectral range of the narrow Michelson. Increasing this spacing, which does increase the dynamic range, makes the noise significantly worse at some velocities. Narrowing it decreases the dynamic range.

3.2.4 Disk Averaged Noise

Since the number of pixels averaged together to make the disk average is very large, the photon noise can be ignored and only errors coherent over the disk need to be considered. These include the following:

**Exposure knowledge.** Since the noise is almost independent of position on the disk and since the errors will be highly positively correlated it is easy to derive the exposure knowledge requirement. Since an rms noise of 0.3% in the intensity corresponds to an rms noise of 13 m/s in the velocity it follows that a 1 m/s error corresponds to an exposure knowledge error of 0.003 × (1/13) = 2.3 × 10^{-4} or 215 ppm. Similarly 0.1 m/s corresponds to 22 ppm.

Note that this does not impose a requirement on the actual exposure times since it is possible to correct for the measured exposure time. To be specific, the requirement is on the variation of the ratio of the actual exposure time to the measured exposure time.

**Wavelength repeatability.** Another, perhaps even more significant, contribution to the disk averaged noise is the wavelength repeatability. To estimate this a Monte Carlo simulation was performed. Using the MDI-like algorithm the results are that a 1 mÅ error corresponds to the following:

- Lyot: 1.6 m/s
- Wide Michelson: 8.8 m/s
- Narrow Michelson: 21.5 m/s
- Combined: 23.0 m/s

Note that these results are for the average of $V_{\text{LCP}}$ and $V_{\text{RCP}}$, giving a reduction of $\sqrt{2}$. Also note that the combined number is not particularly useful since the error is likely to be proportional to the spacing of the corresponding element. This is covered in Section 4.6.1.

As discussed later, this requirement has significant impacts on the design of the instrument and framelists. In particular it implies that the same tuning sequence has to be used to make every Doppler image.

**Effective wavelength knowledge.** Since the velocities determined from the instrument data are in the frame of the spacecraft they have to be converted to the solar frame. This requires accurate knowledge of the orbit. This is to be quantified.

3.2.5 Absolute knowledge

The achievable absolute knowledge is essentially set by the accuracy of the on ground calibration. The intent is to use the variations in the orbital velocity to calibrate the velocities and thus the main requirement derived is on the accuracy of the line-of-sight orbital velocity, which needs to be known to a better accuracy than the desired calibration accuracy.

This section still need to be finished.
3.3 Line of Sight Field Requirements

3.3.1 Cadence

This requirement flows to a requirement on the length of the framelist used for the measurement.

3.3.2 Noise

It can be shown that the wavelength shift caused by a field of strength $B$ is equivalent to the velocity shift $V$ given by

$$V = g_{\text{eff}} \lambda B \frac{e}{4\pi m_e}$$

$$= 1.400 \times 10^{10} \text{m/s/T/m} \times g_{\text{eff}} \lambda B \quad (4)$$

or in G and nm

$$V = 1.400 \times 10^{-3} \text{m/s/G/nm} \times g_{\text{eff}} \lambda B \quad (5)$$

For the Fe line, $\lambda = 617.3\text{nm}$ and $g_{\text{eff}} = 2.5$ giving

$$V = 2.16\text{m/s/G} \times B \quad (6)$$

or more conveniently

$$B = 0.463G/(\text{m/s}) \times V = c_B V \quad (7)$$

The simplest way to estimate the field is to use the difference of the velocities of the LCP and RCP components

$$B = c_B (V_{\text{LCP}} - V_{\text{RCP}})/2 = c_B V_B \quad (8)$$

Note the similarity of this equation to Equation 3. Since the absolute value of the weights on $V_{\text{LCP}}$ and $V_{\text{RCP}}$ are the same it follows that the noise on $V_B$ and $V$ are the same and thus that

$$\sigma(B) = c_B \sigma(V). \quad (9)$$

In particular 13 m/s velocity noise corresponds to 6G noise.

From this it follows that the MRD requirement of 17G corresponds to an intensity noise of 0.80% and the goal of 10G to 0.47%.

These estimates should be conservative compared to those derived for the more complex algorithms.

3.3.3 Disk Integrated Noise

From the consideration in Sections 3.2.4 and 3.3.2 it follows that 0.3G noise corresponds to 0.65m/s and thus that we need to know the exposure time to 230ppm*0.65=140ppm. For 0.2G 90ppm is needed.

3.3.4 Polarization Knowledge and Repeatability

This section still needs to be written.
3.4 Vector Field Requirements

The expected performance in terms of various vector field variables is described in HMI Technote number.

In terms of zero point errors, etc. the requirements are similar to those of the line-of-sight field.

3.4.1 Cadence

Again this flows to a requirement on the length of the required framelist. The implications of this are discussed in Section 3.7.
3.5 Continuum Intensity Requirements

This section still needs to be written.
3.6 Miscellaneous
3.7 Framelist Considerations

Given the requirements on the filtergrams described above, consideration can now be given to the construction of the framelists. Below is a discussion of the main constraints.

3.7.1 General Considerations

First of all the proposed instrument has two cameras and images will be taken alternately on each of them in order to optimally use the cameras. As discusses below this implies that the vector sequence has to have a length that is an integer multiple of the Doppler sequence.

Note that the framelists are entirely specified in tables which may be modified at any time. This means that a number of possible framelists can be tried and the optimal algorithm selected.

Finally note that the camera readout speed as well as the available data rate are finite, significantly limiting the framelist which can be considered.

3.7.2 Cadence

As discussed in Section 2.1.1 the Doppler cadence should be 50s, 48s, 45s or 40s.

As discussed in Section 4.6.1 the only way the tuning position repeatability requirement can be met is to ensure that the exact same tuning sequence is repeated for every Dopplergram, at least for periods long compared to the 5 minute period of the solar oscillations.

For all practical purposes it thus follows that the vector sequence should have a length that is an integer multiple of the Doppler sequence. Possible multiples are 1, 2 and 3. More than three does not appear necessary.

3.7.3 Number of Tuning Positions

As discussed in Section 3.2.3 the dynamic range may be inadequate with a fixed set of 5 positions. Two solutions to this problem are obvious.

One possibility is to go to a 6 position sequence. The obvious drawback of this is that the cadence is reduced. Since the noise with 5 or 6 positions is essentially the same over most of the dynamic range this also means that the noise per unit time increases for most of the solar image. On the other hand the 6 position sequence guarantees a very uniform time series.

The other possibility is to use a 5 position sequence but to change the corresponding wavelengths to keep the solar velocities within the corresponding dynamic range. During a 24 hour period the line of sight velocity changes by ±3.4 km/s during the worst time of the year. Changing the set of tuning positions twice a day thus reduces the dynamic range requirement by ±1.7 km/s, making the 5 position option possible. The downside of this approach is obviously that there will be discontinuities in the time series every 12 hours. The magnitude of these will depend on the accuracy with which the calibration can be performed.

In addition to the filtergrams for the Doppler and line of sight calculations it may be necessary to include a continuum filtergram, especially for the 5 position option. This is known as a 5.5 position sequence. Whether this is necessary or not will depend on the exact requirements on the intensity and further simulations.

In addition to the number of tuning positions, the order in which they need to be taken has to be determined. The main consideration here is to minimize so-called acceleration effects. These occur because the velocity is changing between the filtergrams and can cause both systematic errors and additional noise. It will almost certainly be necessary to interpolate the filtergrams in time, especially for the vector field measurements.

Another consideration is to minimize the distance the tuning motors move during the framelist since this has a significant impact on the lifetime of the mechanisms.

At the moment the framelists shown all take the positions in wavelength order. The actual sequence used will be determined later based on a simulation.
To get the required camera cadence, note that a 6 position sequence with LCP and RCP on one camera and a basic cadence of 50s requires a single camera cadence of 4.17s. Since a 6 position sequence may be needed a 4s cadence per camera is needed.

### 3.7.4 Doppler and Line of Sight Polarization Scheme

Assuming that the images from the two cameras will not be merged to make the Dopplergrams and line of sight magnetograms, the only reasonable combination of polarizations is alternating Left Circular Polarized (LCP) and Right Circular Polarized (RCP).

The order of the LCP and RCP and whether it is the same at each tuning position, will be determined by considering the acceleration effects and the wear on the mechanisms.

### 3.7.5 Vector Field Polarization Scheme

If, as currently planned, the data for the two cameras are not combined, there are two main options for the vector polarization sequence.

The first option is to have the vector framelist be twice as long as the Doppler/LOS framelist. In this case four different polarization states will be measured, two in each Doppler/LOS cycle. In this case a possible set of polarizations to take are $I \pm bQ + aV$ and $I \pm bU - aV$. This could be done by taking the pairs during alternate Doppler/LOS cycles, which would allow Q and U to be constructed as differences of filtergrams taken without moving the tuning motors, thereby minimizing the zero point noise and acceleration effects for these variables (which are smaller than V). On the other hand, V may suffer from such problems.

The second option is to have the vector framelist be three times as long as the Doppler/LOS framelist. In this case the obvious solution is to cycle through $I \pm Q$, $I \pm U$ and $I \pm V$. The advantage of this scheme is that it makes it possible to measure Q, U and V with all the differences taken without moving the tuning motors. This should provide very good zero point stability. The obvious drawback is that the cadence will be between 120s and 150s, depending on the Doppler cadence. This is rather slow and clearly does not fulfill the Nyquist criterion. However, since I is created in each cycle, it is possible to obtain an accurate velocity every 40s to 50s, which may make it possible to correct for the acceleration effects. The feasibility of this depends on several factors, such as how clean the polarization states are. If they are contaminated, the Is derived will not be identical. Similarly the polarization selectors may introduce small offsets.

It should be mentioned that both of these methods provide the same overall polarization precision per unit time. In both cases the origin of the coordinate system defining Q and U also needs to be chosen. This will likely be done in such a way as to minimize the wear on the polarization selector mechanisms.

If the data from the two cameras are combined to make the vector measurements, but not the Doppler/LOS measurements, only $I \pm Q$ and $I \pm U$ need to be taken with the vector camera. The other camera will provide $I \pm V$. This would allow for an 80s to 100s cadence and eliminate the zero point errors. It will however require mapping the images from the one CCD to the other, making this approach subject to flatfielding problems, etc.

Finally, if the flat fielding problems can be completely corrected, $I \pm bQ + aV$, say may be taken on the one camera and $I \pm bU - aV$ on the other. This would provide a 40s to 50s vector sequence, thereby fulfilling the Nyquist theorem.

Since the feasibility of combining data from the two cameras is not known, the currently baselined framelist does not combine data from the two cameras. However, this decision will be revisited once the flight instrument has been characterized.
Table 2: Example framelists. Time indicate the time of the first exposure at a given wavelength setting relative to the beginning of the framelist. The tuning positions I1 through I5 or I6 are spaced evenly by 0.4 times the FSR of the narrow Michelson or 69mÅ. The tuning position IC is taken in the continuum. Doppler pol. indicates the polarization taken on the Doppler camera. Vector pol. indicates the polarization taken on the Vector camera. L=I+V and R=I-V are LCP and RCP, respectively. 1, 2, 3 and 4 indicate the positions used to generate I, Q, U and V. C indicates a suitable polarization for the continuum intensity, most likely linear. See the text for details.
3.8 Summary of Filtergram Requirements

A summary of the requirements on the filtergrams is given in Table 3.
### Filtergram Requirements Table 3: Summary of filtergram requirements.

<table>
<thead>
<tr>
<th>Filtergram Property</th>
<th>Requirement</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td>Pixel size: 0.5”</td>
<td>3.1.1</td>
</tr>
<tr>
<td></td>
<td>CCD size: 4096²</td>
<td>3.1.1</td>
</tr>
<tr>
<td></td>
<td>Resolution: 1.5”</td>
<td>3.1.1 (MRD)</td>
</tr>
<tr>
<td></td>
<td>Resolution: 1.0”</td>
<td>3.1.1 (Goal)</td>
</tr>
<tr>
<td></td>
<td>Field of View: ± 1006”</td>
<td>3.1.1</td>
</tr>
<tr>
<td></td>
<td>Completeness: 99.99% for 95% of time</td>
<td>3.1.3</td>
</tr>
<tr>
<td></td>
<td>Cadence: 4s per camera</td>
<td>3.7.3</td>
</tr>
<tr>
<td>Intensity Noise</td>
<td>Doppler: 0.55%</td>
<td>3.2.2 (MRD)</td>
</tr>
<tr>
<td></td>
<td>Doppler: 0.28%</td>
<td>3.2.2 (Goal)</td>
</tr>
<tr>
<td></td>
<td>LOS: 0.80%</td>
<td>3.3.2 (MRD)</td>
</tr>
<tr>
<td></td>
<td>LOS: 0.47%</td>
<td>3.3.2 (Goal)</td>
</tr>
<tr>
<td>Exposure knowledge</td>
<td>Doppler: 215ppm</td>
<td>3.2.4 (MRD)</td>
</tr>
<tr>
<td></td>
<td>Doppler: 22ppm</td>
<td>3.2.4 (Goal)</td>
</tr>
<tr>
<td></td>
<td>LOS: 140ppm</td>
<td>3.3.3 (MRD)</td>
</tr>
<tr>
<td></td>
<td>LOS: 90ppm</td>
<td>3.3.3 (Goal)</td>
</tr>
<tr>
<td>Tuning</td>
<td>Positions: 5 or 6</td>
<td>3.2.3, 3.7.3</td>
</tr>
</tbody>
</table>
4 Derivation of Subsystem Requirements

The purpose of this section is to show how the requirements in section 3 flow to requirements on the various subsystems.

The requirements on the various subsystems are summarized in Table 4.
4.1 Angular Resolution

4.1.1 Aperture

The requirement on the aperture diameter $D$ may be calculated from

$$D = \frac{60 \times 60 \times 180 \lambda}{\pi \alpha} = 206265\frac{\lambda}{\alpha}$$

where $\alpha$ is the desired angular resolution. For $\lambda = 617.3\text{nm}$ and $\alpha = 1''$ this gives $D=127\text{mm}$.

Note that the standard Raleigh criterion with an additional factor of 1.22 was not used. The above criterion is the one that assures that the Nyquist criterion is fulfilled. With a 140mm aperture the Nyquist criterion is not fulfilled, however simulations using high resolution solar data indicate that the resulting aliasing is negligible. The aliasing is likely to be even less of a problem when other factors affecting the PSF (such as optical aberrations and CCD charge diffusion) are taken into account.

Optical defects causing a degradation of the PSF should be negligible compared to the diffraction limit.

The other issue affecting the size of the aperture is the available amount of light. Scaling the results for MDI indicate that the resulting exposure time will be around 250ms leaving an adequate margin for unexpected light losses and degradation.

4.1.2 Residual Jitter

Another potential source of PSF degradation is jitter during exposures. Ideally this should be negligible compared to the diffraction limit. The goal is 0.1''. Time scale is the exposure time, corresponding to frequencies above a few Hz.

4.1.3 CCD Charge Diffusion

The charge diffusion should be negligible compared to the diffraction limit.

4.2 Pixel Size and FOV

These translate almost directly to the requirements on the optics. With a physical pixel size of $12\mu\text{m}$ and an angular size of 0.5'', the Effective Focal Length (EFL) needs to be

$$\text{EFL} = \text{pixel size} \times \frac{\text{pixels}}{\text{arcsec}} \times \frac{\text{arcsec}}{\text{radian}} = \frac{0.012\text{mm}}{0.5} \times \frac{1}{60 \times 60 \times 180}$$

$$= 4950\text{mm}$$

Note that with 4096 pixels, the FOV is 2048'', easily meeting the requirement of 2012''.
4.3 Image Offsets

This section and the subsections mostly still need to be written.

4.3.1 Residual Jitter

As discussed earlier any uncorrected motions on time scales of seconds will lead to relative offsets of the different filtergrams. The offsets may take the form of both solid image shifts and relative distortions.

4.3.2 Polarization Selector Wobble

The polarization selectors sit before the ISS and any solid shifts are thus taken out.

4.3.3 Wavelength Selector Wobble

Any offsets caused by the wavelength selectors are not corrected by the ISS and is thus essential that they do not introduce a significant amount of wobble.

4.3.4 Limb Sensor Induced Wobble

The polarization state coming out of polarization selectors will change as a function of the polarization selector setting in strong fields. This may cause small changes to the amount of light reaching the different limb sensors causing small image offsets.
4.4 Flatfield
4.5 Intensity Noise

4.5.1 Full Well

The most stringent requirements for the intensity noise are the Doppler requirements from 3.2.2. The MRD derived requirement of 0.55% noise corresponds to a full well of \((1/0.0055)^2 = 33k^-\), while the 0.28% goal translates to \(128k^-\). The calculations assume that the resulting noise is totally dominated by the photon noise.

4.5.2 Exposure Time Knowledge

The most stringent MRD requirement for the exposure knowledge are 140ppm from Section 3.3.3. With a 250ms exposure time this translates to \(35\mu s\) exposure knowledge. The most stringent goal is from the Doppler with 22ppm which translates to \(5\mu s\) exposure knowledge.
4.6 Wavelength Stability

4.6.1 Tuning Motor Repeatability

As mentioned in Section 3.2.4 a significant contribution to the zero point noise is the repeatability of the hollow core motors used for the tuning. The relationship between variations in the wavelength each filter element has been tuned to and the corresponding velocity noise given in Section 3.2.4 can be translated to a corresponding requirement on the angular repeatability of the hollow core motors. To be specific a 60” error in the orientation of the waveplates lead to the following velocity and LOS noise:

- Lyot: 0.21m/s (0.10G)
- Wide Michelson: 0.58m/s (0.27G)
- Narrow Michelson: 0.69m/s (0.32G)
- Combined: 0.93m/s (0.43G)

It follows that velocity errors of 1m/s and 0.1m/s correspond to 65” and 6”, respectively and that 0.3G and 0.2G correspond to 42” and 28”, respectively.

If it is possible not to move the motors between the LCP and RCP positions, the requirements on the HCM accuracy derived from the field essentially disappear.

Also note that, due to the nature of the motors, it is only possible to meet these requirements if only moves from the same position are used. As mentioned in Section 3.7.2 this puts significant constraints on the framelists which may be considered.

4.6.2 Thermal Stability

This section still needs to be written.
4.7 Filter Profile Knowledge and Coalignment

This section still needs to be written.
4.8 Polarization Accuracy

This section still needs to be written.
4.9 Focus

This section still needs to be written.
4.10 Data Completeness

This requirement carries directly over to the various subsystems (mainly the electronics). However, since the instrument should not contribute significantly to the overall loss rate, which is set at $10^{-4}$, the instrument pixel loss rate should be less than of the order $10^{-5}$. Hits to the CCD pixels are not included in this and should be included in the overall noise budget.

Also, note that the data are compressed and put into packets of length $8 \times 1786 = 14288$ bits. Thus a pixel loss rate of $10^{-4}$ translates into a packet loss rate of roughly $7 \times 10^{-9}$, after the compression has been performed. Since the instrument should not contribute significantly to this number, the instrument should not cause a loss of more than of the order $10^{-9}$. 
4.11 Summary of Subsystem Requirements

The requirements on the various subsystems are summarized in Table 4.
<table>
<thead>
<tr>
<th>Subsystem Property</th>
<th>Requirement</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powered Optics</td>
<td>Primary lens: 14cm</td>
<td>4.1.1</td>
</tr>
<tr>
<td></td>
<td>EFL: 495cm</td>
<td>4.2</td>
</tr>
<tr>
<td>Filters</td>
<td>Front window: 50Å</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Blocking Filter: 5Å</td>
<td>3.2.2, A.1</td>
</tr>
<tr>
<td>HCMs</td>
<td>Repeatability: 42” (see text)</td>
<td>4.6.1 (MRD)</td>
</tr>
<tr>
<td></td>
<td>Repeatability: 65” (see text)</td>
<td>4.6.1 (MRD)</td>
</tr>
<tr>
<td></td>
<td>Repeatability: 6”</td>
<td>4.6.1 (Goal)</td>
</tr>
<tr>
<td>ISS</td>
<td>Jitter 0.1” above 1Hz</td>
<td>4.1.2</td>
</tr>
<tr>
<td>CCD</td>
<td>Full well: 33ke⁻</td>
<td>4.5.1 (MRD)</td>
</tr>
<tr>
<td></td>
<td>Full well: 128ke⁻</td>
<td>4.5.1 (Goal)</td>
</tr>
<tr>
<td>Shutter</td>
<td>Knowledge: 35µs</td>
<td>4.5.2 (MRD)</td>
</tr>
<tr>
<td></td>
<td>Knowledge: 5µs</td>
<td>4.5.2 (Goal)</td>
</tr>
<tr>
<td>Data loss</td>
<td>Pixel loss: &lt; 10⁻⁵</td>
<td>4.10 (MRD)</td>
</tr>
<tr>
<td></td>
<td>Packet loss: &lt; 10⁻⁹</td>
<td>4.10 (MRD)</td>
</tr>
</tbody>
</table>

Table 4: Summary of subsystem requirements.
A Details of Derivations

This appendix will contain details of various calculations, simulations etc.

A.1 Velocity Algorithms and Noise Performance

A.2 Filter Trade-Off Studies

A.3 Polarization Selector Studies
B Calibration Procedures

This appendix will describe calibration procedures and how the results will be analyzed to verify performance.
C  Acronyms List
References