Calibration of the Filter System in the Assembled Instrument

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This document describes the calibration procedures needed to characterize the transmission profile of each element of the HMI filter system once the instrument has been assembled. The HMI filter system is composed of: the Lyot filter with its 5 stages (E1 to E5), the 2 Michelson interferometers (narrow-band NB and wide-band WB), the blocker filter, and the front window. We need to know how the transmission profile of these elements vary across the HMI CCD pixels, how they vary with the instrument temperature and with the angle of incidence of light rays.

1. Expression for the transmission profile

The transmission profile $T(\lambda)$ (or transmittance T as a function of the wavelength λ) of each Lyot stage and Michelson can be written as (in a first approximation):

$$T(\lambda) = \frac{1 + B \cos\left(\frac{2\pi\lambda_0}{\mathrm{FSR}} + \phi + \phi_t\right)}{2} \tag{1}$$

where FSR is the free spectral range of the element, B is its contrast, ϕ is its phase, and ϕ_t is its tuning angle in case the element is tunable. B and ϕ vary across the element aperture. Equation (1) is only approximate: if the tuning half-wave plate of the element has a less-than-perfect retardance, or the tuning polarizer between NB and WB leaks the wrong polarization, or an element produces an I-ripple due to, for instance, a defective half-wave plate in-between the two calcite blocks, then additional terms need to be taken into account. For instance if the retardance of the tuning half-wave plate of E1 is $\pi + 2\beta$ instead of π, then the transmittance of this element is, for small β:

$$T(\lambda) = (1 - \frac{\beta^2}{2})\, B \cos^2\left(\frac{\pi\lambda_0}{\mathrm{FSR}} + \frac{\phi}{2} + \frac{\phi_t}{2}\right) + \beta^2\, B \cos^2\left(\frac{\pi\lambda_0}{\mathrm{FSR}} + \frac{\phi}{2}\right) + \frac{1 - B}{2} \tag{2}$$

However, this parameter is difficult to determine because $T(\lambda)$ is not really sensitive to β for reasonable values. Another example is the polarizer between NB and WB in the assembled instrument that might leak the wrong polarization: it transmits a fraction α of the expected polarization, and $1 - \alpha$ of the unwanted one. Then the overall throughput of the instrument is reduced and the contrasts of both NB and WB appear to be reduced. The transmittance of NB or WB can be writeen as (for α close to 1):

$$T(\lambda) = \alpha^2 \, B \cos^2\Big(\frac{\pi\lambda_0}{\mathrm{FSR}} + \frac{\phi}{2} + \frac{\phi_t}{2}\Big) + (1-\alpha)^2 \, B \sin^2\Big(\frac{\pi\lambda_0}{\mathrm{FSR}} + \frac{\phi}{2} + \frac{\phi_t}{2}\Big) + \alpha^2 \, \frac{1-B}{2} \qquad (3)$$

Therefore the amount of leakage of the polarizer is degenerate with the contrasts, which makes it difficult to determine this parameter. Thus the parameters we most easily can and need to determine during the calibration tests are B and ϕ, and we assume that Equation (1) holds.

1.1. Determination of the Spectral and Spatial Properties

As previously mentioned the spectral properties of the HMI filter system are best understood by deriving, for each element but the front window and blocker filter, its contrast $B(x, y)$ and phase $\phi(x, y)$ maps, where (x, y) are the coordinates of a CCD pixel. Such maps can be obtained from sequences of filtergrams called detune and cotune sequences, in which the tuning waveplates of the 3 tunable elements are rotated at various angles independently of, or in phase with, each others.

1.1.1. Tunable elements: NB, WB, and E1

To learn how to cotune HMI, meaning how to get the transmission profiles of the tunable elements all in phase and centered on a specific wavelength, we must measure $\phi(x, y)$. We will then be able to produce a cotune table and measure the Doppler velocity at the solar surface. To this end we use a specific detune sequence: the hollow-core motors of the three tuning waveplates are rotated at three different angles (0, 120, and 240 degrees), producing a $3 \times 3 \times 3$ =27-position sequence (see Table 1). Monte-Carlo simulations show that this detune sequence is long enough to allow a precise determination of the phases and contrasts of the tunable elements, and we are guaranteed to always have some light transmitted by the filter whatever these phases are. The light source that feeds the instrument during the calibration tests is either the Sun through an heliostat, a dye laser with its wavelength set close to the solar Fe line wavelength, or a lamp.

When **using sunlight** and running a detune sequence, the solar line is used as an absolute reference for the derivation of the phases. Therefore, we need to know precisely when each detune sequence is taken, in order to correct the solar line central wavelength at rest (6173.3433 Å) from the Sun-Earth motions. In sunlight we do not have access to the contrasts of the Michelsons and the tunable Lyot element, and only their phases can be derived. Therefore, in the code used to analyze the test data, their contrasts have to be set to a given value, usually 0.95. We also need to provide the code with the transmission profile of the non-tunable part of the HMI filter. We use either a spatially averaged transmission profile obtained when the Lyot+blocker filter was outside the instrument, or we set the contrasts and phases of E1, E2, E3, and E4 to a given value. A least-squares fit is then performed that returns $\phi(x, y)$ and the solar line parameters. The Fe line is assumed to have a Gaussian profile, which is only approximate but close enough to the actual line profile. The solar linewidth, linedepth, and continuum intensity are fitted for at the same time as the phases of the three elements. The fitting procedure has been thoroughly tested on simulated data. This calibration procedure is performed only in Calmode and is to be performed in vacuum and in air. When done in air, an air-to-vacuum corrector is added, and we have to "rebin" the filtergrams to lower the thermal noise: we usually rebin the 4096×4096 dataset into 256×256. Thermal noise is a problem because the HMI CCDs cannot be cooled down for in-air calibration. Before and after the detune sequence one dark frame is taken: a time-interpolated dark frame is then removed from each filtergram before analysis. Bad filtergrams sometimes occur due to an erroneous exposure time or similar problems and have to be discarded. A result obtained with this calibration procedure is shown on Figure 1. Figure 2 compares the spatially-averaged filtergrams along the actual detune sequence with the reconstructed detune sequence based on the fitted tunable element phases: the reconstruction is good, with a relative error always smaller than 1.5%.

A problem with this simple data analysis code is that the blocker filter and front window exhibit some fringes that impact on the precision of the calibration results. These fringes can be reasonably well modeled as interference patterns produced by semi-reflective surfaces, like a Fabry-Perot cavity, and have to be calibrated out. Therefore the calibration code in sunlight must also fit for the Fourier coefficients describing the transmittance I due to these fringes:

$$I(\lambda) = 1 + \sum_i (a_i \cos(2\pi\lambda f_i) + b_i \sin(2\pi\lambda f_i)) \tag{4}$$

where f_i is the frequency due to the specific Fabry-Perot cavity i:

$$f_i = (2d_i\, n_i + \lambda_0)/\lambda_0^2 \tag{5}$$

where n_i is the refractive index of the cavity, d_i is its thickness, and λ_0 is the Fe line central wavelength. We usually fit for 4 frequencies: 3 due to the front window, and 1 due to the blocker filter.

When **using the laser** as a light source, no fit is required since a mathematical property of the selected detune sequence allows for an analytical determination of both the phases

Table 1. 27-position Detune Sequence used for the calibration tests

Angle of NB (°)	Angle of WB (°)	Angle of E1 (°)
0	0	0
80	0	0
160	0	0
0	80	0
80	80	0
160	80	0
0	160	0
80	160	0
160	160	0
0	0	80
80	0	80
160	0	80
0	80	80
80	80	80
160	80	80
0	160	80
80	160	80
160	160	80
0	0	160
80	0	160
160	0	160
0	80	160
80	80	160
160	80	160
0	160	160
80	160	160
160	160	160

and contrasts of the tunable elements. Suppose we tune E1 to 0, 120, and 240 degrees. We name T_1, T_2, and T_3 the resulting intensities measured on the HMI CCD. We have:

$$\begin{aligned}
T_1 &= F(\lambda_0)\,\frac{1+B\cos(\frac{2\pi\lambda_0}{\mathrm{FSR}}+\phi)}{2}\\
T_2 &= F(\lambda_0)\,\frac{1+B\cos(\frac{2\pi\lambda_0}{\mathrm{FSR}}+\phi+2\pi/3)}{2}\\
T_3 &= F(\lambda_0)\,\frac{1+B\cos(\frac{2\pi\lambda_0}{\mathrm{FSR}}+\phi+4\pi/3)}{2}\\
T_1+T_2+T_3 &= 3\frac{F(\lambda_0)}{2} \qquad (6)
\end{aligned}$$

where λ_0 is the laser wavelength, assumed to be known, and $F(\lambda_0)$ is the transmittance of the non-tunable part of the HMI filter. The previous system can be written as:

$$\begin{aligned}
T_1 &= \left[\cos\left(\frac{2\pi\lambda_0}{\mathrm{FSR}}\right) B\cos(\phi) - \sin\left(\frac{2\pi\lambda_0}{\mathrm{FSR}}\right) B\sin(\phi)\right] * T + T\\
T_2 &= \left[\cos\left(\frac{2\pi\lambda_0}{\mathrm{FSR}}+2\pi/3\right) B\cos(\phi) - \sin\left(\frac{2\pi\lambda_0}{\mathrm{FSR}}+2\pi/3\right) B\sin(\phi)\right] * T + T\\
T &= \frac{T_1+T_2+T_3}{3} \qquad (7)
\end{aligned}$$

we have a system of 2 equations with 2 unknowns: B and ϕ. Thus it is easy to calculate these parameters. This time, we do not need to make any assumption regarding the non-tunable transmission profile, unlike with sunlight. A major difficulty with this calibration test is that the laser intensity and wavelength have to be stable during the entire detune sequence: both are monitored. The filtergrams taken by HMI are corrected for any laser intensity changes. This procedure is performed in both Calmode and Obsmode: this is important because the ray paths through the instrument are slightly different in these two configurations, and therefore the phase and contrast maps are expected to change. The test configuration is the following: the laser lights a target located at the focal plan of the stimulus telescope (field stop). This target must have a diameter close to the solar disk as it appears on the HMI CCDs (about 23.3 mm for a solar radius of 970”), to ensure that the ray paths inside the instrument are close to the ones obtained with sunlight. Another difficulty with this calibration procedure is to produce uniform light with the laser: a diffuser can be added, even though the overall intensity is consequently decreased. For in-air calibration an air-to-vacuum corrector is also added. Finally dark frames must be recorded before and after the detune sequence to correct the filtergrams for the CCD dark current.

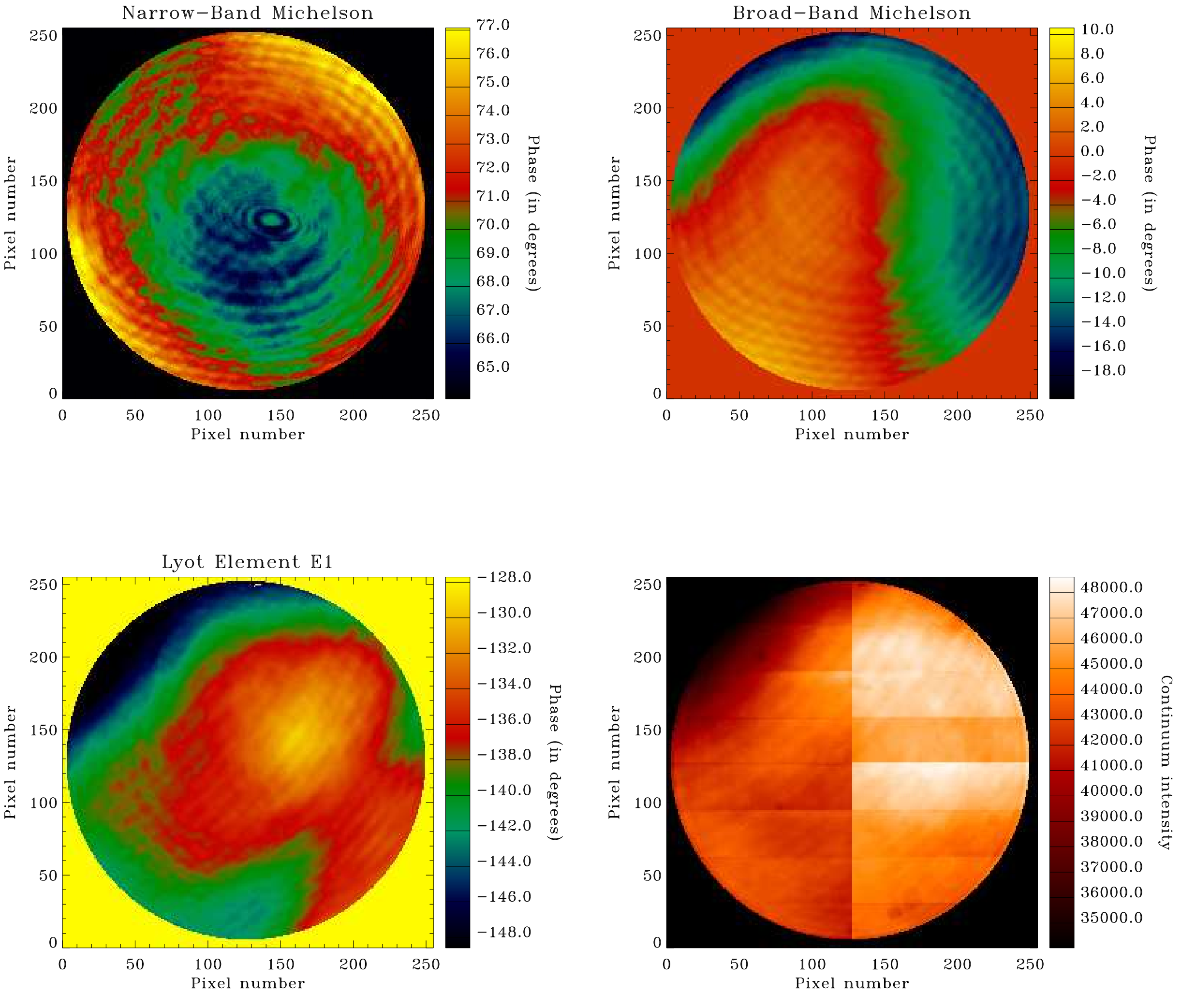

Fig. 1.— Phase ϕ maps of the tunable Lyot elements obtained with a detune sequence in sunlight and Calmode taken on October 31, 2006. The fringes due to the front window and blocker filter have not been fitted for. The 4096×4096 filtergrams have been rebinned into 256×256 to reduce the photon and thermal noise.

1.1.2. Non-tunable Lyot elements: E2 to E5

To gain access to the phases and contrasts of the non-tunable Lyot elements —namely the four stages E2 to E5 of the Lyot filter—, we only use the **dye laser**. We need to repeat a detune sequence at different laser wavelengths. Alternatively, to speed up the procedure, we can use cotune sequences instead: once we know the phases of the tunable elements, it is possible to produce a cotune sequence, *i.e.* a sequence in which the transmission profiles of the three tunable elements vary in phase and the transmitted intensity is maximum. Such a cotune sequence has typically only 10 positions, much less than the 27-position detune sequence. Using these cotune sequences taken at different wavelengths, we can fit for the phases and contrasts of the first four Lyot stages. This procedure is performed in Obsmode and Calmode. The laser wavelength and intensity must be known, stable enough, and constantly monitored. The filtergrams have to be corrected for any intensity variation. A major problem with this procedure is the photon noise: to characterize the elements with the largest FSR (E4 and E5), we need to take cotune sequences as far as ± 5 Å from the target solar wavelength. At this distance, the transmittance of HMI is extremely low, and therefore the photon noise is a bottleneck that limits the precision we can reach. Another major problem for in-air calibration is the thermal noise on the CCDs that seriously hampers any attempt to measure intensities at these wavelengths. Therefore this calibration procedure should be mainly performed in vacuum. Dark frames should be taken before and after each cotune sequence. Overall it is more difficult to characterize the non-tunable Lyot elements than the tunable ones once the Lyot is assembled inside the instrument.

1.1.3. Front window and blocker filter

Other than the five Lyot stages and the two Michelsons, we need to characterize the front window and blocker filter. As mentioned earlier, due mainly to internal interferences between their optical layers, both these filters produce a fringe pattern on the filtergrams obtained with HMI. **Using a lamp** as the light source lighting a Sun-like target at the focal plan of the stimulus telescope, and using the phase maps previously obtained for the tunable elements, we can fit for 15 parameters characterizing the transmission profile of the four non-tunable Lyot stages, the blocker filter, and the front window. The data are obtained through a detune sequence. The fitted parameters are the seven first Fourier coefficients (seven for the cosines, seven for the sines) plus the average transmittance that describe the transmission profile in the range $[-2\,\mathrm{FSR}_{NB}, 2\,\mathrm{FSR}_{NB}]$, where FSR_{NB} is the free spectral range of the narrow-band Michelson, as a function of the location on the filter aperture. Since the front window is in focus in Calmode, but not in Obsmode, performing this calibration procedure in these two configurations should ensure that we can separate the fringes due to the front window from the fringes due to the blocker filter. It can be proved that we obtain information only about the first seven Fourier coefficients and that the transmittance of the

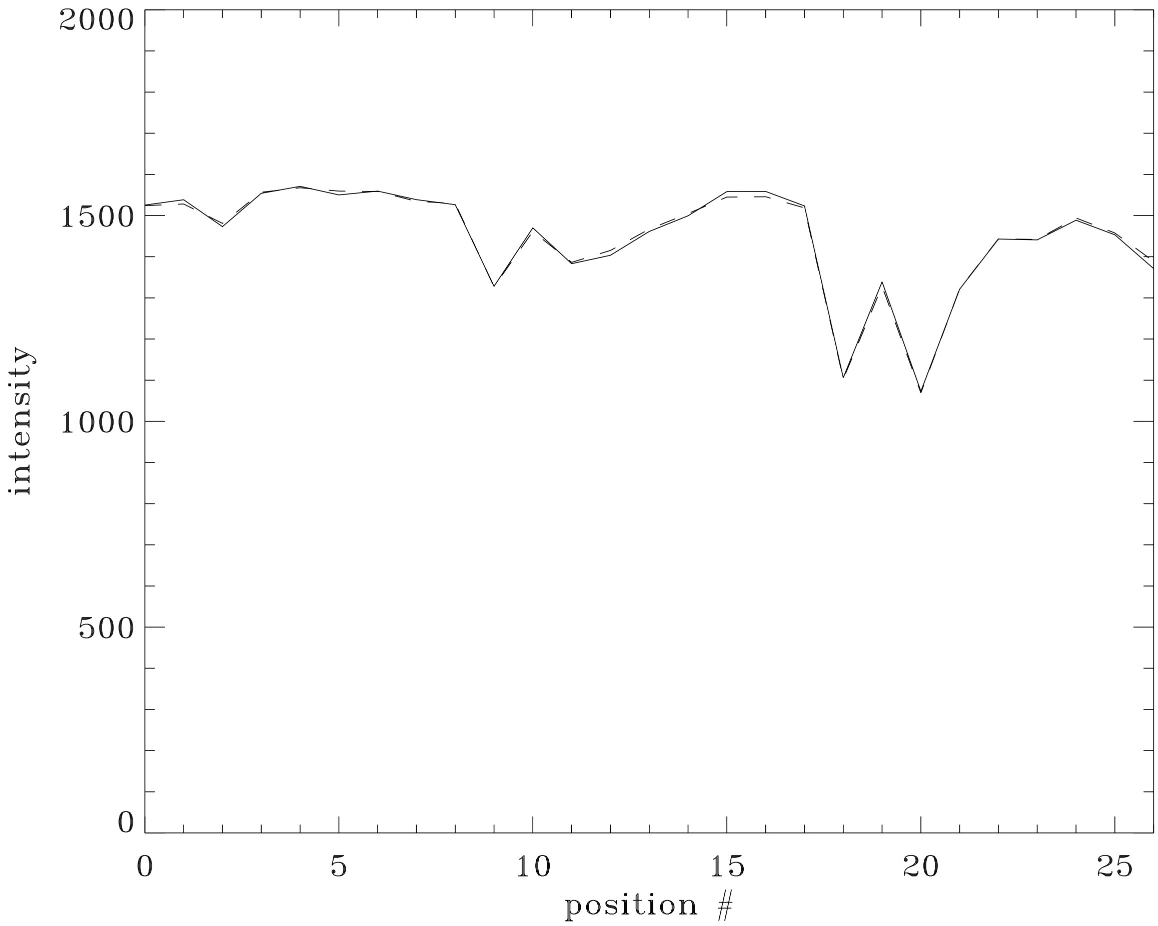

Fig. 2.— Reconstructed detune sequence (dashed line) and actual detune sequence (solid line) for the dataset of October 31, 2006 taken in sunlight and Calmode.

non-tunable part of the HMI filter can be approximated by:

$$T(\lambda) = a_0 + \sum_{i=1}^{7} \left(a_i \cos\left(i \frac{2\pi\lambda}{4\,\mathrm{FSR}_{NB}} \right) + b_i \sin\left(i \frac{2\pi\lambda}{4\,\mathrm{FSR}_{NB}} \right) \right) \tag{8}$$

Using a least-squares fit procedure, we can derive the a_i and b_i parameters. Figure 3 shows some results based on a detune sequence taken in March 2006. The intensity of the lamp must be stable and the lamp must have a white light spectrum. The phases and contrasts of the tunable elements are input parameters. Therefore, and also because of the relatively large number of parameters to fit for, this procedure might not give very accurate results.

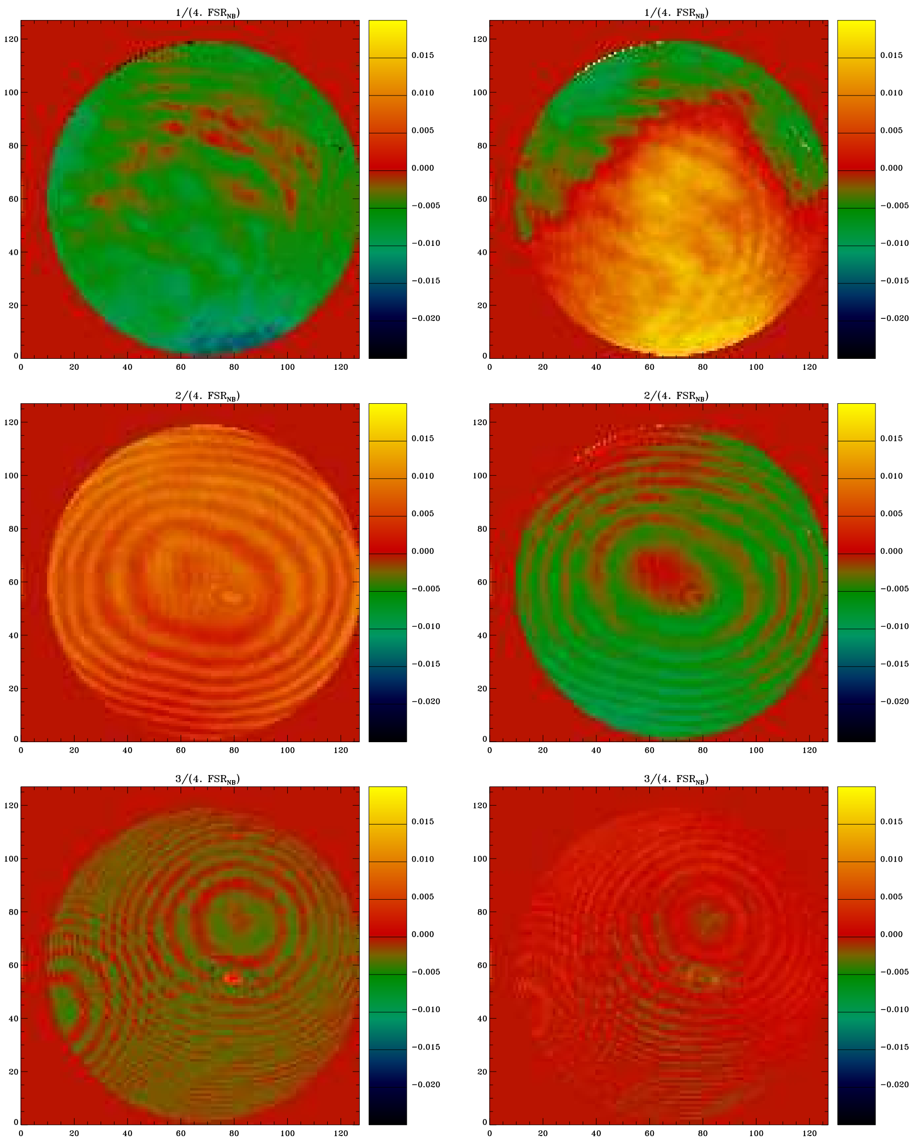

Fig. 3.— Interference pattern (fringes) due to the front window and blocker filter and captured in lamp light and Calmode on March 4, 2006. We show the cosine (left panels) and sine (right panels) Fourier coefficients for the first three frequencies.

1.1.4. I-ripple

Another use of the lamp light is to measure the potential I-ripples produced by the HMI filter: a wrong retardance or a wrong orientation of the half-waveplate in-between the two calcite blocks of E1, or a defective polarizing beamsplitter in a Michelson, can create a sinusoidal variation on the transmission profile of HMI. This variation is called an I-ripple and is easier to detect with the lamp. With the laser light, an I-ripple will appear as a change in the contrast of the defective tunable element as a function of the laser wavelength, while with the sunlight a faint sinusoidal variation may be observed on the spatially averaged intensity along the detune sequence. It must be noticed that because of the presence of the blocker filter, the transmission profiles of the tunable elements are not "orthogonal" anymore, and therefore we expect a small I-ripple with a peak-to-peak amplitude of the order of 1.5%. However, taking a detune sequence with the lamp light in Calmode and/or Obsmode is the easiest way to detect a larger-than-expected I-ripple and measure its phase and amplitude.

1.2. Determination of the Angular Dependence Properties

The transmission profile of each Lyot and Michelson element is expected to vary as θ^2, where θ is the incidence angle of the light rays onto the intrument. We need to characterize this wavelength drift as a function of the incidence angle and of the location on the filter aperture. Two different settings are required, one for the Calmode, one for the Obsmode.

In Calmode, we use the laser and a field stop of small diameter at the focal plan of the stimulus telescope that feeds the instrument. We take a detune sequence at each incidence angle. These incidence angles can be selected by moving the legs of HMI, even though this is a very slow method. It might be more convenient to just manually move the orientation of the light source. At each angle, the light rays cross a slightly different part of the HMI filter aperture. Therefore the intensity on a CDD pixel has a spatial dependence as well as an angular one. This must be accounted for when we analyze the data. An image taken in Obsmode shows the location of the laser dot and is used to accurately determine the angle of incidence of light rays.

In Obsmode, a plate with a hole must be inserted in between the instrument and the stimulus telescope (aperture stop). The radial distance of the hole to the center of the light beam determines the angle of incidence. The diameter of the hole determines the range of angles tested. An image taken in Calmode shows the location of the hole and is used to accurately determine the angle of incidence. Due to the hole plate, the path of light rays inside HMI differs from the usual situation where there is no plate. Moreover, like in Calmode, it also varies with the incidence angle. Consequently, two phenomena are again mingled: the transmittance of the HMI filter varies due to its dependence to the incidence angle, but also due to a spatial dependence to the path of the light rays inside the instrument. These two phenomena must be disentangled: we must make sure that the set of incidence angles we test for allows for a significant overlapping of the areas crossed by the light rays at each angle. For both modes, detune/cotune sequences must be taken

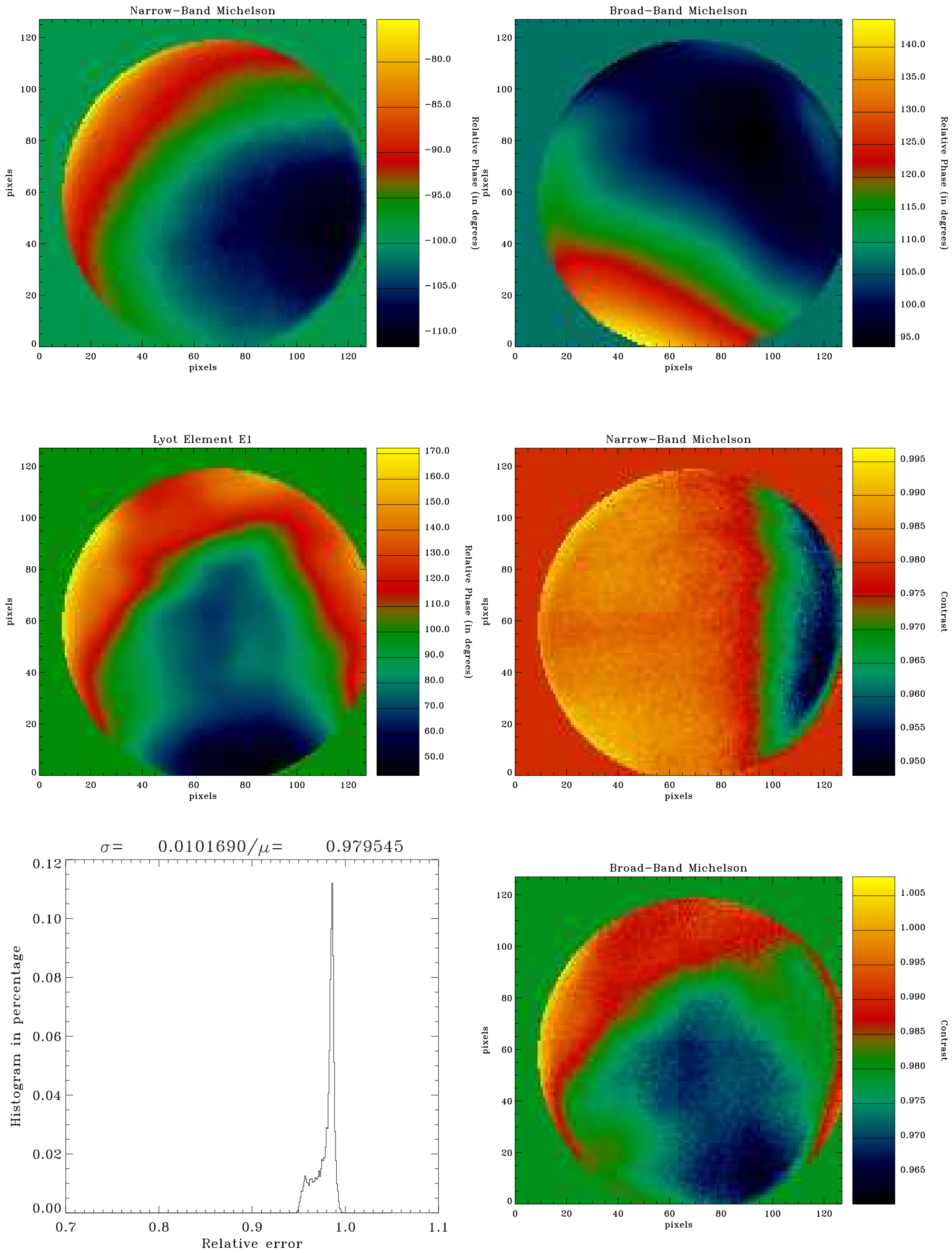

Fig. 4.— Phase ϕ and contrast B maps of the tunable Lyot elements obtained with a detune sequence in laser light and Calmode taken on June 20, 2006.

at different dye laser wavelengths, and a least-squares fit is performed to retrieve the phases and contrasts of the non-tunable elements. The laser intensity and wavelength must be

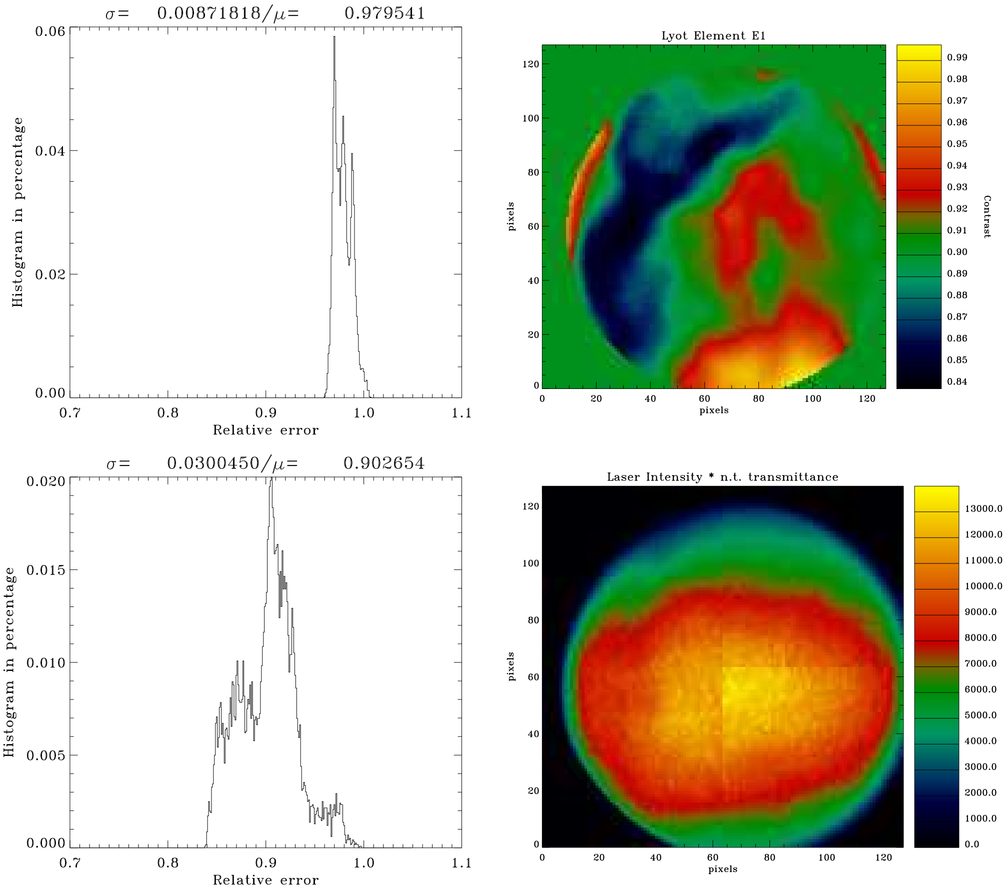

Fig. 5.— Phase ϕ and contrast B maps of the tunable Lyot elements obtained with a detune sequence in laser light and Calmode taken on June 20, 2006. The lower right panel shows the transmittance of the non-tunable part of the filter multipled by the laser intensity.

monitored, and several dark frames must be taken during the procedure to remove the dark current from the filtergrams. An analytical expression returns the phases and contrasts of the tunable elements from one detune sequence. A least-squares fit is necessary to retrieve the phases and contrasts of non-tunable elements from several cotune sequences taken at different wavelengths spanning the FSR of E5. The change in phases compared with the phases at zero incidence angle is directly related to the wavelength drift we want to characterize. Even though we do not expect any azimuthal dependence of the overall transmission profile of HMI, this assumption can be tested by selecting angles of incidence both in the vertical and horizontal directions.

A problem with this procedure is that we do not correct for the shift in the blocker filter transmission profile with the angle of incidence, which may contaminate the fitted phases of the non-tunable elements (no fit for the tunable ones, and no assumption regarding the blocker filter profile). The blocker filter is an interference filter and therefore if the incidence angle θ is not zero the transmission profile varies, and the shift in wavelength $d\lambda$ is:

$$d\lambda = \frac{\lambda_0}{2}\left(\frac{\sqrt{n^2 - n_e^2 \sin^2\theta}}{n} - 1\right) \tag{9}$$

where λ_0 is the solar Fe line central wavelength, n is the refractive index of the Fabry-Perot cavities, and n_e is the refractive index of the glass substrates surrounding these cavities. In a similar fashion, the interference fringes produced by pseudo Fabry-Perot cavities in the front window and the blocker filter also change with the incidence angle. This can be further studied by taking detune sequences with lamp light at different incidence angles, in both Obsmode and Calmode to separate the fringes due to the front window from those due to the blocker filter.

1.3. Determination of the Temperature Dependence Properties

In a first approximation, the transmission profile of each filter element drifts in wavelength when the temperature in the filter oven varies. To characterize this wavelength drift, we must take detune sequences at different temperatures spanning the range of the oven (*e.g.* 28, 30, and 35 degrees Celsius). This test needs to be performed in vacuum only, unlike the other calibration tests. The light source can only be the Sun or the lamp, for stability purpose (the dye laser is too unstable in wavelength to be able to detect a small drift). Again, we take a 27-position detune sequence at each temperature, and we only have access to the temperature dependence of the tunable elements. In sunlight, we can only perform the analysis in Calmode: the Obsmode images display too large a range of solar wavelength shifts. We fit for the phases of the tunable elements at the different temperatures, and as a function of the location on the filter aperture. The wavelength drift is related to the change in phase of each element as a function of temperature.

With the lamp, we can again fit for the Fourier coefficients of the non-tunable part of the HMI filter and see how the fringe pattern evolves with temperature, both for the blocker filter and the front window. To test the front window the oven temperature must remain constant while we take detune sequences at different room temperatures.