Effects of solar evolution on finite acquisition time of Fabry–Perot interferometers in high resolution solar physics

R. Schlichenmaier©, D. Pitters, J. M. Borrero, and M. Schubert

Leibniz-Institut für Sonnenphysik (KIS), Schöneckstr. 6, 79104 Freiburg, Germany

Received 30 July 2022 / Accepted 24 October 2022

ABSTRACT

Context. The Visible Tunable Filter (VTF) imaging spectropolarimeter will be operated at the Daniel K. Inouye Solar Telescope (DKIST) in Hawaii. Due to its capability in resolving dynamic fine structure of smaller than 0.05 arcsec, the finite acquisition time of typically 11 s affects the measurement process and potentially causes errors in deduced physical parameters.

Aims. We estimate these errors and investigate ways of minimising them.

Methods. We mimicked the solar surface using a magnetohydrodynamic simulation with a spatially averaged vertical field strength of 200 G. We simulated the measurement process scanning through successive wavelength points with a temporal cadence of 1 s. We synthesised Fe I 617.3 nm for corresponding snapshots. In addition to the classical composition of the line profile, we introduce a novel method where the intensity in each wavelength point is normalised using the simultaneous continuum intensity, and then multiplied by the temporal mean of the continuum intensity. Milne-Eddington inversions were used to infer the line-of-sight velocity, \( u_{\text{los}} \), and the vertical (longitudinal) component of the magnetic field, \( B_\parallel \).

Results. We quantify systematic errors, defining the temporal average of the simulation during the measurement as the truth. We find that with the classical composition of the line profiles, errors exceed the sensitivity for \( u_{\text{los}} \) and in filament regions also for \( B_\parallel \). The novel method that includes normalisation reduces the measurement errors in all cases. Spatial binning without reducing the acquisition time decreases the measurement error slightly.

Conclusions. The evolutionary timescale in inter-granular lanes, in particular in areas with magnetic features (filigree), is shorter than the timescale within granules. Hence, depending on the science objective, fewer accumulations could be used for strong magnetic field in inter-granular lanes and more accumulations could be used for the weak granular magnetic fields. As a key result of this investigation, we suggest including the novel method of normalisation in corresponding data pipelines.

Key words. Sun: magnetic fields – instrumentation: polarimeters – instrumentation: high angular resolution – Sun: photosphere

1. Introduction

The solar photosphere and chromosphere are highly dynamic and exhibit a wealth of magnetic structures and phenomena. The underlying processes operate on small spatial and temporal scales and are a consequence of fundamental interactions between plasma, magnetic fields, and radiation. These interactions leave spectropolarimetric imprints in absorption and emission lines, which form in the photosphere and chromosphere, that can be measured with sophisticated instrumentation. Classically, there are two types of instruments: slit-scanning spectrographs and narrow-band imagers scanning in wavelength through a spectral line. Both types can be equipped with polarimetric modulators. While grating spectrographs have the advantage of spectral integrity, high spectral resolution, and large spectral coverage, Fabry–Perot interferometer (FPI) narrow-band imagers have the advantage of image integrity, large fields of view, and short cadences. New technical developments aim to combine spectral and image integrity with short cadences in integral field units. Currently, two concepts look very promising: image slicers and micro-lens arrays (see e.g. Jurčák et al. 2019; Kaithakkal et al. 2020; Dominguez-Tagle et al. 2022).

Here, we investigate the spectral integrity of an FPI-based narrow-band imager that may suffer from scanning in wavelength through a spectral line, resulting in a finite acquisition time, during which the solar scene may change (as already noted in Schubert et al. 2017). We use the Visible Tunable Filter (VTF, Schmidt et al. 2014) which is planned to be installed in 2023 at the Daniel K. Inouye Solar Telescope (DKIST, Rimmele et al. 2020). VTF is an imaging spectropolarimeter for the wavelength range between 520 and 860 nm. It is based on two FPIs that scan the narrow-band images in wavelength, which means that the spectral points of a solar line are not acquired simultaneously, but during a finite acquisition time. In general, the integration time at each wavelength step is determined by the desired signal-to-noise ratio (S/N, i.e. polarimetric sensitivity). A default measurement at full spatial resolution of the photospheric magnetic field with VTF in Fe I 617.3 nm takes 11 s to reach the desired polarimetric accuracy at 11 wavelength points (see Sect. 2). VTF is designed to operate at the diffraction limit of DKIST, which has an aperture of 4 m (i.e. at 520 nm scales of 20 km are resolved on the solar surface). On such small scales, dynamical processes in the solar photosphere potentially lead to spurious signals that spoil the measurement.

Short timescales observed with GREGOR. To demonstrate these short timescales in the solar photosphere, in Fig. 1 we present images from GREGOR (Schmidt et al. 2012; 1 At first light, VTF will be equipped with only one FPI (also named etalon), but the second FPI is manufactured and will be integrated soon after the first.
In this contribution, we investigate the effects of spurious signals that are expected from temporal evolution during the measurement process. The evolution is mimicked by a realistic magneto-hydrodynamic simulation of a plage region. The VTF measurement process is described in Sect. 2. The method we applied to mimic the measurement process and how to describe the measurement error is explained in Sect. 3. Our results are presented and discussed in Sect. 4. Section 5 presents our conclusion and an important suggestion concerning the data pipeline of Fabry–Perot-based spectropolarimeters.

2. VTF measurement process

The VTF measurement process is described in Schmidt et al. (2014) and summarised here as follows. The cameras of VTF have a pixel size of 12 μm, which corresponds to 0.014 arcsec and 10 km on the sun. This corresponds to a diffraction-limited spatial resolution of 0.028 arcsec at a wavelength of 520 nm.

To reach its spectral resolution of $\Delta \lambda / \Delta \lambda = 100,000$, the wavelength spacing amounts to 3 pm at a wavelength of 600 nm. For our study we use Fe I 1617.3 nm ($g = 2.5$), which has very similar properties to Fe I 630.2 nm. The VTF cameras are operated with a frame cycle time of 40 ms, of which 25 ms are used as exposure time. Simultaneously with each narrow-band image, a broad-band image is recorded in a separate channel of the instrument.

The VTF can be operated in spectroscopic and spectropolarimetric mode. For both modes the number of scanning steps, number of accumulations, and the binning size can be adjusted. The VTF Instrument Performance Calculator (IPC, Version 3.4)\(^2\) was developed to tune these free parameters and to estimate the resulting S/N as well as the time of the measurement. We note that the IPC calculates the S/N for Stokes I, and does not take into account polarimetric efficiencies. A default spectroscopic measurement with one accumulation at full spatial resolution with a S/N above 200 takes less than one second ($\approx 0.88$ s) to measure, for example Fe I 617.3 nm with 11 wavelength scan steps (each scan step to tune the FPIs takes one camera cycle time of 40 ms). In the photosphere, changes in physical parameters on a timescale of one second are not expected within resolution elements as large as 20 km.

Spectropolarimetric measurements take more time, on the one hand because four modulation states need to be measured instead of one, and on the other hand because the polarimetric signal in the spectral line is weak and requires a large number of photons. To minimise seeing-induced cross-talk, in addition to doing dual-beam polarimetry, the four modulation states are acquired consecutively with four single exposures. To increase the number of photons and reduce the photon noise, consecutive accumulations can be chosen at each wavelength position. With six accumulations, a 1σ noise level of 1/577 = 0.0017 is reached (with continuum intensity being normalised to 1). To detect a signal it should have a minimum amplitude of $3\sigma$, which corresponds to about 0.005. This limits the minimum magnetic field strength which can be detected. In our case computing synthetic line profiles for Fe I 1617.3 nm of a quiet-Sun model and a spectral resolution of 100,000, we find that a Stokes V amplitude of 0.005 is produced by a constant vertical field of ~20 G at disc centre (cf., Schubert 2016; Schubert et al. 2017). We note that a horizontal homogeneous field needs 175 G to produce a Q-signal of 0.005. With a horizontal field strength of 100 G, the Q-amplitude amounts to 0.0017 (see also Borrer & Kühle 2012, 2013).

Schmidt et al. (2016) estimate the Doppler shift sensitivity to approximately 80 m s$^{-1}$, taking into account photon noise and stray light. We note that non-parallelism of the FPI plates was not considered as a source of error in this estimate.

With six accumulations, $6 \times 4 = 24$ single frames are recorded at each wavelength step; 11 spectral points are measured in 11 s (i.e. 1 s per spectral point). This means that a single spectropolarimetric VTF measurement with six accumulation takes 11 s in total. The task of this contribution is to investigate, based on realistic numerical simulations, whether dynamic changes are expected in the photosphere within 11 s, and if yes, how much these changes affect the measurement. We note that many science cases require a noise level lower than 0.0017. With 12 accumulations, which take 21.6 s, VTF reaches a 1σ noise level of 0.0012; instead, 18 accumulations and 31 s are needed to reach a noise level of 10$^{-3}$. Measurements with longer

---

\(^2\) [https://www.leibniz-kis.de/en/forschung/wissenschaftliche-instrumentierung/vtf/performance-calculator/](https://www.leibniz-kis.de/en/forschung/wissenschaftliche-instrumentierung/vtf/performance-calculator/)
scanning times are more affected by the dynamic evolution in the photosphere. However, in this contribution we assume that the measurement process takes 11 seconds for 11 scan steps (i.e. we imitate the case of six accumulations).

3. Methods

To mimic the measurement process of VTF, we took consecutive snapshots of a realistic magnetohydrodynamic simulation of a solar plage region (Sect. 3.1), synthesised Stokes profiles and adapted them to the VTF spectral resolution and acquisition procedure (Sect. 3.2). In Sect. 3.3, we introduce an alternative way to construct the line profiles, normalising each wavelength point to the local continuum intensity. As a result, we produced different sets of Stokes profiles from the 11 time steps of the simulation. In Sect. 3.4, we describe how these different sets of profiles are inverted to retrieve the physical parameters of the line-of-sight velocity and the vertical component of the magnetic field strength.

To quantify the error of the measurement process, we need to define a reference or true map. As true maps, we use the maps that result from the inversion of profiles that are synthesised from time-averaged simulation boxes (over all 11 snapshots), which means that these profiles are not affected by the finite acquisition time, and therefore serve as reference. Finally, all the different sets of maps are compared in Sect. 4. By comparing the physical parameters between the inverted maps from constructed profiles and the reference maps, we can estimate the error that is introduced by the finite acquisition time.

3.1. Solar plage simulation with MURAM

As a typical target for VTF observations we take a plage region with a spatially averaged vertical magnetic strength of 200 G. This simulation was performed with MURAM by Matthias Rempel (private communications, and see Rempel 2014). With a grid cell size of $8 \times 8 \times 8 \text{ km}^3$, the simulation reaches the spatial resolution of VTF mounted at DKIST. The simulation box has $768 \times 768 \times 384$ cells. The box reaches from the upper photosphere into the solar interior. The upper end of the box lies 704 km above the average $\tau = 1$ level. As the lateral box sides have periodic boundary conditions, the magnetic flux through each depth layer is the same and is constant in time.

The internal numerical time step of the simulation is around 0.1 s. We limit our analysis to snapshots with a temporal cadence of 1 s (i.e. ten numerical time steps). Changes within ten time steps can be considered small for our purpose, but they contribute to an increase in the measurement errors. For this work we assume that it is sufficient to have a snapshot sequence of 1 s. This is the same cadence that VTF needs for each wavelength step when using six accumulations ($S/N = 577$).

In Fig. 2a, we display a vertical cut of the absolute magnetic field strength of the computational box. It displays a vertical strong flux concentration in the middle of the box at $x = 3 \text{ Mm}$. There the local field strength exceeds 3 kG. For the horizontal layer at which the spatially averaged temperature is 5560 K, we show the vertical components of the velocity and the horizontal magnetic field strength in Figs. 2b and c. This horizontal layer roughly corresponds to the formation height of Fe I $630.25 \text{ nm}$ such that these maps can be compared with the maps that we retrieve after line synthesis, convolution with the VTF spectral resolution, resampling, and Milne-Eddington inversion.

3.2. Synthetic line profiles with FIRTEZ adapted to VTF

From a number of suitable photospheric absorption lines we chose to analyse the Fe I $617.3 \text{ nm}$.

VTF will use Fe I $630.25 \text{ nm}$

This line has very similar properties to the iron lines at 630 nm and at 525.0 nm (Graham et al. 2003). Initially, the intention of this work was to compare VTF measurements with HMI on board SDO. The focus changed, and we continued to use Fe I $617.3 \text{ nm}$. Fe I $617.3 \text{ nm}$ has the advantage of being surrounded by a clean continuum.

Fig. 2. MURAM simulation snapshot. (a) Vertical cut through numerical box showing the modulus of the magnetic field strength in logarithmic scale, clipped between 10 and 2500 G, with the colour bar in logarithmic scale. (b) Horizontal cut at mean temperature of 5560 K of vertical velocity in $\text{km s}^{-1}$ with positive values pointing upwards (being blue-shifted to observer). (c) Same as panel b, but for the vertical component of the magnetic field strength in kG.

A78, page 3 of 10
for the first observations as long as only one FPI is available, but Fe I 617.3 nm will be available as soon as the second FPI is in place.

To synthesise Stokes $I, Q, U,$ and $V$ of Fe I 617.3 nm along vertical lines of sight in the MURAM box, we used FIRTEZ-dz (Pastor Yabar et al. 2019). FIRTEZ was chosen because it operates on the geometrical scale, which is intrinsic to the simulation box. As the conversion into optical depth along the line of sight is not needed, the computation time for the line synthesis is very short. We calculated the set of Stokes profiles for each horizontal pixel yielding maps with 768 by 768 pixels.

For the line synthesis the spectral resolution is assumed to be infinity, and is only limited by the spectral sampling. We used a spectral sampling of 0.4 pm, and computed the range from –40 pm to +40 pm.

Spectral convolution and spectral sampling. The spectral resolution of VTF follows from the properties of the first FPI. The spectral transmission profile (see e.g. Sect. 3.4.4 in Stix 2002) can be computed for small angles of incidence from its reflectance, $R = 0.95$, and its cavity separation, $d = 0.55$ mm (Kentischer et al. 2012; Schmidt et al. 2014; Sigwarth 2017). A prefiler is assumed to suppress the side peaks and to transmit only the central peak. The transmission profile of the central peak corresponds to a spectral resolution of 100 000 and has a full width at half maximum of 5.7 pm. All FIRTEZ profiles are convolved with this transmission profile and resampled to the VTF spectral step width of $\Delta \lambda = 3.15$ pm. A set of sample profiles are depicted in Fig. 3. The synthetic lines of Stokes $I, Q, U,$ and $V$ of a sample pixel are drawn in red. The blue lines display the same profiles after accounting for the spectral resolution of VTF, and the blue crosses show the spectral sampling of VTF. To sketch the shape of the tuneable VTF transmission profile, it is plotted as a green line in the Stokes $U$ plot. Thus, in the end we have Stokes profiles (at the spectral resolution and sampling of VTF) for a set of 11 snapshots, which have a temporal cadence of 1 s.

Temporal sampling. To mimic the VTF line scan, we composed the Stokes profiles with one wavelength step per consecutive snapshot; in other words, we produced a set of profiles with 11 wavelength points ($t = 0, 1, \ldots, 10$ s). We do this in two modes: straight and rabbit. In the straight mode the wavelength step increases monotonically by one: $\lambda_{i+1} = \lambda_i + \Delta \lambda$. In the rabbit mode we jump from the blue wing to the red wing, successively approaching the line core: $\lambda_{i+1} = \lambda_i + 2 \times (\lambda_{\text{ic}} - \lambda_i)$ and $\lambda_{i+2} = \lambda_i + \Delta \lambda$, with $\lambda_{\text{ic}}$ being the wavelength step closest to the spatially averaged line core. The idea of the rabbit mode is to sample both line wings as close in time as possible. Here, the Doppler shift error from the finite acquisition time is expected to be minimised.

Seeing and solar evolution. The rabbit mode was devised for VTF to also minimise the effects of seeing. The seeing is partially corrected by the adaptive optics system. The resulting degree of image correction varies on scales of seconds and shorter. With the rabbit mode the goal is to record the two line wings with similar seeing. However, the effects of seeing are not analysed in this work. We ignore seeing effects, and only consider the effects of solar evolution during the line scan.

Reference profile and temporal changes. In order quantify the systematic measurement errors, we need to define a reference. We used profiles from temporally averaged snapshots for each pixel as the reference, which means that we averaged all 11 snapshots and performed the line synthesis on the averaged box. Alternatively, it is possible to average the synthesised profiles from the 11 snapshots and do the inversion on the time-averaged profiles. We checked that both approaches lead to identical results within the noise, which is on the same scale as the difference between two consecutive snapshot maps.

In Fig. 4, we illustrate the temporal change of the profiles. We select a sample pixel and plot the Stokes profiles retrieved from the first snapshot 1 (blue line), from the last snapshot 11 (red line), and from the temporally averaged profiles from all 11 snapshots (black line). In the upper left panel, it can be seen that the intensity of the left-most wavelength point drops from approximately 1.28 to 1.02 (i.e. by more than 25% during the measurement process across 11 wavelength points).
3.3. Profile composition with normalisation

Viewing animations of the snapshots, it becomes apparent that magnetic concentrations, which are visible as bright points in the inter-granular lanes, are shuffled around by the granular flow field. As a consequence, the continuum intensity of an inter-granular pixel can change significantly during the wavelength scan. This is demonstrated in Fig. 5, where we display the normalised continuum intensity of the first snapshot and the difference map between the first (snapshot 1) and last (snapshot 11) snapshot. The difference map is clipped at absolute differences of 0.1. We compute that in 13% of all pixels the intensity difference is larger than 0.05, and in 4% of all pixels the difference is larger than 0.1. The standard deviation amounts to 0.034. In comparison, the standard deviation of intensity differences between the first and second snapshot amounts to 0.006.

If the continuum intensity, for example, decreases continuously during a straight wavelength scan, an analysis of the corresponding composed Stokes $I$ profile would yield different intensity levels of the blue and red continua. This would be interpreted as an additional line absorption in the red wing (i.e. as an enhanced red-shift). This example suggests that it might be an advantage to normalise the line absorption to the continuum. Since we have the full simulated profiles at each time step (= wavelength step), it is possible to do this. Obviously, this is not straightforward for the VTF measurement. However, as VTF is operated with a simultaneous broad-band channel, this normalisation could be performed using the broad-band intensity as it varies during the line scan at a given spatial pixel.

In Fig. 6, we illustrate how the straight profile is normalised, and compare the different Stokes $I$ profile types for the same spatial pixel as in Fig. 4. The black line displays the time-averaged profile. The red line displays the straight VTF measurement mode. The rabbit mode behaves similarly to the straight profiles and is not displayed. The green line denotes the continuum intensity variation during the measurement process. From these continuum points, the temporal mean is calculated. This mean value, $⟨I(\text{cont}_i)⟩_{i=1,...,11}$, is used to normalise each wavelength point of the straight profile (red line):

$$I_{\text{normalised}}(λ_i) = \frac{I(λ_i)}{I(\text{cont}_i)} · ⟨I(\text{cont}_i)⟩_{i=1,...,11}.$$  \hfill (1)

This normalised profile is drawn as blue line in Fig. 6, which shows that the normalised straight profile becomes very similar to the time-averaged profile. Therefore, we expect the normalised profiles to lead to physical parameters that are closer to the reference (time-averaged) parameters. For pixels in which the continuum intensity is constant in time, the straight, normalised, and time-averaged profiles are identical.

3.4. Milne-Eddington inversion with VFISV

To compare the differently composed Stokes profiles, we performed Milne-Eddington inversions and compared inverted
maps of the line-of-sight velocities, $v_{\text{los}}$, and of the vertical (line-of-sight) component of the magnetic field strength, $B_{\text{los}}$, for the different profile types. The Milne-Eddington approximation assumes that $v_{\text{los}}$, $B$, and $B_{\text{los}}$ are constant along the line of sight across the solar photosphere. An inspection of the numerical simulation (see e.g. the vertical cut of $B_{\text{los}}$ in Fig. 3.1) shows that this is clearly not the case, and these quantities change significantly along the line of sight. However, in order not to introduce additional error sources due to sophisticated inversions, we limit our analysis to Milne-Eddington inversions.

As inversion code, we used the “Very Fast Inversion of the Stokes Vector” (VFISV, Borrero et al. 2011). This code was originally devised to invert data from the Helioseismic and Magnetic Imager (HMI) on board the Solar Dynamic Observatory and was later adapted to data acquired with slit spectrographs as for GRIS installed at GREGOR (Collados et al. 2012), and to data acquired with Fabry–Perot systems. In the Fabry–Perot version, the VTF transmission file can be selected in such a way that it is taken into account in the inversion process. We note that we use the identical transmission profile in the convolution with the synthetic profiles in Sect. 3.2. As free parameters we use $\eta$, field inclination $\gamma$, field azimuth $\phi$, damping $a$, Doppler width $\delta v_{\lambda}$, field strength $B$, line-of-sight velocity $v_{\text{los}}$, source function continuum, and the source function gradient. The magnetic filling factor is put to unity and is not used as free parameter.

4. Results and discussions

4.1. Inverted maps for reference (time-averaged) profiles

Inverted maps for $v_{\text{los}}$ and $B_{\text{los}} = B \cdot \cos(\gamma)$ of the reference (time-averaged) profiles are displayed in Fig. 7. These maps correspond to the average along the line of sight, but for consistency, they can be compared to the horizontal geometrical cuts at the mean temperature of $5560 \text{ K}$ in Figs. 2 b and c. In both figures, we use the same colour-coding and clipping values. They are obtained after line synthesis with FRTIEZ on the time-averaged numerical box, convolution with the instrument transmission profile (Sect. 3.2), and VFISV inversion (Sect. 3.4).

These maps reflect the ideal theoretical expectation of what VTF mounted at DKIST will measure in a plage region with an average vertical magnetic field strength of 200 G. It is therefore of interest to plot the histogram distribution for $v_{\text{los}}$ and $B_{\text{los}}$ in Fig. 8. Both distributions are non-symmetric. The up-flow velocities do not reach values as high as the down-flow velocities, but occupy a larger area for small absolute values. Opposite polarity in the magnetic field is present and reaches values of up to –400 G. The distribution of the positive vertical component of the magnetic field peaks at approximately 1300 G and $B_{\text{los}}$ reaches values of up to 2.4 K G.

4.2. Average of the vertical magnetic field strength

The horizontal average vertical magnetic field strength (magnetic flux through a horizontal cut) in the simulation box is constant at all depth layers and at all times due to the periodic boundary conditions on the sides of the box. It was chosen to be 200 G. This number can be compared with maps of $B_{\text{los}}$ for the various types of profiles. Averaging the $B_{\text{los}}$ across the inverted maps we obtain $\langle B_{\text{los}} \rangle = 208 \text{ G}$ for the reference profiles, 203 G for the straight normalised VTF profiles, and 206 G for the rabbit VTF profiles.

4.3. Oscillation of the numerical box

Similarly to Sun, the MURAM box exhibits five-minute oscillations that are visible in maps of $v_{\text{los}}$. Therefore the average line-of-sight velocity is not constant. The particular snapshots that we analyse change from a mean velocity of 41 m s$^{-1}$ in the first snapshot by approximately 2 m s$^{-1}$ to 18 m s$^{-1}$ in the figure.

---

4. gitlab.leibniz-kis.de/borrero/vfisv_spec
5. gitlab.leibniz-kis.de/borrero/vfisv_fpi
eleventh snapshot. Hence, the spatially averaged $v_{\text{los}}$ changes by $21 \text{ m s}^{-1}$ during the analysed VTF measurement process.

4.4. Difference maps for maps of $v_{\text{los}}$ and $B_{\text{los}}$

As explained in Sect. 1, the purpose of this study is to quantify the measurement error due to a finite measurement time of $11 \text{ s}$. To determine the error we compare simulated VTF maps to the reference (time-averaged) maps by computing difference maps. In the upper two panels of Figs. 9 and 10, we display the difference maps from the inversion of straight VTF profiles and the straight normalised VTF profiles with the reference maps. For $v_{\text{los}}$, the differences are clipped at $\pm 200 \text{ m s}^{-1}$, and for $B_{\text{los}}$ at $\pm 150 \text{ G}$. By visual inspection it is seen that the differences are smaller for the straight normalised profiles if compared to the straight VTF profiles. The improvement of the normalisation is clearly seen in $v_{\text{los}}$ and less prominent but still visible in $B_{\text{los}}$.

These differences are quantified in the next subsection.

The lower two panels of Figs. 9 and 10 illustrate the solar evolution during the measurement process by displaying the difference maps between the first and second snapshot (separated by one second, snap1 and snap2) and between the first and eleventh snapshot (separated by $10 \text{ s}$, snap1 and snap11). As expected the difference between snap1 and snap11 is much larger than between snap1 and snap2. The difference between snap1 and snap2 can have two causes: solar evolution and/or sensitivity of the inversion process. As the solar evolution on a timescale of one second is expected to be insignificant, we ascribe these differences mostly to the sensitivity of the inversion process which is limited by the spectral resolution and the Milne-Eddington approximation.

Fig. 9. Difference maps for $v_{\text{los}}$ (in m s$^{-1}$). From top to bottom: Difference between reference map and straight VTF map; same for straight normalised VTF map; difference from first snapshot (snap1) to second snapshot (snap2); same for eleventh snapshot (snap11).
Fig. 10. Same as Fig. 9, but for $B_{\text{los}}$ (in gauss).

Fig. 11. Histograms of difference maps for line-of-sight velocity, $\Delta v_{\text{los}}$, in upper panel a and the vertical component of the magnetic field strength, $\Delta B_{\text{los}}$, in lower panel b. The histograms include pixels that have $100 \, \text{G} < |B_{\text{los}}| < 2500 \, \text{G}$. This corresponds to 25% of all pixels. The differences are taken for different cases: Red line $\rightarrow$ straight VTF and reference map; blue line $\rightarrow$ normalised straight VTF and reference map; green line $\rightarrow$ rabbit VTF and reference map; black line $\rightarrow$ snapshot 1 and snapshot 2; yellow line $\rightarrow$ snapshot 1 and snapshot 11.

4.5. Error quantification

In order to quantify the visual impression of the difference maps, we compute histograms and plot them in Fig. 11. As the deviations are largest in the inter-granular lanes and in the filigree (magnetic) regions, we consider only pixels in which the vertical line-of-sight field strength of the reference map exceeds 100 G. We ignore 67 pixels with $B_{\text{los}} > 2500 \, \text{G}$ as outliers. The histograms then include 25% of the pixels (i.e. 146 529 out of 589 824 pixels). The different line colours correspond to the different cases (see figure caption).

- (straight VTF–reference) $\rightarrow$ red line
- (normalised straight VTF–reference) $\rightarrow$ blue line
- (rabbit VTF–reference) $\rightarrow$ green line
- (snapshot 1–snapshot 2) $\rightarrow$ black line
- (snapshot 1–snapshot 11) $\rightarrow$ yellow line.

The histograms of the $v_{\text{los}}$ maps are plotted with a bin width of 10 m s$^{-1}$ in Fig. 11a. The distributions peak close to vanishing differences. The peak height and the width are a quantitative measure for the measurement error: the larger the peak and the smaller the width, the smaller the measurement error. The visual impression of Fig. 9 is reflected in the distributions in terms of peak height and width: snapshot 1–snapshot 2 has the largest peak and the
by a factor of 1.65. Analogously, we determine the width, $w_{\text{los}}$, for different mask criteria: all pixels (first column), pixels with $|B_{\text{los}}| < 0.1$ kG (second column, 75%), pixels with $0.1 < |B_{\text{los}}| < 2.5$ kG (third column, 25%), pixels with $0.2 < |B_{\text{los}}| < 2.5$ kG (fourth column, 20%).

The histograms of the $B_{\text{los}}$ maps are plotted with a bin width of 0.1 kG in Fig. 11b. Again, the black line (snap 1 – snap 2) has the largest peak at 11 716 and 10 177, respectively (i.e. again, the normalised straight mode performs better than the straight mode). These two distributions peak substantially by roughly a factor of two: $1\sigma = 182$ m s$^{-1}$ for $B_{\text{los}} > 100$ G and 201 m s$^{-1}$ for $B_{\text{los}} > 200$ G. Hence, the $1\sigma$ errors from solar evolution are substantial for a measurement span of 11 s.

In the normalised straight mode, the $1\sigma$ error decreases substantially by roughly a factor of two: $1\sigma = 36$ m s$^{-1}$, if no mask is applied, which is of the same order of magnitude as the VTF sensitivity. For magnetic pixels (last two columns in Table 1), the $1\sigma$ error is more than double the size of the noise level: $1\sigma = 182$ m s$^{-1}$ for $B_{\text{los}} > 100$ G and 201 m s$^{-1}$ for $B_{\text{los}} > 200$ G. The errors of the rabbit mode are slightly better than those of the straight mode, but not as small as those of the normalised straight mode.

Comparing the errors of snap 1 – snap 2 and snap 1 – snap 11 demonstrates that the temporal evolution is significant. The differences between the first two snapshots are small, much smaller than the VTF sensitivity. They are probably mostly caused by the low spectral resolution which does not allow for a more accurate determination. However, the errors between the first and the eleventh snapshot increase by a factor of eight or more: from $1\sigma = 18$ m s$^{-1}$ to $195$ m s$^{-1}$ for all pixels, and from $1\sigma = 50$ m s$^{-1}$ to $433$ m s$^{-1}$ for the pixels with $B_{\text{los}} > 100$ G.

We also computed the histograms for spatially binned data and list the results in Table 3 for the magnetic pixels with $B_{\text{los}}$ between 0.1 and 2.5 kG. We find that the $1\sigma$ errors of the straight mode decrease from $1\sigma = 181$ m s$^{-1}$ for no binning, to $1\sigma = 169$ m s$^{-1}$ for two by two binning, to $1\sigma = 148$ m s$^{-1}$ for four by four binning. Hence, even with a four by four binning the time-evolution error exceeds significantly the VTF sensitivity if the measurement is done in the straight mode. A four by four binning would correspond to the diffraction limit of a 1 m aperture telescope.

It should be noted that if the measurement objective is to measure only velocities and not magnetic fields, the non-polarimetric Doppler mode can be chosen in which one accumulation is enough to measure the Stokes $I$ line profile. This measurement only takes 0.9 s (VTF IPC, v.3.4, see Sect. 2), and deviations due to solar evolution can be safely neglected.

4.5.2. Errors in $v_{\text{los}}$ maps

In Table 2, the error values characterising the distribution of the $\Delta B_{\text{los}}$ map are listed. These errors are to be compared to the VTF measurement sensitivity of 20 G, which results from the photon noise (see Sect. 2). It is seen that the $1\sigma$ errors for the entire map and for weak-field pixels ($<100$ G) are negligible for straight and normalised straight modes. However, within the magnetic filigree the time-evolution errors are substantial. Considering all
pixels with $B_{\text{los}}$ between 100 and 2500 G, the error amounts to 48 G in the straight mode and to 36 G in the normalised straight mode, which is significantly larger than the 20 G error due to noise. Interestingly, the rabbit mode has an error of 84 G, and thus performs worse than both the straight and the normalised straight mode. It seems that the Milne-Eddington inversion can deal better with profiles where the neighbouring wavelength points are recorded close in time. It is not straightforward to explain this behaviour.

The differences between two consecutive snapshots (1 and 2) are negligible and smaller than 20 G in all cases. The time evolution is well reflected in the differences between the first and the eleventh snapshot (1 and 11). These differences correspond to an error of $1\sigma = 91$ G for the magnetic pixels exceeding 100 G. Hence, for filigree and magnetic features which are shuffled around in the inter-granular lanes, the fields are strong enough, and more accumulation and longer effective exposure times will not improve the measurement. Due to their dynamic behaviour and strong fields, it may even be better to measure them with fewer accumulations (i.e. shorter effective exposure times). To measure magnetic fields in and above granules, the situation is different: the evolution timescale is longer and the magnetic fields are weaker. Hence, for granular magnetic fields more accumulations might be wanted to improve the S/N. However, one should be aware that a homogeneous horizontal field of 100 G produces a $Q$-amplitude of only some 0.0017 for Fe I 617.3 nm.

### 4.6. Implication for data pipelines

We have seen that the errors due to solar evolution can in all cases be reduced by normalising the continuum intensity to the instantaneous continuum intensity during the measurement as indicated by Eq. (1). This can be done in our case because we compute the whole line profile and its continuum for each snapshot. However, a Fabry–Perot instrument measures only one wavelength point at a time.

Instruments like VTF, CRISP, CHROMIS, and IBIS simultaneously measure a broad-band image at a neighbouring wavelength. These broad-band images can be used to mimic the temporal variation of the continuum intensity. To our knowledge, this is not currently done in existing Fabry–Perot data pipelines. In order to apply Eq. (1), one needs to scale the broad-band images to the continuum intensity of narrow-band images. As seen in Fig. 3, a complication may arise if a true continuum wavelength point is not part of the measurement sequence. Hence, in practise two approaches could do the job. The first is to add one more wavelength point to include a true continuum point outside the line. This point can then be used to determine the scaling factor between the broad-band intensity and the narrow-band continuum intensity. In the second approach, if the continuum intensity cannot be measured, for example because the line is too broad for the narrow pre-filter, it is necessary to compute the average measured profile of a quiet-Sun region, fit a quiet-Sun profile to it, and determine the continuum intensity from the fitted profile to scale the broad-band intensities.

### 5. Conclusions

We investigated the measurement errors that arise due to temporal changes during the measurement process. Already with the 1.5 m telescope GREGOR (see Fig. 1), it could be seen that magnetic features in inter-granular lanes are shuffled around on a timescale of 11 s. This was also seen in the MURAM numerical simulations of a region with a mean vertical field strength of 200 G (see Fig. 5). Based on these simulations, we mimicked the measurement process of VTF and determined the measurement error by defining the truth to be the temporal average of the time that elapses during the measurement.

We find that granules are less affected and inter-granular areas with magnetic features are strongly affected. Depending on the science objective, it might be advisable to adapt the effective exposure time in the measurement. To measure strong fields in the inter-granular lane only a few accumulations may be enough, and would reduce the measurement error as the effective exposure time is reduced. For weaker fields within granules, more accumulations can be used as the evolution timescale is longer. For predominantly horizontal (perpendicular to line-of-sight) fields, more accumulations are necessary because the amplitude of linear polarisation in horizontal fields is much weaker than circular polarisation in vertical fields.

A key result of this investigation is the finding that a normalisation of the narrow-band intensities with the temporally averaged continuum intensity, following Eq. (1) (see Fig. 6 for an illustration), leads to a significant reduction in the measurement errors. In Sect. 4.6, we discuss how this normalisation could be integrated in existing pipelines, taking advantage of the simultaneously measured broad-band image.

Acknowledgements. We thank Matthias Rempel for providing the MURAM simulations, and Markus Schmassmann for making the data accessible and software to read the data. We thank Philipp Lindner for providing the GREGOR data used in Sect. 1.

References

Berkfeld, T., Schmidt, D., Soltau, D., von der Lühe, O., & Heidecke, F. 2012, Astron. Nachr., 333, 863
Borrero, J. M., & Kobel, P. 2012, A&A, 547, A89
Borrero, J. M., & Kobel, P. 2013, A&A, 550, A98
Borrero, J. M., Tomczyk, S., Kubo, M., et al. 2011, Sol. Phys., 273, 267
Collados, M., López, R., Páez, E., et al. 2012, Astron. Nachr., 333, 872
Denker, C., Kuckein, C., Verma, M., et al. 2018, ApJS, 236, 5
Domínguez-Tagle, C., Collados, M., López, R., et al. 2022, J. Astron. Instrum., 11, 2250014
Graham, J. D., Horton, A., López Ariste, A., et al. 2003, in Solar Polarization, eds. J. Trujillo-Bueno, & J. Sanchez Almeida, Astronomical Society of the Pacific Conference Series, 207, 131
Jurčák, J., Collados, M., Leenaarts, J., van Noort, M., & Schlichenmaier, R. 2019, Adv. Space Res., 63, 1389
Kathakkal, A. J., Borrero, J. M., Fischer, C. E., Domínguez-Tagle, C., & Collados, M. 2020, A&A, 634, A131
Kentschis, T. J., Schmidt, W., & Sigwarth, M. 2012, VTF: ETALONS, Tech. Rep. VTF-Project Documentation: ATST-KIS-VTF-ET1000-TN-001, Leibniz-Institut für Sonnenphysik (KIS)
Pastor Yabar, A., Borrero, J. M., & Ruiz Cubo, B. 2019, A&A, 629, A24
Rempel, M. 2014, ApJ, 789, 132
Rimmele, T. R., Warner, M., Keil, S. L., et al. 2020, Sol. Phys., 295, 172
Schmidt, W., von der Lühe, O., Volkmmer, R., et al. 2012, Astron. Nachr., 333, 796
Schmidt, W., Bell, A., Halbgewachs, C., et al. 2014, SPIE Conf. Ser., 9147, 91470E
Schmidt, W., Schubert, M., Ellw arth, M., et al. 2016, SPIE Conf. Ser., 9908, 99084N
Schubert, M. J. 2016, Ph.D. thesis, Albert Ludwigs University of Freiburg, Germany
Schubert, M., Kentschis, T., & von der Lühe, O. 2017, J. Astron. Telescopes Instrum. Syst., 3, 1
Sigwarth, M. 2017, VTF Etalon 1 Coating and Stress Compensation Processing. VTF Technical Note ATST-KIS-VTF-ET1000-TN-016, Tech. rep., Kiepenheuer-Institut für Sonnenphysik (KIS)
Stix, M. 2002, The Sun: An Introduction, 2nd edn. (Berlin, Heidelberg: Springer-Verlag)
Wöger, F., von der Lühe, O., & Reardon, K. 2008, A&A, 488, 375