ABSTRACT

The Visible-light Imager and Magnetograph (VIM) proposed for the ESA Solar Orbiter mission will observe a photospheric spectral line at high spatial resolution. Here we simulate and interpret VIM measurements. Realistic MHD models are used to synthesize "observed" Stokes profiles of the photospheric Fe I 617.3 nm line. The profiles are degraded by telescope diffraction and detector pixel size to a spatial resolution of 162 km on the solar surface. We study the influence of spectral resolving power, noise, and limited wavelength sampling on the vector magnetic fields and line-of-sight velocities derived from Milne-Eddington inversions of the simulated measurements. VIM will provide reasonably accurate values of the atmospheric parameters even with filter widths of 120 mÅ and 3 wavelength positions plus continuum, as long as the noise level is kept below $10^{-3} I_c$.

The purpose of the present work is to investigate how well we are able to infer atmospheric parameters from VIM-HRT data, providing feedback to optimize its design. In many respects, VIM-HRT is very similar to the Imaging MAgnetograph eXperiment (IMaX; Martínez Pillet et al. 2004), the vector polarimeter of the SUNRISE balloon mission (Gandorfer et al. 2006). We have carried out extensive tests to improve the SUNRISE/IMaX performance (e.g. Orozco Suárez et al. 2006). Here we use this experience to study the influence of spectral resolution and wavelength sampling on the accuracy of the atmospheric parameters derived from VIM-HRT measurements. We show that filter widths of 120 mÅ and 4 wavelength samples (3 across the line and one in the continuum) would allow VIM to achieve its science goals.

1. INTRODUCTION

The goal of the Visible-light Imager and Magnetograph (VIM; Marsch et al. 2005), one of the remote sensing instruments onboard Solar Orbiter, is to obtain high resolution maps of the vector magnetic field and the line-of-sight velocity in the solar photosphere. This information is essential to understand not only the physical processes occurring there, but also the magnetic coupling of the different atmospheric layers. In addition, VIM will carry out local and global helioseismic studies of the Sun.

The inference of LOS velocity and vector magnetic field (strength, inclination and azimuth) maps, commonly called Dopplergrams and vector magnetograms, requires the observation and subsequent analysis of a spectral line in polarized light. The atmospheric parameters (physical quantities) are retrieved from the polarimetric measurements by techniques based on either the radiative transfer equation or look-up tables (Bellot Rubio 2006). VIM consists of two telescopes: the High Resolution Telescope (VIM-HRT) and the Full Disk Telescope (VIM-FDT). Spectropolarimetry is carried out using a double Fabry-Pérot interferometer, conceptually based on LiNbO$_3$ etalons, which performs the wavelength selection within the spectral line, and two polarization modulation packages, based on liquid crystal retarders, to modulate the polarization of the incident light. Solanki et al. (2006) describe the main properties of the instrument and a possible configuration for VIM on Solar Orbiter.

The photospheric line to be observed is Fe I 617.3 nm.

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2. METHODOLOGY

We simulate the observational process of VIM, from the measurement of spectra to the determination of physical quantities, as follows. First, we use model atmospheres that describe the Sun in the more realistic way possible. These atmospheres allow us to simulate observations by synthesizing the Stokes profiles ($I$, $Q$, $U$, $V$) of Fe I 617.3 nm. The polarization signals are spatially degraded considering telescope diffraction and detector pixel size. We also degrade the profiles applying a spectral PSF, add noise, and select a few wavelength samples across the line. The simulated "observations" are then analyzed by means of inversion techniques. Comparing the retrieved parameters with the real ones we estimate the uncertainties of the inferences.

VIM-HRT is expected to observe the solar photosphere at resolutions of $\sim$ 150 km. No ground-based telescope has
ever provided spectropolarimetric measurements at such a resolution. For this reason, the atmospheres needed to synthesize the Stokes profiles are taken from MHD simulations (Vögler et al. 2005; Schüssler et al. 2003). More specifically, we use a simulation run representing a quiet Sun area with mixed-polarity magnetic fields and unsigned average flux of $\sim 150$ G. The duration of the simulation sequence is roughly 5 minutes with a cadence of 10 seconds. The horizontal and vertical extents of the computational box are 6 and 1.4 Mm, respectively. The synthesis of Stokes profiles is carried out using the SIR code (Ruiz Cobo & del Toro Iniesta 1992). The line considered here, Fe I 617.3 nm, is sampled at 61 wavelength positions in steps of 1 pm. The atomic parameters have been taken from the VALD database (Piskunov et al. 1995). These Stokes profiles represent the real Sun. To determine the atmospheric parameters from them we use a least-square inversion technique based on Milne-Eddington (ME) atmospheres.

The sampling interval in the MHD simulations is $0.0287''$ (grid resolution), implying a spatial resolution of $0.057$ or $41.6$ km on the solar surface. The spatial resolution provided by the aperture of VIM$^1$ operating at 617.3 nm is $\sim 0.17$ (i.e., $\sim 127$ km on the Sun), but the sampling interval ($0.11$) imposed by the CCD limits the spatial resolution to 162 km ($\sim 0.22$) on the Sun. Thus, in order to properly simulate VIM observations, the data images derived from the model (the synthetic Stokes profiles) have to be spatially degraded by telescope diffraction and detector pixel size. Figure 1 shows maps of the normalized continuum intensity for the original data (the theoretical model) and for the spatially degraded data. The main visible effect of the degradation process is the loss of contrast from $\sim 14\%$ to $\sim 11\%$ in the continuum. The CCD grid and the disappearance of small scale structures are also very noticeable. Figure 2 shows the MTFs representing, in the Fourier domain, the filtering of spectral components induced by telescope diffraction and pixelation effects in the CCD.

The most favorable (ideal) case is one in which the instrument measures the spatially degraded Stokes profiles with no noise, very high spectral resolution, and critical wavelength sampling. Inversion techniques would be able to infer correct atmospheric parameters from this kind of observations, but one needs complex model atmospheres with vertical gradients to describe the height variation of the physical quantities within the same pixel. Such models are not feasible because of the limited data processing capabilities onboard Solar Orbiter. Thus, ME inversions represent the best option to interpret VIM-HRT measurements: they do not retrieve stratifications, but are simple and often provide reasonable averages of the physical quantities over the line formation region (Westendorp Plaza et al. 2001; Bellot Rubio 2006).

In the present work we consider the results of ME inversions of the spatially degraded Stokes profiles with no noise, no spectral PSF, and 61 wavelength samples as the reference solution. By comparing this reference with the

$^1$VIM-HRT is equivalent to a 0.73m telescope at 1 AU
3. TEST RESULTS

VIM uses a Fabry-Pérot interferometer to perform the wavelength selection within the line. The finite spectral resolution of the instrument reduces the amount of information carried by the line, and therefore is a source of uncertainties in the determination of atmospheric parameters. The spectral PSF of VIM can be described as a Gaussian function whose FWHM lies somewhere between 75 and 120 mÅ.

We estimate the effect of limited spectral resolution as follows. The synthetic Stokes profiles are convolved with PSFs of different widths. Specifically, we vary the FWHM from zero to 200 mÅ in steps of 10 mÅ. We then add noise at the level of $10^{-3}$, apply a ME inversion to the profiles sampled at 61 wavelength positions, and compare the inferred maps with our reference. The ME inversion process determines 9 free parameters. The magnetic filling factor is fixed to unity and no stray light is considered. We use the same initial guess model for all inversions, allowing a maximum of 300 iterations. Three simulation snapshots (17700 pixels) have been inverted in this way.

To analyze the test results we calculate the mean and rms values of the errors (defined as the difference between the inferred and the reference parameters). As an example, Fig. 3 shows the field strength errors resulting from the inversion of the Stokes profiles convolved with a 120 mÅ FWHM filter. Each point represents an individual pixel. The solid lines give the mean and rms errors.

Figure 4 shows the variation of the mean (black) and rms (red) values of the error with the FWHM of the instrumental PSF. Top: LOS velocity. Middle: magnetic field strength. Bottom: magnetic field inclination. The dashed curve in the central and bottom panels represents pixels with field strengths larger than 750 G (in the reference map) and the solid curve field strengths ranging from 150 to 750 G.

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The outcome of ME inversions of the same Stokes profiles affected by noise, limited spectral resolution, and wavelength sampling, we quantify the loss of information induced by the measuring process, avoiding errors due to the ME assumption.
The mean and rms errors of the velocity increase with filter width, although the variation is weak. We estimate rms errors of about 30 m/s and 50 m/s for 60 mA and 120 mA filter widths, respectively. The errors in the magnetic field strength also vary smoothly with the FWHM. For filters narrower than 120 mA, the rms errors are always smaller than ~30 G. Interestingly, the mean errors increase with increasing field strength: in the range 150–750 G they are roughly constant, which is not the case for fields stronger than 750 G. The fact that the mean errors of field strength and velocity vary with the FWHM is related to the asymmetries of the profiles. Stokes profiles formed in real atmospheres exhibit asymmetries induced by vertical gradients of the atmospheric parameters. The Stokes profiles coming from ME atmospheres are symmetric, however. While the spectral PSF smears out the asymmetries, it also allows better fits to the observations. Consequently, the mean errors vary with filter width, and the variation is larger for stronger fields.

From this analysis we conclude that instrumental profiles of up to 120 mA FWHM provide accurate results. It is important to keep in mind, however, that the spectral PSF also affects the Stokes profiles in two different ways: first it reduces their amplitudes, and second it smooths the asymmetries out. To quantify the first effect, the upper panel of Fig. 5 shows, as a function of filter width, the percentage of pixels whose Stokes Q or U amplitudes exceed twofold the noise level. This percentage decreases rapidly with the FWHM of the PSF. In other words: the ability to detect linear polarization signals strongly depends on the instrumental profile, at least in quiet Sun regions. For instance, 6% of the pixels are no longer detectable in linear polarization when the filter width is increased from 75 to 120 mA. This loss of sensitivity can be compensated by lowering the noise level. In the bottom panel of Fig. 5 we represent the percentage of pixels with detectable linear polarization signals against the signal-to-noise ratio (SNR) for a fixed filter width of 120 mA. The variation is almost linear. If we are to recover the previous loss of 6% of the pixels, the SNR has to be increased from 1000 to 1300. This translates into a 1.7 factor in exposure time, which may have some unwanted consequences on high spatial resolution observations.

VIM-HRT will achieve a spatial resolution of about 150 km in the solar photosphere. At this resolution the smallest dynamical structures accessible evolve on time scales of 10–50 seconds (assuming a scale height of 100 km). Thus, the scanning of the spectral line should not take longer. This fact limits VIM to sample only a few wavelength positions within the line. Currently, scans of five wavelength positions plus one in the nearby continuum are being considered. The limited wavelength sampling introduces additional uncertainties in the inference process. To determine these errors we carry out ME inversions of the Stokes profiles sampled with different numbers of wavelength points, from 2 to 8, plus the continuum. First, the profiles have been convolved with a 120 mA FWHM filter and have been added noise at the level of $10^{-3}I_c$. The inversion is carried out in the same conditions as before. Again, we compare the inferred maps with the reference solution.

Figure 5 shows the variation of the mean and rms errors with the number of wavelength samples, for the LOS velocity (top), field strength (middle), and field inclination (bottom). Only pixels whose Stokes Q, U or V amplitudes are larger than three times the noise level have been considered for the magnetic parameters. The results are somewhat surprising. We find that the mean and rms errors of the velocity do not change much with the number of samples if the line is observed in at least three wavelength positions. In that case, the mean and rms errors are about 10 and 50 m/s, respectively. The field strength and field inclination errors do not change either with the number of samples, provided it is larger than 3. The reason for such a behavior is the strong smearing of the Stokes profiles after the instrument action. No conspicuous details remain that can be detected by five or six samples better than by just three. It is important to remark, however, that the sampling will further reduce the number of detectable profiles over those shown in Fig. 5 since in general the observed wavelength positions will not coincide with the maximum Stokes Q or U signals.

Figure 6 is a graphical illustration of the kind of results we can expect from the analysis of VIM measurements. The upper panels show a cut of the atmospheres provided by the MHD simulations at optical depth $\log(\tau) = -1.5$. The second row display the reference solution, i.e., the
results of ME inversions of the spatially degraded Stokes profiles with no noise, no spectral PSF, and 61 wavelength samples. The third row shows the atmospheric parameters derived from the ME inversion in the specific case of five wavelength samples at $-100$, $-50$, $0$, $50$, and $100$ mÅ from line center plus the continuum, a SNR of 1000, and an instrumental profile width of $120$ mÅ. The last row shows the same parameters when the inversion is applied to the Stokes profiles sampled at only three wavelength positions ($-60$, $-10$, and $60$ mÅ) plus the continuum, for a filter width of $120$ mÅ and a SNR of 1000.

The various physical parameters are qualitatively well determined, although we observe some differences between the real and the inferred parameters. The magnetic field strength, for example, is not particularly well recovered inside the granules. There, the fields are weak and the corresponding polarization signals are strongly affected by the noise. In the inclination and azimuth maps we see regions fully dominated by noise. In general, however, the inversion algorithm is able to recover magnetic fields above $100$ G with accuracy: *pixels with weak fields are assigned weak fields, and pixels with strong fields get strong fields.* This is in contrast with the results of inversions of full Stokes profiles of internetwork fields in the quiet Sun at resolutions of $1''$ (Martínez González et al. 2006). Velocities are less affected by noise. We find larger velocity errors in intergranular regions, probably due to the larger asymmetries exhibited by the Stokes profiles in those regions, where vertical gradients are more pronounced.

4. CONCLUSIONS

We have analyzed simulated VIM-HRT observations to study the performance of the instrument. Stokes profiles of the Fe I 617.3 nm line have been calculated using realistic MHD simulations of a quiet sun region at disk center and then spatially degraded by telescope diffraction and detector pixel size to match the VIM-HRT resolution. Additionally, we have convolved the profiles with spectral PSFs of different widths (from 0 to 200 mÅ), added noise at the level of $10^{-3}I_c$, and selected a few wavelength samples across the line.

The instrumental filter width and the limited wavelength sampling influence the determination of vector magnetic fields and LOS velocities. However, the atmospheric parameters retrieved from VIM-HRT measurements are reasonably accurate: ME inversions of the Stokes profiles broadened by a $120$ mÅ filter and sampled at three wavelength positions within the line plus a continuum point indicate rms errors of $\sigma_B \approx 30$ G, $\sigma_v \approx 50$ m/s and $\sigma_\gamma \approx 10^o$ for SNRs of 1000. As expected, the rms errors are much smaller for fields stronger than $750$ G.

The results of ME inversions seem to be accurate enough even with filters as wide as $120$ mÅ FWHM and four wavelength samples. This may allow both a significant reduction of the mass of VIM and better signal-to-noise ratios through longer exposure times. There are some drawbacks in using broad filters and few wavelength samples, however. They include the decrease of the number of detectable polarization signals and the reduction of the dynamical range the instrument is able to cope with. Such effects are important and have to be investigated in detail. We also note that the observation of only four wavelength samples may prevent estimates of the magnetic filling factor from being made, although our tests show that unity filling factors produce good results with high spatial resolution data.

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Figure 7. First row: Cut at optical depth $\log(\tau) = -1.5$ in the model atmospheres provided by the MHD simulations. Second row: Maps of the physical quantities retrieved from the ME inversion of the Stokes profiles with no noise, no spectral PSF, and 61 wavelength samples. Third row: Maps of the physical quantities retrieved from a ME inversion of the Stokes profiles convolved with a 120 mÅ filter and sampled at five wavelength points across the spectral line, plus a continuum point. The SNR of the profiles is 1000. Fourth row: Same as the third row, but for the profiles sampled at three wavelength positions plus continuum. From left to right: magnetic field strength, inclination, azimuth, and LOS velocity.

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