The Helioseismic and Magnetic Imager (HMI) on SDO: 
Full Vector Magnetography with a Filtergraph Polarimeter

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Abstract. We extend our previous work (Graham et al. 2002) to investi-
gate the diagnostic potential of polarimetric measurements with a filter-
graph instrument utilizing three different photospheric lines. Numerical 
simulations are used to determine the information content of the Ni I line 
at 6768 Å, the Fe I line at 6173 Å, and the Fe I line at 6302 Å when ob-
served with the filter set of the Helioseismic and Magnetic Imager (HMI). 
Simulations indicate the 6173 Å line is preferred over the 6768 Å line for 
magnetic measurements. We also include a preliminary look at observed 
solar profiles and find good indication that inversions on real data will be 
successful.

1. Introduction

The HMI (Helioseismic and Magnetic Imager) has been selected for the Solar 
Dynamics Observatory (SDO). It is a polarimeter that will image the entire so-
lar disk at 1" resolution with a 90 second cadence for measurement of the full 
Stokes vector. It will be a filter-based instrument that takes measurements at 
5 positions across a single photospheric absorption line with 90 mA filters (see 
Fig 1). These HMI measurements will improve upon the helioseismic accuracy of 
the Michelson Doppler Imager (MDI, Scherrer et al, 1995). Furthermore, using 
appropriate inversion techniques, it will be possible to infer the full vector mag-
netic field and its filling factor. This is not the approach taken with MDI, where 
only the line-of-sight magnetic flux over the effective MDI resolution element is 
inferred in the weak-field regime, assuming that the intensity profile from the 
magnetic atmosphere is proportional to the profile from the surrounding area. 
Many other filter-based polarimeters also assume unit filling factor: a damaging 
assumption when measuring magnetic elements smaller than the resolution of 
the telescope or when scattered light in the telescope can not be eliminated. In-
stead, our aim is to take the approach of an instrument like the Advanced Stokes 
Polarimeter (ASP, Elmore et al, 1992) which, however, spectrally resolves the 
Stokes vector across two photospheric lines. We recover the same information 
with only 20 total measurements across a single photospheric line, albeit with 
less accuracy.

In this paper we report on numerical simulations of the HMI filter set for 
three different lines to determine the so-called information content (best pos-
Figure 1. One possible configuration of the HMI filter set overlayed with the absorption line for 6768 Å (solid line). The central filter is 90 mÅ FWHM and the spacing is 76 mÅ between filter centers.

sible accuracy) for each candidate line. We also examine an ASP map taken simultaneously in 6301 Å - 6302 Å and 6768 Å. We compare these results with our simulations and make a line choice recommendation for HMI.

2. Numerical Simulations

We design numerical simulations to estimate the best accuracy obtainable with our 20 polarimetric measurements. For clarity, we emphasize we are not creating an inversion technique. We are instead measuring the information content of the polarimetric measurements—the best accuracy that any inversion technique would be able to obtain.

To this end, we simulate Stokes profiles with the Milne Eddington (ME) approximation for various magnetic field strengths, field orientations, filling factors and thermodynamic conditions. The ME atmosphere constitutes a good compromise between simplicity and applicability. When these conditions are not met, ME inversions often provide a mean value of the magnetic field over the line formation region (Westendorp Plaza et al., 1998). In addition, we consider that only a fraction, $f$, of our resolution element is occupied by the constant magnetic field (this also accounts for scattered light in the instrument). We then apply the HMI filters to each profile and add expected HMI noise, a polarization precision of $2.2 \cdot 10^{-3}$. This is what we call a simulated observation.

Now, to measure the information content of our simulated observation, we employ a weighted Levenberg-Marquardt (LM) least-squares minimization to fit Milne-Eddington models to our simulated observation (del Toro Iniesta & Ruiz Cobo, 1996). By starting our fitting technique from the same model parameters that produced the simulated observation, we can determine how much information was lost by the application of filters and noise. The difference between the initial model parameters and those found by the fit is labeled our error. This number should be useful for comparing the suitability of different lines for use with HMI.
The simulations are first conducted with the Ni I line at 6768 Å. We have generated more than 30,000 sets of model parameters from a sunspot and surrounding area (see Section 3). We have plotted the error for 6768 Å as the dotted lines in Fig. 2. The first thing to note is that full vector magnetography with a filtergraph polarimeter is possible with this line. Some information content survives the filtering and the observational noise. So, it is not necessary to ignore the filling factor with a filter-based instrument—the intrinsic magnetic field strength can be recovered. The next thing to note is that it works best when the flux density is between 1 and 2 kG. There, the error is less than 100 G and less than 2 or 3° in field direction. For flux densities below 1000 G, however, the accuracy is reduced. The magnetic field strength accuracy is only ± 300 G and the field direction accuracy is ± 30°.

It is no surprise that we do not have the 20 G and 1° accuracy of ASP but it is reassuring that so much of the information is left with only 5 filter positions. Much more is possible than just measuring the line-of-sight flux under limited circumstances.

Two lines are currently under consideration for HMI: the Ni I line at 6768 Å and the Fe I line at 6173 Å. These lines are of interest due to their clear continuum. We simulate results for these two lines and the Fe I line at 6302 Å. The latter is interesting because of its popular usage in spectropolarimetry. However it is not useful for HMI due to the proximity of the Fe I line at 6301 Å. Accuracies are plotted in Fig. 2 for 6173 Å (solid line) and 6302 Å (dashed line). It is immediately obvious that 6768 Å has the worst performance for measuring magnetic fields. Both of the other lines have ± 100 G accuracy for a wider range of flux densities than does 6768 Å. The improved accuracies for these lines are likely due to greater Landé factors as well as line
depths. The effective Landé factors for 6173 Å, 6302 Å and 6768 Å, are 2.5, 2.5 and 1.43, respectively.  

In Fig 3 we plot the estimated information content for HMI in ‘magnetograph mode.’ That is, we simulate using only the information in Stokes I and V by weighting Q and U to 0. We see that better accuracy is obtainable with 6173 Å for both velocity and longitudinal flux density measurements than with 6768 Å.

![Graphs](image)

Figure 3. Information content for Fe I 6173 Å (solid) and Ni I 6768 Å (dashed) in numerical simulations using only Stokes I and V. Left panel is velocity error versus model velocity. Right panel is longitudinal flux density, $F_L$, error versus apparent flux density.

3. Observations

Here we present the first application of our work to actual solar observations. The observations are a map of a ‘delta’ sunspot and surrounding area (AR 9866 S9W65 on 10 March 2002) obtained with ASP, taken simultaneously in 6768 Å and the 6301 Å / 6302 Å line pair. This data was used as a reference to create the simulations in Section 2. To use the observations as a test for HMI we apply the simulated HMI filters to these data. The anticipated HMI noise is not added at this time in order to first see the effect of the filters alone.

We must supply our LM inversion with an initial guess. For convenience, we use ASP results as the initial guess for field strength, field direction, and the filling factor and quiet sun values as the initial guess for thermodynamic parameters. In Fig. 4, the results of the LM filtergraph inversion are plotted along with the ASP uncertainties and the simulation results of Section 2.

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1 During the proofs of this paper we found an unfortunate error in the quantum numbers of the transition for 6173 Å. The result is that the effective Landé factor was changed from 2.5 to 1.5. Additionally, a separate error was made while generating model parameters using the ASP map of Section 3 as a reference. After correcting for these errors, we still find that 6173 Å performs nearly as well as 6302 Å and that 6768 Å performs substantially worse for magnetic measurements. The exception being between 1 kG and 2 kG flux density where all three lines perform similarly. The effect of these corrections on velocity accuracies is yet to be determined. Lastly, these errors have no bearing on the observational results.
Figure 4. 68% confidence intervals for the difference between the filtergraph inversion and the ASP inversion (solid line), the ASP estimated uncertainties from the two line inversion (dashed line), and the simulation results from Fig 2 (dotted line). 6302 Å field strength results (upper left) and field inclination to line of sight (upper right). 6768 Å field strength results (lower left) and field inclination to line of sight (lower right).

For the 6302 Å line observations we see that, above 500 G, the filtergraph inversion result is less than 2° outside of the ASP uncertainty range (azimuth results are not shown, but they are better). We also see that above 1800 G, the magnetic field strength is recovered to within 100 G of ASP uncertainties. The estimates of magnetic field strength for moderate flux densities leaves much to be desired (recall HMI noise is not yet applied). It is worthwhile to recall that a significant difference in magnetic field strength estimates is introduced by observing a single photospheric line (Lites et al. 1994). This explains much of the difference between the ASP uncertainties and the simulation results (see Fig. 5). While the lack of accuracy in field measurements may be due to our initial guess in addition to limitations on inferences from real solar data, we can only conclude that filtergraph inversion results may differ from ASP inversion results by 300 G except for strong magnetic fields. We point out that the capability to determine accurate field directions (inclination and azimuth) exists for a wide range of flux densities.

For the Ni I line at 6768 Å, the range of flux densities over which the filtergraph inversion has an accuracy of a few degrees in field direction is reduced in comparison with 6302 Å, but not by much. There is good agreement for this line between the filtergraph inversion and the ASP inversion. That is, the difference between the two is not more than 100 G greater than the ASP uncertainty except for very small polarization signals. This leaves little hope of improving filtergraph inversion results with this line. The conclusion from these observations is the same as for the simulations—6302 Å performs better
than 6768 Å for magnetic measurements both below 1 kG and above 2 kG flux density.

Figure 5. Comparison of one line inversion vs two lines inversion. The lines are Fe I 6301 Å and Fe I 6302 Å. The data here are inverted by ASP.

4. Conclusions

With both observational data and numerical simulations, we have compared magnetic field estimates for 6768 Å and 6302 Å. Below 1 kG and above 2 kG flux density, we have demonstrated inferior performance for 6768 Å. We have demonstrated with simulations that the filtergraph polarimeter performance of 6173 Å should be satisfactory and similar to the performance of 6302 Å if that line had clean continuum. We have shown with observational data of this latter line that filtergraph inversions can be achieved. There will be a discrepancy between inversions with such an instrument and those of ASP due to the instrumental constraint of observing only one photospheric line, but those are minimized with the choice of a line like 6173 Å. These results point to 6173 Å for the line selection of HMI.

References


