Information of Spectral Lines FeI 6173Å, FeI 6302Å and NiI 6768Å

ABSTRACT

This technical note presents information on the spectral lines FeI 6173Å, FeI 6302Å and NiI 6768Å collected from previous papers, observations, and simulations. The FeI 6173Å and NiI 6768Å lines are candidates to be used in the Helioseismic Magnetic Imager (HMI) for observation of the Doppler velocity and the vector magnetic field. Information on the 6302Å line is included because it is considered the benchmark in observing vector magnetic fields. The performance of each line for vector magnetic field and Doppler velocity measurements is evaluated.

Subject headings: Instrument: spectral lines; Sun: velocity and magnetic field.

1. Requirements of Spectral Line for HMI

HMI needs to accurately measure Doppler velocity and vector magnetic field with limited spectral information, sampling roughly half a dozen wavelengths across the line. The spacecraft is expected to have a large velocity range of ±4000 m/s. Therefore, the first requirement for choosing a spectral line is that it contain a clear continuum with no blends and no near-by lines. Helioseismology also requires that a spectral line be narrow and deep since a steep dI/dλ ensures greater sensitivity to small Doppler shifts. The NiI 6768Å line satisfied these requirements and was selected as the operating spectral line for the Michelson Doppler Imager (MDI) and Global Oscillations Network Group (GONG) instruments.

Vector magnetic field measurements benefit from a high Landé factor, $g_{eff}$, and a simple Zeeman splitting geometry. It is also important to minimize the number of blends that become apparent in sunspot umbra where the lower temperatures allow for molecular absorption. Due to satisfying these requirements and others, the FeI 6302Å and 6301Å line pair was selected for use in the Advanced Stokes Polarimeter.

Also, an understanding of the center-to-limb variations of the selected spectral line is important because the accuracy of 'look-up' algorithms (such as used by MDI) are based on line depth and wing slope parameters. In addition, it is desirable for a line to be insensitive to thermodynamic changes so that heights of formation don’t drastically change due to moderate perturbations of temperature and density. Of course, optimum transmission at the selected wavelength is also a requirement.

2. General Information of FeI 6173Å, FeI 6302Å and NiI 6768Å

2.1. Parameters of FeI 6173Å and NiI 6768Å

Five papers (Stenflo and Lindegren, 1977; Auer et al, 1977; Simmons et al 1982; Solanki and Stenflo, 1985; Landi Degl'innocenti, 1985) discuss solar spectral lines that include FeI 6173Å, and two papers detail NiI 6768Å (Jones, 1989; Bruls, 1993). The parameters of the first four columns of Table I are from these papers; there are slight differences in line width of the FeI 6173Å (0.103 Å in Simmons et al. paper (1982); 0.099Å in Stenflo et al. s paper (1977); 0.100 from direct measurement of the FWHM based on Kitt Peak
data, and 0.106Å from direct measurement of the Equivalent Width based on Kitt Peak data), and of the NiI 6768Å (0.110Å from direct measurement of the FWHM based on Kitt Peak data, and 0.121Å from direct measurement of the Equivalent Width based on Kitt Peak data). The values in Table I are the averages of the above values.

The heights of line formation of these two lines are estimated using Maltby-M umbral model (Maltby, et al., 1986) and VAL-C model (Vernazza, et al., 1973; 1976; 1981) under non-LTE assumption. Stokes profiles were simulated using a non-LTE numerical radiative transfer code (Uitenbroek, 2001) based on the multilevel accelerated lambda iteration (MALI) formalism of Rybicki and Hummer (1991). All calculations were made in a 1-dimensional plane parallel geometry. The model atoms used were a 52 level atom used for Fe calculations and a 25 level atom used for Ni. A magnetic field gradient observed by Socas-Navarro (1999) in a sunspot was used in conjunction with the Maltby-M umbral atmosphere for height of formation calculations. The calculated results are listed in the last two columns of Table I.

Table 1: Parameters of FeI 6173Å and NiI 6768Å

<table>
<thead>
<tr>
<th>Wavenum. (Å)</th>
<th>g_{eff}</th>
<th>Excit. Pot. (eV)</th>
<th>Depth</th>
<th>FWHM (Å)</th>
<th>Height(core) (km)</th>
<th>Height(cont.) (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeI 6173.21</td>
<td>2.499</td>
<td>2.22</td>
<td>0.62</td>
<td>0.102</td>
<td>302 (VAL-C)</td>
<td>16 (VAL-C)</td>
</tr>
<tr>
<td>NiI 6767.68</td>
<td>1.426</td>
<td>1.83</td>
<td>0.53</td>
<td>0.116</td>
<td>288 (VAL-C)</td>
<td>18 (VAL-C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>291 (Maltby-M)</td>
<td>26 (Maltby-M)</td>
</tr>
</tbody>
</table>

The calculations of NiI 6768Å height of formation agree well with other literature sources, but the FeI 6173Å heights differ from Bruls (1990). Bruls values are (using VAL-C model) h=238 (core) in quiet Sun and (using Maltby-M model) h=386 (core) in umbrae for FeI 6173Å.

2.2. Line Profiles in Sunspot Umbrae and in Quiet Sun

Line profiles of FeI 6173Å, FeI 6302Å, and NiI 6768Å in sunspot umbrae and in quiet Sun have been scanned by the Kitt Peak McMath telescope and 1m Fourier transform spectrometer. These data are available at ftp://argo.tuc.noaa.edu/pub/atlas. Using these data, we plot the lines in the same scale for comparison (see Figure 1, Figure 2 and Figure 3). The upper panels of these figures show the lines in the quiet Sun (thick) and in umbrae (thin), and the bottom panels show the transmission (dashed) and the lines in umbrae (solid). The blends marked in the figures were identified at the Kitt Peak National Solar Observatory.

The profiles of these lines in the quiet sun are relatively clean. NiI 6768Å has no nearby lines or blends. FeI 6173Å has a blend 0.6Å away from the center of FeI 6173Å identified as LaII, which is at 6172.72Å. This LaII blend is the transition of 3F3 - 3F2 where the lower level excitation potential is 0.13 eV and the effective g-factor is 1.50. There are many Zeeman components (15-plet). It doesn’t simply split, it broadens as shown in the photographic sunspot atlas. Simulations have been done to estimate the LaII blends influence on Doppler velocity measurement. Results shows that the errors induced by this blend are very small.

Since HMI will make vector magnetic field observations, the behavior of these lines in umbrae are of
Fig. 1.— Upper panel: line profile of FeI 6173 Å in umbrae (thin line) and in quiet Sun (thick line); Bottom panel: instrument transmission (dashed) and observed umbral profile (solid).

interest. In considering the umbral profiles, it is important to realize that almost all umbral profiles are contaminated by molecular blends because the lower temperature of the sunspot allows for such spectral absorption not present in the quiet Sun spectra. The FeI 6173 Å umbral profile shows an obvious blend in the blue wing which is marked as R_{1/2} both on the NSO atlas and in Figure 1. This blend is invisible in the quiet Sun spectra. This blend is EuII at 6173.0 Å and there are other two blends close to this line (see Figure 1). NiI 6768 Å observations in umbras have shown an obvious blend suggested to be TiO; and two other blends near this line (see Figure 2).

The profile of FeI 6302/6301 Å pair are shown in Figure 3 for comparison (lines are actually located at 6302.5 and 6301.5 Å). Several blends are present and are noted on the spectra. A ScII line is identified and found at 6300.6 Å. The Zeeman splitting is obvious in the umbral profiles.
2.3. Trade-off Between Landé Factor and Velocity Range

There is a trade-off between a line with higher $g_{eff}$ and having a greater velocity range in which the velocity calculation algorithm performs well. Having a line with a higher $g_{eff}$ means that the Zeeman splitting is greater and the effective velocity range is smaller when in the presence of a high magnetic field. When the velocity algorithm no longer responds linearly to the Doppler shift due to one wing of the line profile moving out of the spectral sampling range, this is called 'saturation'. (Note, this is distinctly different from the saturation of Zeeman splitting with increasing field strength.) For example, FeI 6173Å will reach 'saturation' at 7 km/s or with a magnetic field of 3 kGauss. NiI 6768Å will reach 'saturation' at 6 km/s or with a magnetic field of 4 kGauss. The difference between magnetic field at which saturation occurs for these lines is that FeI 6173 has a $g_{eff}$ of 2.5 while NiI 6768 has a $g_{eff}$ of 1.5.
Fig. 3.— Upper panel: line profile of FeI 6302Å in umbrae (thin line) and in quiet Sun (thick line); Bottom panel: instrument transmission (dashed) and observed umbral profile (solid).

3. Observations of FeI 6173 Å and NiI 6768 Å

3.1. Mt. Wilson and ASP Observations of FeI 6173Å

FeI 6173Å line was scanned at Mt. Wilson for quiet sun regions on December 4, 2002, with the KDP analyzer in the beam, see Figure 4. Each profile is a composite obtained by combining the profiles from all 10 channels which scanned the line. The center of the 10-channel head was centered on the solar line so that channels on the edge of the head were offset from the line center. The scanning is alternatively red to blue then blue to red. Each scan takes 15 seconds. The sequence goes for 80 scans or 20 minutes. Thus all these profiles are smeared by the oscillations. The resulting profiles are shown in Figure 4 for three center-to-limb angles; 0, 45 and 60 degrees.

Stokes parameters I, Q, U, and V were acquired by by the Advanced Stokes Polarimeter (ASP) on 2002 March 9. Active region NOAA 9856, located at S3W4, was observed using the Fei 6302/6301Å line pair in channel A and FeI 6173Å line in Channel B. The line profiles of FeI 6173Å in the umbra in circular polarizations are shown in Figure 5. Also plotted in this Figure is the Stokkers I in black, as reference. The profiles are the average of the profiles over 100 pixels in this umbra.
Fig. 4.— The line profiles of FeI 6173Å obtained at Mt. Wilson for the quiet sun regions with the KDP analyzer in the beam. The resulting profiles are shown in this plot for three center-to-limb angles; 0, 45 and 67 degrees.

Fig. 5.— FeI 6173Å observed by ASP. LCP and RCP profiles are shown as well as Stokes I. The profiles shown here are an average over 100 pixels in the umbra.
3.2. Mt. Wilson Observations of NiI 6768Å

Fig. 6.— Comparison of the NiI 6768Å line observed at Mt. Wilson in umbra with a portion of the FTS sunspot atlas.

The umbral NiI 6768Å line profile was scanned at Mt. Wilson (see Figure 6) and compared to the FTS sunspot atlas. The line profiles of the NiI 6768Å for the quiet Sun were also obtained in 1991 at Mt. Wilson for the quiet sun regions without the KDP analyzer in the beam. The resulting profiles are shown in Figure 7 for three center-to-limb angles; 0, 45 and 60 degrees, with a magnetic field strength of, respectively, 0.0, 0.23, and 7.68 Gauss.

Left and right circular polarization of NiI 6768Å are shown for umbral observations in Figure 8.
Fig. 7.— The line profiles of Ni I 6768Å obtained in 1991 at Mt. Wilson for the quiet sun regions without the KDP analyzer in the beam. The resulting profiles are shown in this plot for three center-to-limb angles; 0, 45 and 60 degrees.

3.3. MDI Filtergraph Polarization Signal

In a special observation run, MDI demonstrates that strong transverse field signal can be measured using a filtergraph observations in multiple polarizations. Figure 9 shows observations taken by this run. Since MDI is unable to observe U, only Q is shown. As can be seen, a clear polarization signal can be observed. In the averaged image, linear polarization is visible in the plage.

3.4. Parameters for the lines Fe I 6173Å and Ni I 6768Å

The line depth, width, equivalent width, and slopes for the red and blue wings for the spectral lines Fe I 6173Å and Ni I 6768Å for the quiet sun have been measured, calculated from the Mt. Wilson data shown in Figures 4 and 7 (see Figure 10). The line depth and width are defined here as the height and width of a Gaussian function which fits the observed line profile. Since measurement for Fe I 6173Å was only made at three positions, 0°, 45°, 60°, in the quiet sun, we used the Ni I 6768Å data at the same positions for a comparison. The variation of these parameters with the distance from the solar center still characterizes the center-to-limb variation of these lines, though only three sets of data for each line are available (Figure 10). Basically, the line depths for both lines linearly decrease with the cosine of the center to limb angle, the line widths linearly increase, and the equivalent widths slightly increase. The line depth of Fe I 6173Å is generally 2% deeper than that of Ni I 6768Å, and the line width of Fe I 6173Å is 15% narrower than that of Ni I 6768Å. The equivalent width of Fe I 6173Å is 6% smaller than that of Ni I 6768Å. The slopes for the red wings of the two lines are generally greater than those for the blue wing; while the slope of Fe I 6173Å is
Fig. 8.— NiI 6768Å line in left and right circular polarizations observed at Mt. Wilson.

Fig. 9.— MDI observations of AR9516 on Jun 27, 2001. From left to right: continuum intensity, line of sight magnetogram, Q/I in a single tuning position and a derotated average of Q/I over 43 observations. Note that the grayscales are not linear in order to accommodate the large dynamic range. The field of view is roughly 90Mm squared with disk center towards the lower right.
greater than that of NiI 6768Å.

Fig. 10.— Center-to-limb variation of the lines FeI 6173Å and NiI 6768Å in quiet Sun observed at Mt. Wilson. The x-axis is the central meridian distance of the observations as in $\mu=$cos($\theta$).

3.5. Comparisons of NiI 6768Å/FeI 6302Å and FeI 6173Å/FeI 6302Å in Vector Magnetic Field Measurement

Comparisons of ASP inverted data for NiI 6768Å and FeI 6173Å lines show how well the lines perform for the purpose of vector magnetometry. ASP inversions are a least squares fitting based on the Milne Eddington solution of the Unno-rachkovsky equations of a plane parallel magnetized radiative transfer of the Stokes line profiles. Normal ASP operation utilizes the 6301.5Å and 6302.5Å FeI line pair. However, another spectral line can be observed simultaneously in another channel. On 2002 March 9 a map of an active region was made by scanning the ASP spectral slit across the sunspot observing with the FeI 6302Å/6301Å line pair in channel A and 6173Å FeI line in Channel B. This map of NOAA 9856, located at S3 W4, was made at 19:27 UT. On 2002 March 10 a map of another active region was made observing with the FeI 6302Å/6301Å line pair in Channel A and 6768Å NiI line in Channel B. This map of NOAA 9866, located at S9 W65, was made at 18:58 UT.

Figure 11 shows the magnetic inclination (Psi) in degrees from the inversion of the NiI 6768Å line and the FeI 6302Å/6301Å lines which were recorded simultaneously during observation of a limbward active region (NOAA 9866) on 2002 March 10, and the results from the inversion of the FeI 6173Å line and the FeI
Fig. 11.— This figure shows the scatter plots of the magnetic inclination (Psi) observed simultaneously in different lines. The left panel shows Psi for NiI 6768Å vs FeI 6302Å/6301Å for the active region observed on 2002 March 10, and the right one shows the Psi for FeI 6173Å vs FeI 6302Å/6301Å for the active region observed on 2002 March 9 (right).

6302Å/6301Å lines which were recorded simultaneously during observations of a disk center active region (NOAA 9856) on 2002 March 9.

Figure 12 shows the scatter plots of the values observed simultaneously in different lines. The top two panels show field strength values for NiI 6768Å vs FeI 6302Å/6301Å for the same region observed on 2002 March 10 (on left), and field strength for FeI 6173Å vs FeI 6302Å/6301Å for the active region observed on 2002 March 9 (right). The lower plots are scatter plots in filling fraction (FF) for the same lines and dates.

If we assume that the values determined from the dual line inversion of FeI 6302Å/6301Å are the 'true' values, then it is obvious that FeI 6173Å performs better as a vector field diagnostic than NiI 6768Å. This comparison indicates that the higher Landé factor, $g_{eff}$, in FeI 6173Å enables a much better determination of vector magnetic field and filling fraction.

The large difference in ASP uncertainties for the an inversion using two spectral lines (FeI 6301/6302Å) and an inversion using a single spectral line deserves some comment. Figure 13) shows correlation plots of single line inversion results verses two line results. We see larger discrepancies for single line results with a lower $g_{eff}$ (about 1.5 for 6301) than for a single line with larger $g_{eff}$ (2.5 for 6302). This highlights the necessity for any single line inversion instrument to use a line with a large $g_{eff}$.

In summary, these observations demonstrate that the line FeI 6173Å has much better performance than the line NiI 6768Å in measurement of vector magnetic field.
Fig. 12.— This figure shows the scatter plots of the values observed simultaneously in different lines. The top two panels show field strength values for NiI 6768Å vs FeI 6302Å/6301Å for the same region observed on 2002 March 10 (on left), and field strength for FeI 6173Å vs FeI 6302Å/6301Å for the active region observed on 2002 March 9 (right). The lower plots are scatter plots in filling fraction (FF) for the same lines and dates.
Fig. 13.— Comparison of one line inversion vs two lines inversion. The lines are FeI 6301Å and FeI 6302Å. The data used here are taken by ASP.
4. Simulation of Line Performance Using Artificial Profiles; Artificial Filters

While the full inversion algorithm is still under development, it is possible to determine the information content of filter-polarimetry data and hence to quantify the performance limit of any algorithm applied to HMI. The filter profiles are the same as the filter profiles in the HMI proposal. To measure this information content, the magnetic Sun is represented by Milne-Eddington (ME) atmospheres and solar profiles are simulated using the ME approximation for field strengths, filling factors, and ME thermodynamic parameters that reasonably represent Solar observations. All field directions are investigated and velocity effects are included. An observation is simulated by applying filters and measurement noise. An inversion seeded with the pre-noise input ME parameters is then computed. The differences between the inversion result and the input ME parameters are taken as a measure of the performance of the proposed instrument based on the instrument filters and on photon noise. The noise is taken to be the 0.22 % polarization precision anticipated for HMI. All error values reported are 68 % confidence intervals taken from the statistics of the errors.

![Graphs showing flux density and velocity distributions](image)

Fig. 14.—Simulated profiles model parameters. These model parameters were taken from filtergraph fits to the ASP observation of NOAA 9866 on 2002 March 10. The top panels are histograms of flux and velocity for NiI 6768Å simulations. The bottom panels are the same but for the FeI 6302 Å and FeI 6173Å simulations which used the same magnetic model parameters.

The artificial profiles in this section are generated from parameters obtained from the data shown in Figure 14. This was done in the hopes that the artificial profiles generated would be as close to actual solar profiles as possible.

4.1. NiI 6768 Å

As can be seen from the histograms of model parameters employed (the top panels of Figure 14), not all spacecraft velocities are investigated in this particular data set. Instead, velocities from -1 km/s to -5 km/s are investigated just as in the actual ASP data (see Figure 14). This is done so that we can develop
an idea how the errors change when we move from ideal, simulated data to actual solar data.

![Graphs showing performance comparison](image)

Fig. 15.— Performance comparison for FeI 6173Å (solid), FeI 6302Å (dotted) and NiI 6768Å (dashed). The top panels are velocity errors versus model parameter (flux density) and model parameter (velocity). The bottom panels are errors versus flux density for magnetic field strength, and inclination of the magnetic field to the line of sight. These are results for simulated profiles.

The distribution of input total flux densities extends from 200 G to 2200 G. This will be the horizontal axis in most of our plots.

The errors of measurements vs filter spacing are also estimated. The filter spacing was changed from 76 mÅ to 95 mÅ and 113 mÅ. The 76 mÅ spacing has the best performance and by 113 mÅ some of the line center is no longer sampled.

The dashed line in Figure 15 shows the 6768Å velocity errors as a function of flux density and velocity, the magnetic flux and inclination errors as a function of flux density. The dashed line in Figure 16 shows the 6768Å errors in azimuth, filling factor, longitudinal flux and transverse flux as a function of flux density. Azimuth error is about 2° above 1 kG and filling factor errors are very small in that range. The longitudinal flux density ($F_L$) is about 20 G and the transverse flux density ($F_T$) is about 50 G in the 1 to 2 kG range.

### 4.2. FeI 6173 Å

The artificial profiles in this section are generated from parameters obtained from FeI 6302Å data. Milne-Eddington thermodynamic parameters have been scaled to simulate FeI 6173Å. This was done to ensure that the artificial profiles generated would be as close to actual solar profiles as possible.

This data set contains nearly 10 times as many experiments for which the input flux density is near 0 G (see the bottom panels of Figure 14). It also contains 46844 experiments as opposed to the 34308 experiments in the NiI 6768Å data set. This is an artifact of the ASP analysis used to generate the model parameters for the artificial profiles. The data distribution between 200 G and 2500 G is about the same.
Fig. 16.— Performance comparison for FeI 6173Å (solid), FeI 6302Å (dotted) and NiI 6768Å (dashed). All panels are errors versus flux density. The top panels are magnetic field azimuth and fill fraction. The bottom panels are longitudinal flux density and transverse flux density.

The same simulation as for NiI 6768Å was performed, and the results are presented in Figure 15 and Figure 16. The solid line in Figure 15 shows the 6173Å velocity errors as a function of flux density and velocity, the magnetic flux and inclination errors as a function of flux density. The solid line in Figure 16 shows the 6173Å errors in azimuth, filling factor, longitudinal flux and transverse flux as a function of flux density.

The errors of measurements vs filter spacing are also estimated. Again, the 76 mA of filter spacing has the best performance among three spacings of 76 mA, 95 mA and 113 mA, as for NiI 6768Å.

4.3. FeI 6302Å

The same distributions of flux density and velocity were used here as for the FeI 6173Å simulations, and the results are presented as dotted lines in Figure 15 and Figure 16.

4.4. Comparison of FeI 6173Å , FeI 6302Å and NiI 6768Å

Simulations setting Q and U to be ignored by the inversion code were run to estimate line suitability in the I+V, I−V 45 second MDI-like mode for FeI 6173Å and NiI 6768Å. The results shown in Figure 17 are very favorable for FeI 6173Å.

Figure 15 and Figure 16 show comparison of the performances of those lines. These results indicate that magnetic information content for FeI 6173Å and FeI 6302Å are better than for NiI 6768Å as might be expected from the $g_{eff}$ of the lines. (FeI 6302Å is slightly better than FeI 6173Å). What might be surprising,
Fig. 17.— Errors for FeI 6173Å (solid) and NiI 6768Å (dashed) in simulations using only Stokes I and V. Top panels are velocity errors versus model parameter (velocity) and model parameter (flux density). Bottom panels are longitudinal flux density errors versus velocity and flux density.

Fig. 18.— Error estimates based on ASP observation in FeI 6302Å. Simulation is performed using filtergraph mode.
however, is that they also indicate the velocity information content for FeI 6173Å is more accurate than for NiI 6768Å. FeI 6302Å has distinctly better $F_T$ performance than FeI 6173Å.

Another comparison of the line performance is shown in Figure 17 where only Stokes I and V information is used in the simulations. Errors in the FeI 6768 line are higher then FeI 6173 everywhere excepting $F_L$ at velocities lower than -5000 m/s when presumably the FeI 6173 line moves out of sampling range. In summary, these simulations indicate that the performance of FeI 6173Å is better than that of NiI 6768Å for both velocity and vector magnetic field observations.

5. Simulation of Line Performance Using Artificial Profiles; Artificial Filters; MDI-like Algorithm

Performance of the lines FeI 6173Å and NiI 6768Å for measurement of Doppler velocity and magnetic field is estimated by using artificial line profiles, artificial filter profiles, and a MDI-like algorithm. The line profiles of FeI 6173Å, NiI 6768Å used in this section are the same as in the previous section, which are generated from the parameters from observation shown in Figure 14. Artificial filters are applied to these profiles, and a MDI-like algorithm is performed to calibrate measurements into velocity, magnetic field. The resolution of the filters are the same for the two lines. In other words the filter widths are proportional the wavelength.

The first plots of Figure 19- 20 show filling factor versus magnetic strength. Note that in both cases about half the points have a filling factor of 1. An important thing to note is that the distributions of model parameters are vastly different. Both parameter sets are heavily weighted towards active regions, in particular for the Ni simulations which have essentially no quiet Sun (for example, filling factor below 0.2 and field below 1.5kG). This makes it difficult to judge what happens to the helioseismology.

For the simulated velocities, since the dynamic range of the input profiles was quite limited each profile is shifted by a random number of input wavelength steps to obtain a total dynamic range of just over +/- 4km/s. All the velocity results were done using Stokes I only.

To estimate the velocity from the input intensities, $I_i, i=1,\ldots,5$, a simple "MDI-like algorithm", $V=f((\text{sum } c_i I_i)/(\text{sum } d_i I_i))$, is used, where $c_i$ and $d_i$ are suitably chosen constants and $f$ a suitably chosen function. The choice of constants and function determines the noise level and the sensitivity of the velocity to other parameters (what one might call the linearity). It turns out that the linearity appears to be much more sensitive to the choices than is the noise. At least for the choices which on average give the correct results. It also turns out that it is not too difficult to find the optimal choice since there are really only two coefficients to determine and the function can be determined separately. The coefficients and the function were optimized to limit the scatter for the points with $|B| < 4kG$ and $|V | < 4km/s$. The function $f$ was chosen to make the response to the quiet Sun as good as possible.

For 5 observations there are two substantially different solutions to the optimization. However, it appears that almost all the information is in the one used here. The other solution also works poorly for large filling factors and fields.

The second plots in Figure 19- 20 show the noise as a function of velocity. An exposure level of 125000e− is used for this simulation. The points faintly visible on a line are those for zero filling factor. It is interesting that for the Ni line the noise gets worse in the presence of field while it gets better for the Fe line! This is probably because the equivalent width becomes larger for the Fe line. This would seem to explain why the
results shown in the previous section are so much better for Fe than for Ni. But it is worth to notice that the noise performance is virtually identical for the two lines in quiet Sun.

Next plots show the velocity error as a function of input velocity. While the scatter may seem very large the errors are quite small for the quiet Sun (fillingfactor $< 0.2$ and $B < 1.5kG$), as shown in the next plots. For whatever it is worth 68% of the points are within +/-4.2m/s for the Fe line and +/-12m/s for the Ni line. But given the different parameter distributions it is really difficult to draw any conclusions.

Finally the last two plots show the ability to measure the line of sight field, or whatever one might want to call $B^*$filling$^{*}\cos($incl$)$. The field scaling was chosen to give a linear response for the pixels with nearly line of sight field and 100% filling factor.

It should be mentioned that some tests were also done for different filter widths. As expected increasing the widths improves the dynamic range while increasing the noise. Also the Lyot filter width matters little.

In summary, It is shown that with ‘MDI-like’ algorithm the Fe line at 6173Å has a better performance for measuring magnetic field than the Ni line at 6768Å, and for the Ni line the noise becomes worse in the
Fig. 20.— Performance of NiI 6768Å for measurement of Doppler velocity and magnetic field using artificial line profiles, artificial filter and a ‘MDI-like’ algorithm.

presence of magnetic field and it gets better for the Fe line while they have a similar noise performance in the quiet sun. As addressed before, since the model parameters for these two lines are sufficiently different, it is difficult to draw any other conclusions so far.

6. Simulation of Line Performance Using Observed Profiles; Artificial Filters

Artificial filters are numerically applied to observed ASP profiles in an attempt to quantify any effect asymmetries, molecular blends, etc. will have on the accuracy obtainable from the data. The observed profiles are from the ASP map of NOAA 9866, located at S9 W65, made at 18:58 UT on 2002 March 10. ASP’s polarization precision is .05% per pixel. No noise is added to the current experiments to degrade that precision to the HMI level of .22% per filter.
6.1. FeI 6173 Å

Is in progress.

6.2. FeI 6302 Å

Figure 18 shows error estimate from ASP results and filtergram simulation based on ASP observation. Errors shown as solid lines are 68% confidence intervals of the difference between ASP results and filtergram results. The 68% confidence intervals for ASP (two-line inversion) uncertainties are shown as dotted lines. Filtergram inversion flux density is chosen for the horizontal axis because flux densities were not available for ASP results. Errors from the simulation for FeI 6302 Å are shown as dashed lines for comparison to earlier simulations.

We can see that the filtergram approach recovers the field inclination to within a few degrees of ASP accuracy above 500 G. The azimuth results is within one degree of ASP accuracy down to 250 G. Indeed, for low flux densities, the azimuth result is closer to the ASP result than the magnitude of its simulated error. The |B| results are significantly worse than those predicted by the simulation which predicts we could approach ASP accuracy for flux densities greater than 750 G. Part of these greater errors are due to the fact that we now are looking at real solar data with asymmetries, molecular blends, etc. not considered in our earlier simulations. Another part is the fact that the simulations are determining information content only, not accuracy of a method. Once an initial guess algorithm is developed for the filtergram technique, these errors could increase or decrease.

Fig. 21.— Error estimates based on ASP observation in NiI 6768 Å. Simulation is done in filtergram mode.
Fig. 22.—Comparison of errors for lines FeI 6302Å and NiI 6768Å. The data for the filtergraph simulation are taken by ASP.

6.3. NiI 6768 Å

Errors shown as solid lines in Figure 21 are 68% confidence intervals of the difference between ASP results and filtergraph results. The 68% confidence intervals for ASP uncertainties are shown as dotted lines. As before, flux density is chosen for the horizontal axis. Simulation errors are shown as dashed lines for comparison to earlier simulations. We can see that filtergraph results already approach ASP (one-line inversion) uncertainties for this line. A true initial guess algorithm still needs to be developed as the one employed is based on ASP results.

6.4. Comparison of FeI 6302Å and NiI 6768Å

Shown in Figure 22 again are 68% confidence intervals for the difference between filtergraph inversion for FeI 6302Å and ASP two-line inversion (dotted lines) and between filtergraph inversion for NiI 6768Å and ASP one-line NiI 6768Å inversion (solid lines). We see that, in general, a g_{eff} line of 2.5 has shown superior results to NiI 6768Å.

7. Summary of Lines

Both FeI 6173Å and NiI 6768Å profiles have clean continuum and no blends which threaten performance (see Figures 1-2, 5 and 10). The higher g_{eff} of FeI 6173Å means that its operational range of velocity values in regions of strong magnetic field is smaller than NiI 6768Å. However, the higher g_{eff} ensures more accurate vector magnetic field measurements as well as more accurate velocity measurements as long as the line is within the operational range.
NiI 6768Å parameters of line width, line depth and wing slope show smooth and predictable changes as a function of center-to-limb angle (see Figures 4 and 10). NiI 6768Å has been carefully studied by Bruls (1993). The conclusion from this research confirms that this line is a good choice for helioseismology because the line profile is quite stable and not very sensitive to variation of temperature and temperature gradient in the photosphere. These studies are yet to be carried out for FeI 6173Å, but plans to do so are being made.

An example of a filtergraph system’s capability to measure linear polarization is shown in Figure 9.

ASP observations and data inversions show that the higher $g_{eff}$ line FeI 6173 serves as a much better diagnostic tool than NiI 6768Å to ascertain the inclination angle, field strength and filling factor of the magnetic field (see Figures 11, 12 and 13).

Simulations of line performance using artificial profiles and artificial filters show errors to be smallest at a filter spacing of 76 mÅ for both the NiI 6768Å and the FeI 6173Å lines. Histograms of errors in velocity, field strength, inclination angle, filling factor, longitudinal and transverse flux show FeI 6173Å to be a better diagnostic for vector magnetic fields AND velocities than FeI 6768Å (see Figures 15, 16 and 17).

Simulations of line performance using observed profiles and artificial filters using the FeI 6302Å show that the filtergraph approach is able to recover the inclination and azimuthal angles reasonably well (see Figures 21 and 22). Errors in the field strength were higher than predicted by the simulations using artificial profiles, possibly due to the asymmetries and molecular blends found in real solar data.

REFERENCES


Jones, H., 1989, Solar Physics, 120, 211.


