THE PERFORMANCE OF THE SOLO-VIM INSTRUMENT: EFFECTS OF INSTRUMENTAL NOISE AND LOSSY DATA COMPRESSION

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ABSTRACT

Spectropolarimetric observations in photospheric lines reveal a wealth of information on physical parameters of the solar atmosphere like magnetic field strength and direction or the line-of sight velocity. These observations require the measurement of the four Stokes parameters at a sample of N wavelength positions around the core of the spectral line, resulting in $4N$ images for one observation. The Visible light Imager and Magnetograph (VIM) instrument on board Solar Orbiter is capable of performing these measurements. However, the data rate required to transfer all 4N images with the required cadence is well beyond the telemetry limit. Here we use realistic, three-dimensional MHD simulations in order to simulate science data provided by VIM which are then used to test various compression techniques. We conclude that lossy data compression and instrumental noise have similar effects on the output data.

Key words: VIM; instrument performance; data compression.

1. THE VIM INSTRUMENT

VIM will measure the continuum intensity (I_c), line-of-sight flow velocity ($v_{\rm LOS}$), and the magnetic field vector ($\boldsymbol{B} = [|B|, \gamma, \chi]$) in the solar photosphere, where $|B|$ is the magnetic field strength, γ represents the field inclination with respect to the LOS and χ is the field azimuth. Two-dimensional maps of these physical parameters will be obtained by scanning a Zeeman-sensitive photospheric spectral line (presumably Fe I 6173 Å) and the nearby continuum with a tunable filter and measuring the full Stokes vector at 5 to 6 spectral positions.

2. DATA COMPRESSION

VIM will be equipped with a 2k by 2k detector and will obtain full parameter sets in cadences of about 1 image per minute. Thus, VIM will produce, when observing in its full capacity mode, a huge amount of data which adds up to a approximately 10 to 20 Mbit/s, requiring efficient on-board data compression strategies.

We investigate the effect of two compression strategies. The first strategy involves the on-board retrieval of physical parameters by Milne-Eddington (ME) inversions. Instead of the raw Stokes images only the physical parameters are transmitted to the ground stations. An on-board inversion of the radiative transfer equation (RTE) calculates parameter maps for the magnetic field vector ($|B|$, γ, χ), LOS-velocity and continuum intensity (I_c). This intelligent way of data compression reduces data volume by a factor 4 to 20. The second strategy performs a lossless (compression factor of $\approx$2) or a lossy image compression, to be applied either to the raw Stokes images or to the parameter maps resulting from the RTE inversion. The lossy (e.g. JPG-algorithm) compression reduces the data volume by a factor of $\approx$10.

3. MILNE-EDDINGTON INVERSION

For retrieving the desired physical parameters a numerical ME inversion of the radiative transfer equation

$$\frac{d\mathbf{I}}{ds} = -\mathbf{K}\,\mathbf{I} + \mathbf{j}, \tag{1}$$

where $\mathbf{K}$ is the total absorption matrix and $\mathbf{j}$ is the emission vector, was applied to the simulated VIM Stokes measurements (Lagg et al. 2004). The Milne-Eddington approach assumes that all physical quantities of the solar atmosphere are height independent, except for the source function gradient, which decreases linearly with height.

4. SIMULATING VIM MEASUREMENTS

The performance of the intended data processing algorithms can be simulated by applying it to Stokes profiles obtained from numerical MHD simulations of the photosphere with an unipolar seed field of 200 G strength (see Vögler et al. 2005). The MHD-simulations provide three-dimensional data cubes of all physical parameters

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describing the solar atmosphere. A sophisticated radiative transfer code (STOPRO, Frutiger (2000)) was applied to this data cubes in order to retrieve the 'ideal' Stokes profiles. To simulate the performance of VIM we

- decreased the spatial resolution of the simulation ($\approx$21 km) by applying the point spread function (PSF) of VIM,
- decreased the spectral resolution by convolution with the proposed transmission function of VIM's magnetograph,
- selecting only 5 WL-points for the ME-inversion, and
- added a realistic amount of noise to the data ($\approx 10^{-3} \cdot I_c$), taking into account detector properties and the photon budget.

A typical example of a simulated VIM measurement is presented in (Yelles et al. 2006, Figs. 2 and 3) in this proceedings.

5. MILNE-EDDINGTON INVERSION RESULTS

In Fig. 1 we compare the maps for the atmospheric parameters magnetic field strength, inclination, azimuth and the LOS velocity taken from the MHD-simulations in the original resolution of 20.8 km per pixel at height $z = 0$ (photosphere) with the parameter maps obtained from the ME inversions after degrading the Stokes profiles. Figure 1 clearly illustrates that the parameters magnetic field strength, inclination angle and LOS velocity are retrieved reliably, even after adding random noise ($10^{-3} \cdot I_c$) or after lossy compression of the raw Stokes images by a factor of 10. However, in regions of low magnetic fields (granules) the information on the inclination angle and, especially, the azimuthal angle becomes unreliable.

6. COMPRESSION OF STOKES IMAGES

Figure 2 shows the effect of lossy data compression on the quality of the raw Stokes Q image, taken at the central wavelength of the spectral line. The left image shows the Stokes Q map of an 'ideal' polarimeter behind the VIM telescope (the point spread function of the telescope has been applied). The central image clearly shows that the magnetically quiet, granular regions are dominated by the random noise of $10^{-3} I_c$, which is the expected noise level of the VIM instrument (photon and detector noise). Compression artefacts become clearly visible in the right image. Nevertheless, the results in the stronger field regimes are close to the case without lossy compression.

7. QUALITY OF COMPRESSION TECHNIQUES

The scatter plots in Fig. 3 quantify the error in the retrieval of the physical parameters by ME inversions. Even with an 'ideal' VIM instrument (noise-free, but with the limited spatial resolution due to the diffraction limit of the telescope) the calculated parameters deviate from the MHD simulations (left column in Fig. 3). Adding noise of $10^{-3} \cdot I_c$ (middle column) does not significantly degrade the quality of the parameter retrieval, except for the very low magnetic fields, which tend to be over-estimated by the ME inversion. Applying lossy data compression up to a factor of 10 (right column) does increase the scatter slightly, the results are still in good agreement with the ideal case. Lossy compression rates of higher than a factor of 10 lead to significant increase in the error of the retrieval of the parameters.

Note that the selected MHD simulation box is dominated by very weak magnetic fields (granules), where the determination of the magnetic field vector using Zeeman diagnostics is principally difficult. However, the determination of the magnetic flux ($|B|\times$filling factor) is possible with high accuracy. Also, for data sets of active regions (strong plage, pores or sunspots) with stronger magnetic field the ME inversions will provide reliable magnetic field vector and LOS velocity maps within the solutions possible using ME inversions.

8. CONCLUSIONS

On-board RTE inversion are the most efficient data compression technique. They allow the maximum information contained in the raw Stokes images to be retrieved. A polarimetric measurement in five wavelength points does not allow for a more complex analysis technique than ME. Additionally, it provides the possibility to select only a sub-set of physical quantities to be transmitted to earth, depending on the scientific goal of the measurement (e.g. only velocity maps for helioseismology). The achievable compression ratios with this technique range from a factor of 4 to 20 (instead of 20 raw Stokes images only 1 to 5 parameter maps are transmitted to ground).

Lossless compression to the parameter maps or the raw Stokes images will reduce the data volume by approximately a factor of two. Additionally, lossy compression of up to a factor of 10 can be applied to the parameter maps of the ME inversion or directly to the raw Stokes images, allowing for a more detailed analysis of the data set on ground.

In regions of very low magnetic fields ($\lesssim$200 G) the direction of the magnetic field remains undetermined. This is an intrinsic problem of the measurement technique involving Zeeman polarimetry and is only to a minor degree affected by the compression techniques.

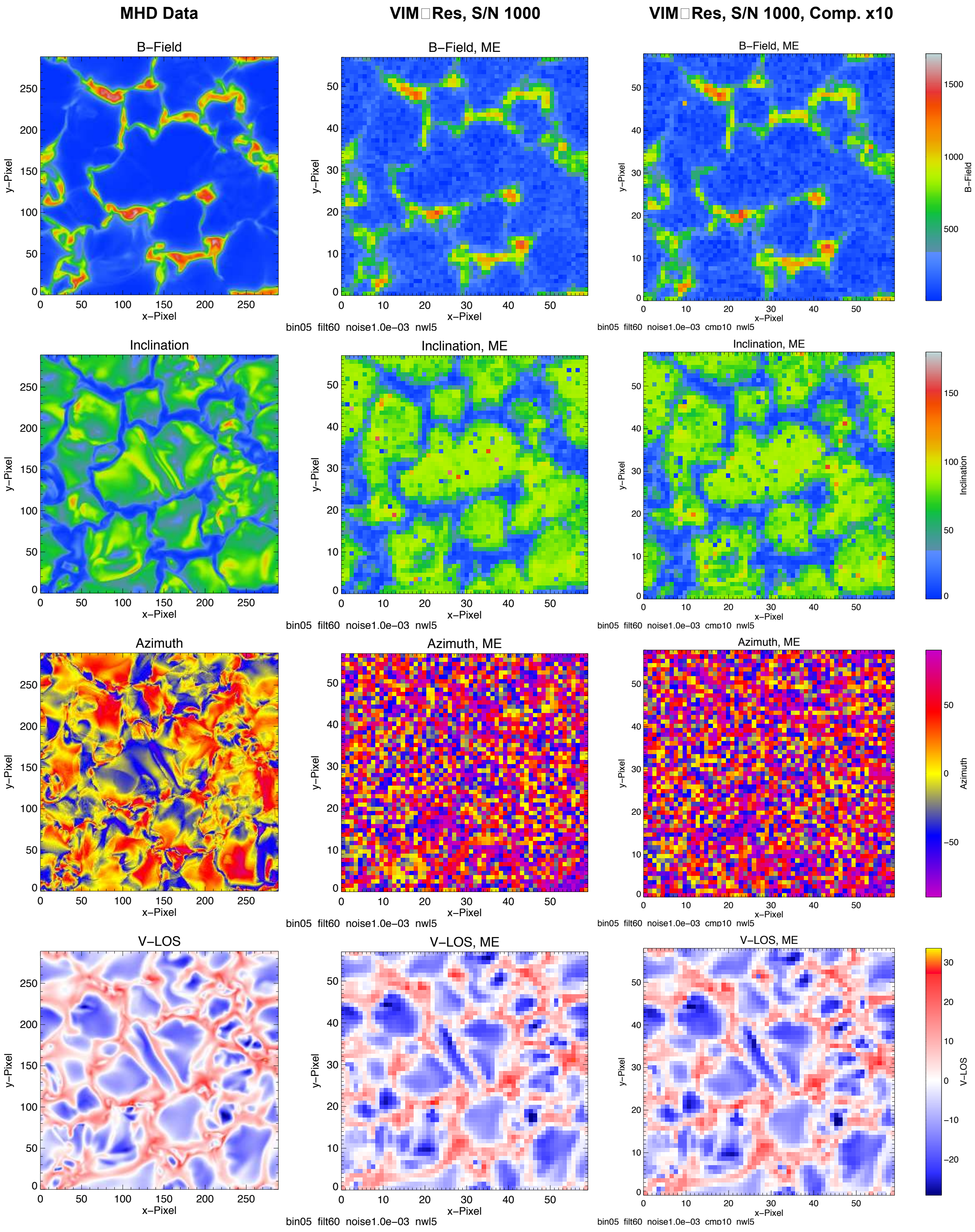

Figure 1. The left column shows the parameters magnetic field strength, inclination, azimuth and the LOS velocity (from top to bottom) at height $z = 0$ *(photosphere) taken from the MHD-simulations in the original resolution of 20.8 km per pixel. The results of the Milne-Eddington inversions from simulated VIM measurements (decreased spatial resolution by applying the PSF of the telescope) after adding realistic noise (*$10^{-3} \cdot I_c$*) and a lossy compression (factor 10) are shown in the middle and right column respectively.*

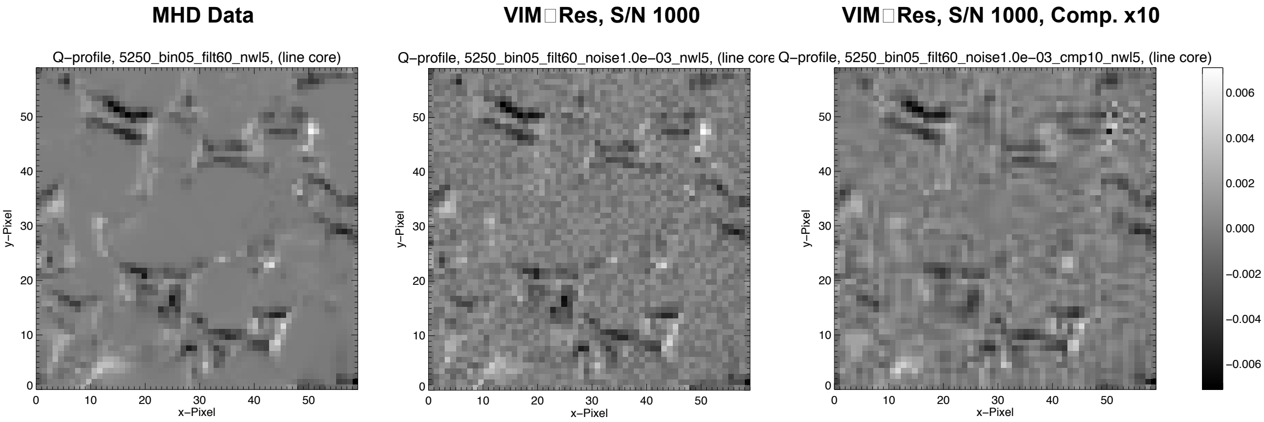

Figure 2. Effects of lossy data compression: 'ideal' polarimeter (left), random noise ($10^{-3}I_c$, middle) and random noise plus lossy data compression (factor 10).

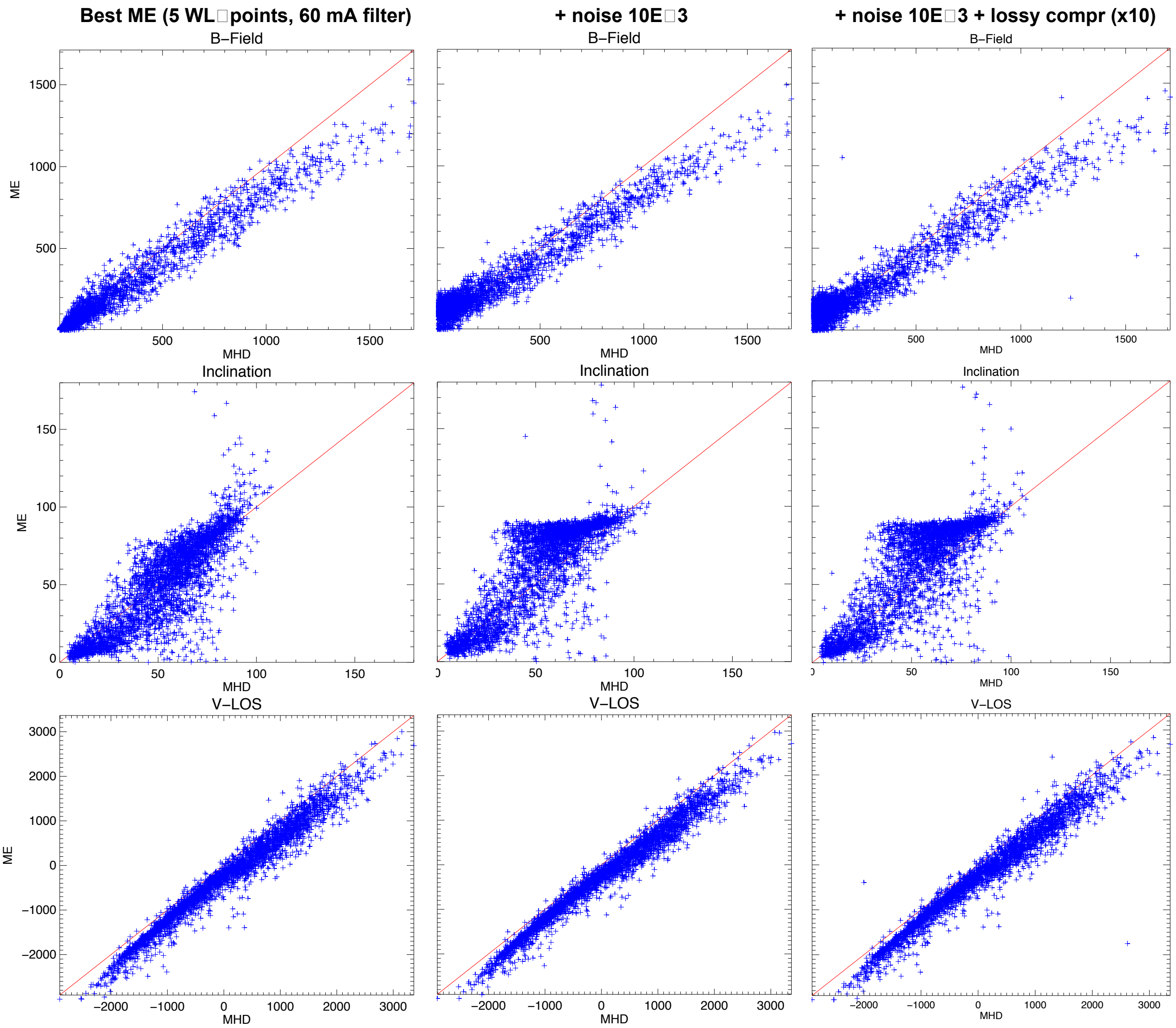

Figure 3. Comparison of ME-inversion results with MHD-simulations at the height $z = 0$ for the magnetic field strength (top row), the inclination angle to the LOS (middle row) and the LOS velocity (bottom row): ideal, noise-free instrument (left column), realistic noise of $10^{-3} \cdot I_c$ (middle column), and additional lossy compression of the raw Stokes images (right column).

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