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

ABSTRACT

This technote presents information of the spectral lines FeI 6173Å, FeI 6302Å and NiI 6768Å collected thus far from previous papers, observations, and simulations. These lines are candidates to be used in HMI for observation of the Doppler velocity and vector magnetic field.

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

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

1.1. 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); 0.099 Å in Stenflo et al’s paper (1977); 0.100 from direct measurement of the FWHM based on Kitt Peak data, and 0.106 Å from direct measurement of the Equivalent Width based on Kitt Peak data), and of the NiI 6768Å (0.110 Å from direct measurement of the FWHM based on Kitt Peak data, and 0.121 Å 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 NLTE 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>Wavelength (Å)</th>
<th>gf</th>
<th>Excit. Pot. (eV)</th>
<th>Depth (km)</th>
<th>FWHM (Å)</th>
<th>Height (core) (km)</th>
<th>Height (cont.) (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeI 6173</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></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>269 (Maltby-M)</td>
<td></td>
</tr>
<tr>
<td>NiI 6768</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></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 umbras for FeI 6173Å.

![Graphs showing line profiles and transmission](image)

Fig. 1.— Upper panel: line profile of FeI 6173Å in umbras (thin line) and in quiet Sun (thick line); Bottom panel: instrument transmission (dashed) and observed umbral (solid).

1.2. Line profiles in sunspot umbræ and in quiet Sun.

Line profiles of FeI 6173Å, FeI 6302Å, and NiI 6768Å in sunspot umbræ 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.noao.edu/pub/atlas. Using these data, we plot the lines in the same scale for comparison (see Figure1, Figure 2 and Figure 3). The upper panels of these figures show the lines in the photosphere (thick) and in umbræ (thin), and the bottom panels show the transmission (dashed) and the lines in umbræ (solid). The blends marked in the figures were identified by NSO at Kitt Peak.

The profiles of these lines in the photosphere are clean, and NiI 6768Å has no nearby lines. There is a blend 0.6Å away from the center of FeI6173Å identified as La II, which is at 6172.72Å (3F3 - 3F2). The lower level excitation potential is 0.13 eV and the effective g-factor is 1.50. There are many Zeeman
components (15-plet), and it doesn’t split, just broaden shown un the photographic sunspot atlas. Simulation has been done to estimate its influence on Doppler velocity measurement. It shows that the errors induced by this blend is very small.

Since HMI will make vector magnetic field observations, the behavior of these lines in umbrae are of interest.

A blend is obviously visible in the blue wing of FeI 6173Å umbra’s profile which is $R_1, 3\sigma$; and there are other two blends near this line (see Figure 1). The $R_1 3\sigma$ is at 6173.0Å, and this line is much stronger in the umbra spectrum (indeed it is invisible in the photospheric spectrum shown). The ‘saturation’ might occur when the velocity reaches 7km/s, or the magnetic field reaches 3k Gauss.

The profile of FeI 6302Å clearly shows Zeeman splitting (see Figure 2).

Observations of NiI 6768Å in umbrae have shown an obvious blend in this line, which is suggested to be TiO; and other two blends near this line (see Figure 3). The ‘saturation’ might occur with a velocity of 6km/s, or with magnetic field of 4k Gauss.
Fig. 3.— Upper panel: line profile of NiI 6768Å in umbrae (thin line) and in quiet Sun (thick line); Bottom panel: instrument transmission (dashed) and observed umbral (solid).

The 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.

2. Observations in FeI 6173 Å and NiI 6768Å

2.1. 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. The circular polarization separated line profiles confirm that the field was small for these regions. 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 67 degrees.

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.

Stokes parameters I, Q, U, and V were acquired by the Advanced Stokes Polarimeter (ASP) on 2002 March 9. This observation run observed an active region NOAA 9856, located at S3W4, using the FeI 6302Å/6301Å line pair in channel A and 6173Å FeI 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 Stokers I in black, as reference. The profiles are the average of the profiles over 100 pixels in this umbra. The line center needs to be precisely determined.

Fig. 5.— FeI 6173Å observed by ASP. The profiles shown here are an average over 100 pixels in the umbra.
2.2. NiI 6768Å

Fig. 6.— NiI 6768Å line observed at Mt. Wilson.

NiI 6768Å line profile was scanned at Mt. Wilson (see Figure 6). The center-to-limb variation of this Nickel line at 6768Å was also measured in the quiet sun by Mt. Wilson observatory (see Figure 7). The slopes at the red wing and blue wing is slightly different.

Mt. Wilson observation also shows the NiI 6768Å line profiles in circular polarizations in umbrae (see Figure 8 and Figure 9).

In a special observation run, MDI demonstrates that strong transverse field signal can be measured using a filtergraph observations in multiple polarizations. Figure 10 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.
Fig. 7.— Center-to-limb variation of the line NiI 6768Å in quiet Sun observed at Mt. Wilson. The x-axis for the top four panels is the central meridian distance of the observations in cos(angle).

2.3. Comparisons of NiI 6768Å/FeI 6302Å and FeI 6173Å/FeI 6302Å in vector magnetic field measurement

A set of vector magnetic field data was acquired by the Advanced Stokes Polarimeter (ASP) using the NiI line at 6768Å in March 2002. This observation run measured a “delta” sunspot (AR9866 at S9W65) near the solar limb. The magnetic field deduced from those data demonstrates capability of the Ni I line at 6768 Å as a diagnostic of solar vector magnetic fields.

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.
Fig. 8.— NiI 6768Å line in circular polarizations observed at Mt. Wilson.

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 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 lande g factor in FeI 6173Å enables a much better determination of vector magnetic field and filling fraction.

The large difference in ASP uncertainties for the two line (FeI 6301Å and FeI 6302Å) inversion and the NiI 6768Å inversion deserves some comment. Here we have a comparison based on ASP results (see Figure 13). They are correlation plots of single line inversion results verses the two line (FeI 6301Å and FeI 6302Å) result. We see larger discrepancies for a single line with 'low g_{eff}' (about 1.5 for 6301Å) than for a single line with larger g_{eff}. 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. 9.— NiI 6768Å line observed at Mt. Wilson. The dotted line represents blueshift component, and the dashed line, redshifted component. The solid line represents Stokes I.

Fig. 10.— 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.
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 same 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).

3. Simulation of performance of FeI 6173Å, FeI 6302Å, and NiI 6768Å

3.1. Simulations: 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.

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.
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 Ni I 6768 Å vs Fe I 6302 Å/6301 Å for the same region observed on 2002 March 10 (on left), and field strength for Fe I 6173 Å vs Fe I 6302 Å/6301 Å 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 6301 Å and FeI 6302 Å. The data used here are taken by ASP.
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 Ni I 6768 Å simulations. The bottom panels are the same but for the FeI 6302 Å and FeI 6173 Å simulations which used the same magnetic model parameters.

3.1.1. Ni I 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.

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.

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 (The dashed line in Figure 15 and Figure 16).

3.1.2. FeI 6173 Å

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

This data set is that it 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.

The same simulation as for NiI 6768Å was performed, and the results are presented in Figure 15 and Figure 16 (the solid line).

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

3.1.3. FeI 6302 Å

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.

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

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
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.

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, 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.

In summary, these simulations indicate that the performance of FeI 6173Å is better than that of Ni 6768Å for both velocity and vector magnetic field observations.

3.2. Simulations: Observed Profiles; Artificial Filters

Artificial filters are numerically applied to observed ASP profiles in an attempt to quantify any effect of asymmetries, molecular blends, etc. will have on the accuracy obtainable from the data. 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.

The observed profiles are from the ASP map of NOAA 9866, located at S9 W65, made at 18:58 UT on 2002 March 10.

3.2.1. FeI 6173 Å

Is in progress.
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.
3.2.2. 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. Filtergraph inversion flux density is chosen for the horizontal axis because flux densities were not available for ASP results. Errors from the simulation for HeI 6302 Å are shown as dashed lines for comparison to earlier simulations. We can see that the filtergraph 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 filtergraph technique, these errors could increase or decrease.

Fig. 19.— Error estimates based on ASP observation in NiI 6768 Å. Simulation is done in filtergraph mode.

3.2.3. NiI 6768 Å

Errors shown as solid lines in Figure 19 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.
Fig. 20.—Comparison of errors for lines FeI 6302Å and NiI 6768Å. The data for the filtergraph simulation are taken by ASP.

3.2.4. Comparison of FeI 6302Å and NiI 6768Å

Shown in Figure 20 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.

REFERENCES

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


