Prominence and Filament Magnetometry Simulations

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Summary: The purpose of this note is to determine the maximum level of polarimetric noise that can be tolerated when performing filter polarimetry of the He I lines at 5876 Å and 10830 Å. The objective is to ensure that their Stokes parameters still carry enough information for an acceptable magnetic inversion.

The simulations reported in this Note cover the cases of both prominence (i.e., off-limb) and filament (i.e., on-disk) observations. The various plots illustrate the statistics of the inversion of the magnetic topology—field strength ($B$), LOS inclination ($\Theta_B$), and POS direction ($\Phi_B$)—from different sets of 2700 synthetic observations, in the form of error scatter plots (top panels) and error histograms (bottom panels). The inversions are performed via Principal Component Analysis (PCA) of the synthetic observations, based on the search within different databases of 100,000 models.

The parameter ranges of the models, for both the synthetic observations and the databases, are the following:

- **Height**: $0 R_\odot \leq h \leq 0.1 R_\odot$
- **LOS incl.**: $70^\circ \leq \vartheta \leq 110^\circ$ (prominence case; off-limb check)
  $0^\circ \leq \vartheta \leq 90^\circ$ (filament case; on-disk check)
- **Field**: $0 \text{ G} \leq B \leq 100 \text{ G}$ (arbitrary geometry)
- **Temp.**: $10^4 \text{ K} \leq T \leq 2 \times 10^4 \text{ K}$
- **Opt. depth**: $0.1 \leq \tau \leq 1.0$
- **LOS vel.**: random within the spectral resolution element

Because the contrast of He I 5876 on the solar disk is extremely small, only He I 10830 can be used for measuring magnetic fields in filaments. Instead both lines show strong signals ($I \sim 10^{-2} I_{\text{disk}}$) in prominences, so they should be observed simultaneously in order to improve the statistics of off-limb magnetic inversions.

Both lines are actually multiplets, so the magnetic diagnostics is generally helped by the way that magnetic fields differently affect the component lines. He I 10830 originates in the transition $^3S_1 \leftrightarrow ^3P_{0,1,2}$. At the solar temperature, the 1–1 and 1–2 transitions are blended into a single (red) component, separated from the 1–0 (blue) component by $\sim 1.25 \text{ Å}$. Because the upper level of the blue component cannot be polarized ($J = 0$), the off-limb emission of this component tends to show extremely weak signals in both Stokes $Q$ and $U$. So one can anticipate that the He I 10830 line will consistently give worse inversions when applied to prominences. For this reason, He I 5876 plays the dominant role for prominence diagnostics, but the redundancy offered by “simultaneous” observations of He I 10830 can help reducing the inversion errors further. On disk, both components of He I 10830 become visible in linear polarization, because the lower level ($J = 1$)
is generally polarized, and thus it acts as a linear polarizer that filters the solar radiation from the disk through absorption. (For this reason the blue component of He I 10830 on disk typically shows a sign reversal with respect to the red component, whose linear polarization is instead dominated by the atomic polarization of the upper level.) Because both components of He I 10830 are visible in all four Stokes parameters on the disk, the magnetic diagnostics of solar filaments with this line is going to be more reliable than in the application of the same line to prominence diagnostics. The He I 5876 multiplet originates in the transition $^3P_0,1,2 \leftrightarrow ^3D_{1,2,3}$, with the 0–1 (red) component separated from the blend of the remaining 5 transitions by $\sim 0.34 \, \text{Å}$. Because all upper levels of the He I 5876 multiplet can be polarized, the polarized emission of this line shows both the red and blue components.

The two lines also have different critical $B$-values for the Hanle effect. The critical Hanle field for He I 10830 is $\sim 1 \, \text{G}$. Therefore, for the typical average field of quiescent prominences and filaments ($B \sim 10^{-20} \, \text{G}$), this line forms already in the saturated regime of the Hanle effect, where the atomic-polarization signal is no longer dependent on the field strength. In other words, He I 10830 behaves very much like the M1 coronal lines, with the LOS field strength information almost completely encoded in Stokes $V$, whereas Stokes $Q$ and $U$ mostly carry the information on $\Phi_B$. In contrast, the critical Hanle field for He I 5876 is $\sim 10 \, \text{G}$, and in addition several level crossings occur above 30 G, which further augment the diagnostic potential of this line for magnetic diagnostics between 0 and 100 G.

To test the precision of magnetic inversions based on filter observations of the He I lines, we first created reference cases by simulating and inverting observations for a typical spectrograph configuration. We assumed 0.040 for both the spectral sampling and the width of the spectrograph PSF in the case of He I 5876. In the case of He I 10830, both widths were scaled to 0.072 Å. Since He I 10830 plays a minor role in prominence observations, we did not consider a “spectrograph” case for this line for off-limb observations. Figures 1 through 3 present the results for He I 5876 observed off-limb, for different levels of polarimetric noise: i) without noise; ii) with normal noise of $5 \times 10^{-4} \, I_{\text{max}} \, \text{rms}$, and iii) with normal noise of $10^{-4} \, I_{\text{max}} \, \text{rms}$. Figures 10 through 12 present analogous results for He I 10830 observed on disk. For on-disk observations the polarimetric noise is normalized by the maximum depth of the absorption intensity profile, $I_c - I_{\text{min}}$.

For the filtergraph case, we considered a Gaussian passband with FWHM = 250 mÅ and FWHM = 460 mÅ, respectively for He I 5876 and 10830. For both lines, the spectral information is acquired by sampling 12 frequencies across the full line spectral range, with a spacing of 150 mÅ for He I 5876, and of 310 mÅ for He I 10830. Figures 4 through 6 show the results for the inversion of He I 5876 observed off limb, whereas Figs. 13 through 15 show analogous results for the inversion of He I 10830 observed on disk. We see that with such filtergraph configuration, the loss of information content is modest with respect to the spectrograph case. This is especially true in the case of He I 10830, likely because of the largest separation of the two visible components, which allows a better sampling of this line by filter than in the case of He I 5876.

Figures 7 through 9 show the inversion results for He I 10830 observed off limb. We see that the performance of this line is inferior to that of He I 5876 for prominence diagnostics. We also see that the inversion of this line is affected by larger errors than in the case of on-dish observations. The reason for this is the non-polarizability of the $J = 0$ level of the upper state of the He I 10830 line, which reduces the amount of polarization information in the radiation scattered off limb. In contrast, the general presence of atomic polarization in the $J = 1$ lower state of He I 10830 adds important information in the absorption polarized spectrum off this line, thus favoring its use in the magnetic diagnostics of filaments. This tendency seems to be contradicted by the more extended tail of erroneous inversions observed in the case of on-disk observations. However, we must keep in mind that the size of the solid angle of the allowed LOS directions is much larger.
in this case (practically approaching $2\pi$). So the limited size and the coarseness of the inversion database for on-disk observations tend to produce larger errors for the magnetic configurations that are completely missed by the inversion, compared to the off-limb case. In other words, the larger coarseness of the on-disk database will tend to make wrong inversions “wronger”. On the other hand, the larger spectro-polarimetric information of the on-disk observations tends to increase the number of magnetic configurations that are correctly inverted, thus decreasing the width of the error distribution peak closer to zero.

From the results shown in the figures, we can conclude that the use of a filter instrument is viable, if the polarimetric noise can be contained at a level lower than $10^{-3}$ at all times. The filter widths adopted for the simulations (FWHM = 250 mÅ for He I 5876, and FWHM = 460 mÅ for He I 10830) seem to provide a good compromise between spectral resolution and photon count. The filter configuration has the advantage of allowing the acquisition of spectro-polarimetric data on a large FOV simultaneously (possibly full disk). The obvious trade off is that the spectral information for each line must be built up during a time sequence, whose duration is determined by the number of sampling wavelengths (at least 12), and by the integration time for each wavelength position, which must be sufficient to achieve the prescribed S/N.

Because of the importance of “time coherence” of the spectral information across a line for inversion purposes, we suggest that the acquisition sequence be designed so to minimize the systematics that may be caused by the temporal scan in frequency. In fact, we cannot expect that the coherence time interval of solar phenomena be always smaller than the duration of a typical data acquisition sequence for the full line. In particular, we should worry about velocity effects that could make the spectral information in the two wings of a line physically inconsistent. A possible strategy could be that of sampling the line spectral range from the wings towards the center, starting the sequence with the coarsest spectral grid (consisting of just the two extremal points of the spectral range), and successively refining the grid until all sampling wavelengths have been selected. With this scheme, one should be able to acquire spectro-polarimetric information across the line, which can be considered “simultaneous” compared to the typical coherence times of quiescent prominences (say, 0.5–1 minute). The coarseness of the spectral grid in the initial steps of the acquisition sequence would then only compromise on the information content of spectro-polarimetric data for inversion purpose, but NOT on the physical consistency of that data. In other words, this scheme would ensure the feasibility of Stokes inversion according to the prescribed forward model, with a spectro-polarimetric error (and therefore, with corresponding errors on the inverted physical parameters) that decreases as the spectral grid gets refined during the acquisition sequence.
OFF-LIMB OBSERVATIONS AT 5876 Å

Fig. 1. Inversion test on off-limb observations at 5876 Å of 2700 magnetic models (0 G ≤ B ≤ 100 G; arbitrary geometry): 42 sampled wavelengths with Δλ = 40 mÅ (spectrograph case). A Gaussian instrumental profile with FWHM = 40 mÅ (slit+grating profile) was assumed.

Fig. 2. Same as Fig. 1, with the addition of normal spectro-polarimetric noise (1σ = 5 × 10⁻⁴ Iₘₐₓ).

Fig. 3. Same as Fig. 1, with the addition of normal spectro-polarimetric noise (1σ = 10⁻³ Iₘₐₓ).
OFF-LIMB OBSERVATIONS AT 5876 Å

Fig. 4. Inversion test on off-limb observations at 5876 Å of 2700 magnetic models (0 G ≤ H ≤ 100 G; arbitrary geometry): 12 sampled wavelengths with Δλ = 150 mÅ (filtrograph case). A Gaussian instrumental profile with FWHM = 250 mÅ (filter profile) was assumed.

Fig. 5. Same as Fig. 4, with the addition of normal spectro-polarimetric noise (1σ = 5 × 10⁻⁴ I_max).

Fig. 6. Same as Fig. 4, with the addition of normal spectro-polarimetric noise (1σ = 10⁻³ I_max).
Fig. 7. Inversion test on off-limb observations at 10830 Å of 2700 magnetic models (0 G ≤ B ≤ 100 G; arbitrary geometry): 12 sampled wavelengths with \( \Delta \lambda = 310 \, \text{mÅ} \) (filtrograph case). A Gaussian instrumental profile with FWHM = 460 mÅ (filter profile) was assumed.

Fig. 8. Same as Fig. 7, with the addition of normal spectro-polarimetric noise (\( 1\sigma = 5 \times 10^{-4} I_{\text{max}} \)).

Fig. 9. Same as Fig. 7, with the addition of normal spectro-polarimetric noise (\( 1\sigma = 10^{-3} I_{\text{max}} \)).
ON-DISK OBSERVATIONS AT 10830 Å

Fig. 10. Inversion test on on-disk observations at 10830 Å of 2700 magnetic models ($0 \text{ G} \leq B \leq 100 \text{ G}$; arbitrary geometry): 46 sampled wavelengths with $\Delta \lambda = 72 \text{ mÅ}$ (spectrograph case). A Gaussian instrumental profile with $\text{FWHM} = 72 \text{ mÅ}$ (slit+grating profile) was assumed.

Fig. 11. Same as Fig. 10, with the addition of normal spectro-polarimetric noise ($\sigma = 5 \times 10^{-4}(I_c - I_{\text{min}})$).

Fig. 12. Same as Fig. 10, with the addition of normal spectro-polarimetric noise ($\sigma = 10^{-3}(I_c - I_{\text{min}})$).
ON-DISK OBSERVATIONS AT 10830 Å

Fig. 13. Inversion test on on-disk observations at 10830 Å of 2700 magnetic models (0 G ≤ B ≤ 100 G; arbitrary geometry): 12 sampled wavelengths with ∆λ = 310 mÅ (filter case). A Gaussian instrumental profile with FWHM = 460 mÅ (filter profile) was assumed.

Fig. 14. Same as Fig. 13, with the addition of normal spectro-polarimetric noise (1σ = 5 × 10⁻⁴ (Ic − Imín)).

Fig. 15. Same as Fig. 13, with the addition of normal spectro-polarimetric noise (1σ = 10⁻³ (Ic − Imín)).