Presence Of 12- And 24-hour Period Oscillations In Line-Of-Sight Observables And Milne-Eddington Inversion Results From SDO/HMI

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ABSTRACT

Oscillations with 12 and 24 hour periods are present in line-of-sight (LOS) observables and, to a lesser extent, in Milne-Eddington (ME) inversion results from the SDO/HMI instrument. Such oscillations are artifacts produced by the observables codes, and are not a solar phenomenon. Their likely origin is a combination of errors in the Fe I line profile and HMI filter transmission profiles used by the LOS (MDI-like) algorithm, and errors in the filter profiles used by the ME inversion code. Here, we present some properties of these oscillations, discuss their origin and the possibility of improving the observables codes to reduce their amplitudes.

INTRODUCTION

The *Helioseismic and Magnetic Imager* (HMI; Schou *et al.*, 2012) instrument onboard SDO images the Sun at 6 wavelengths and produces line-of-sight (LOS) observables: Doppler velocity, LOS field strength, continuum intensity, Fe I line width, and line depth. It also produces full Stokes vectors, fed into the Milne-Eddington (ME) inversion code VFISV (Borrero *et al.*, 2011) to derive corresponding magnetic-field strength, inclination, and azimuth.

LOS observables are computed from the I+V and I-V Stokes parameters using an MDI-like algorithm (*e.g.* Couvidat *et al.*, 2012): by combining the intensity images taken at 6 wavelengths, a discrete estimate of the 1st and 2nd Fourier coefficients of the Fe I line profile is obtained separately for I+V and I-V. The 1st Fourier coefficients are then converted into velocities through a look-up table derived from estimates of the HMI filter transmission profiles (which vary across the CCDs and with time) and from an estimate of the Fe I line profile at rest. Additionally, a polynomial correction is applied to velocities returned by the look-up tables: the daily difference between median Doppler velocity over 99% of the solar disk (keyword RAWMEDN in hmi.V_45s) and SDO orbital velocity OBS_VR is fitted as a function of RAWMEDN, by a 3rd order polynomial. Finally, the Doppler velocity is computed as the average of the I+V and I-V corrected velocities, while the LOS field strength is proportional to the difference of these velocities. Linewidth, linedepth, and continuum intensity are not corrected by polynomial fit or look-up tables: they are estimated directly from 1st and 2nd Fourier coefficients through analytical formulae assuming a Gaussian shape for the Fe I line. The ME inversion code also uses estimates of the HMI filter transmission profiles, and assumes that the Fe I line has a Voigt profile. For all practical purposes, line width and depth are fitted at each CCD pixel: unlike with the LOS algorithm, the line profile is therefore not fixed with VFISV.

Oscillations with periods of 12 and 24 hours are visible in both the LOS and ME-inverted observables and have been reported by various groups (*e.g.* Smirnova *et al.*, 2013). Even though their periods are too long to negatively impact most HMI science goals, we aim at modifying the observables codes to mitigate the impact of, or suppress, these oscillations.

Here we describe the oscillations using the 12 min averaged HMI observables (series hmi.X_720s) obtained with the side camera, explain their potential origin, and explore the possibility of suppressing them.

OSCILLATIONS IN THE LOS OBSERVABLES

Figure 1 shows power spectral densities of the Doppler velocity in the quiet Sun and in the umbra of a sunspot (where umbra is defined

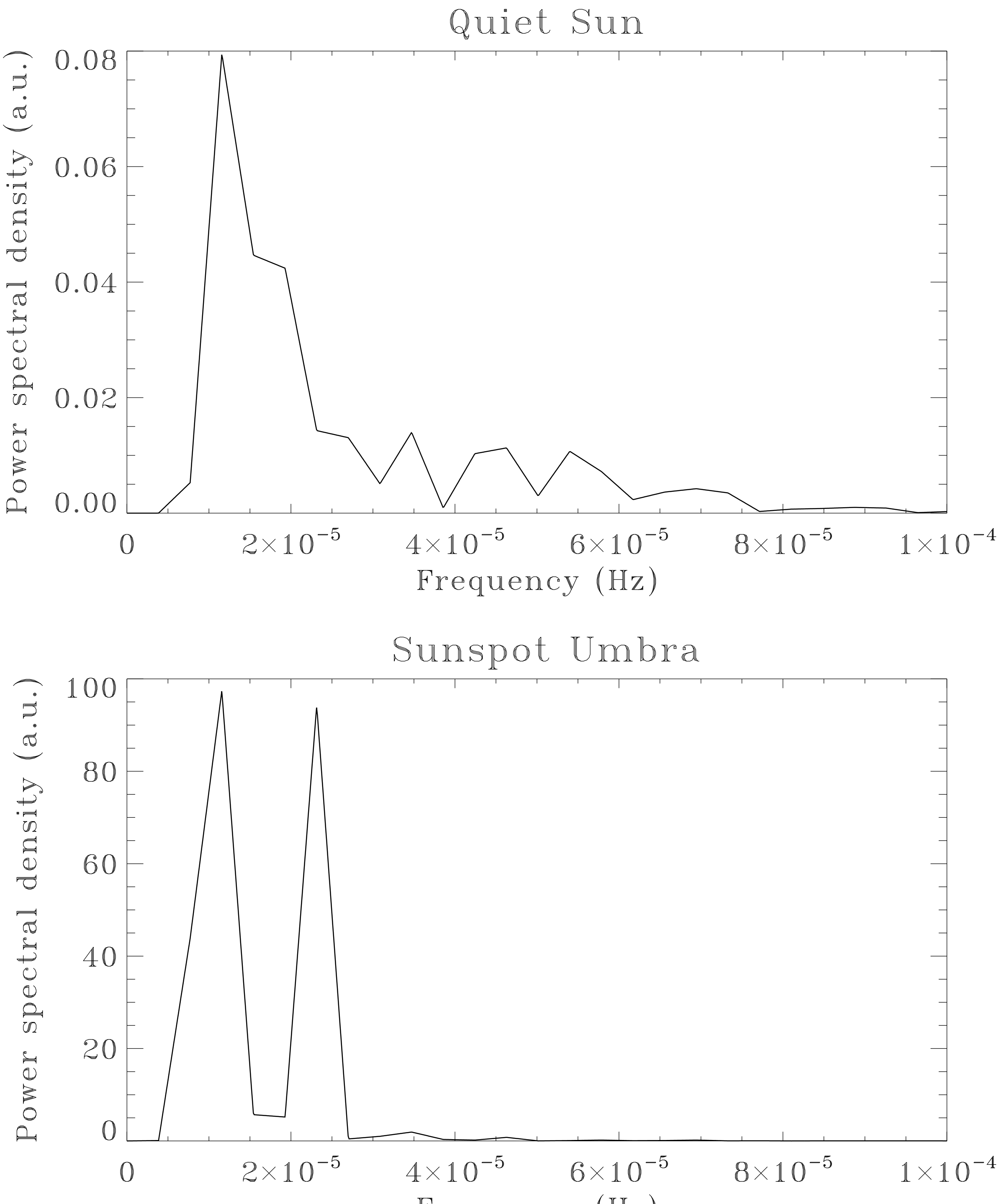

Fig. 1.— Power spectral density of HMI Doppler velocity obtained with the LOS algorithm, both in the quiet Sun (upper panel) and in a sunspot umbra (lower panel).

as the part of the spot where continuum intensity is lower than 35% of the surrounding quiet-Sun value). A polynomial fit of Doppler velocity as a function of time was subtracted from the Doppler data to remove low frequency trends prior to computing the FFT. Two peaks at $\nu = 1.16$ μHz (24 hour period) and $\nu = 2.31$ μHz (12 hour period) are clearly visible in the sunspot umbra. A much lower peak is also present at $\nu = 1.16$ μHz in quiet Sun data: oscillations are detected even in the absence of strong fields.

Figure 2 illustrates these oscillations for active region NOAA 11084 and with umbral data only. On the upper and middle left panels, the LCP (Stokes I+V) and RCP (I-V) velocities V_{LCP} and V_{RCP}, minus the average velocity V_{los} in a quiet Sun region, are plotted as a function of V_{los}. The result of a 3rd order polynomial fit of $V_{LCP} - V_{los}$ and $V_{RCP} - V_{los}$ as a function of time was subtracted and the residual (representing the error in velocity) was plotted vs time on the upper and middle right panels. Sinusoidal oscillations with a peak-to-peak amplitude of up to 900 m/s are present in the residuals. The amplitude is larger for LCP velocities when it is lower for RCP velocities, and *vice versa*. On the lower panels, the average umbral LOS field strength is plotted as a function of time (left panel), and the residual of the field strength (strength minus the 3rd order polynomial fit shown as a red curve on the left panel) is plotted as a function of mean velocity in the quiet Sun: the residual (lower right panel), representing the error in field strength, shows a quadratic dependence on velocity. A similar plot (Figure 3) using

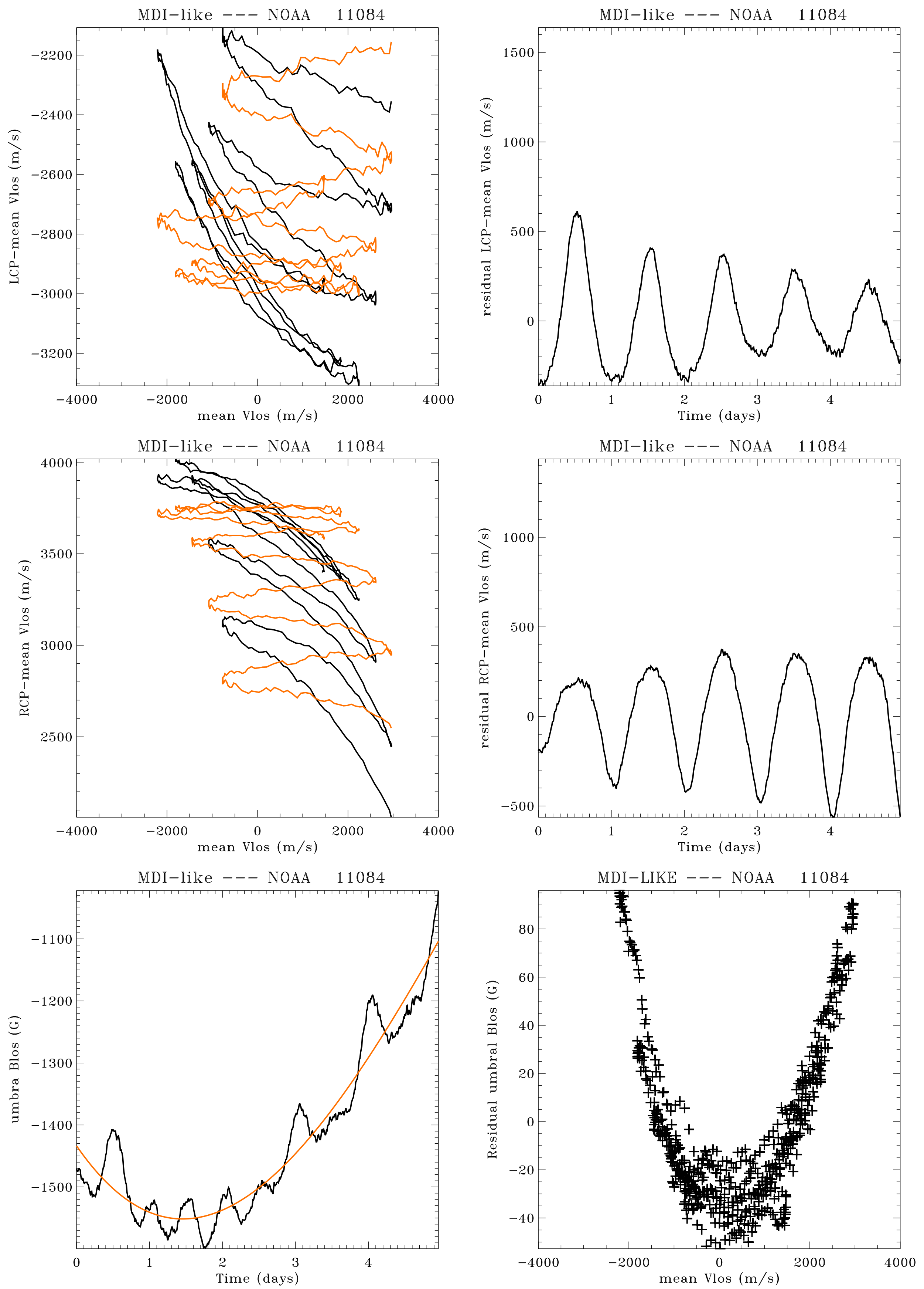

Fig. 2.— LCP and RCP velocities and LOS field strength from LOS algorithm for the umbra of NOAA 11084. Red curves in the upper and middle left panels are velocities corrected from the oscillations, while in lower left panel it is a polynomial fit of field strength.

penumbral data only (where penumbra is defined as continuum intensity between 65% and 75% of quiet-Sun intensity) confirms the presence of oscillations in weaker fields, but with a reduced peak-to-peak amplitude. The residual of the LOS field strength does not show a quadratic behaviour anymore.

Figure 4 is similar to Figure 2, but the polynomial correction was disabled before computing the LOS observables. The result is unaffected by this lack of correction, demonstrating that the correction is not responsible for the oscillations observed.

OSCILLATIONS IN THE MILNE-EDDINGTON RESULTS

Oscillations are also present in the VFISV inversion results, as shown on Figure 5 for the umbra of NOAA 11084. However, the peak-to-peak amplitude is significantly reduced compared to LOS observables. Indeed, this amplitude is only about 300 m/s for the LCP velocity residual, *i.e.* a third of the LOS algorithm amplitude. Moreover the residual of the LOS field strength (total field strength returned by VFISV multiplied by the cosine of the inclination angle) exhibits a different behaviour: it appears to be mainly linear as a function of velocity, unlike the quadratic dependence obtained with the MDI-like algorithm.

In the penumbra, the ME inversion results are much more similar to the MDI-like algorithm ones, as can be seen on Figure 6.

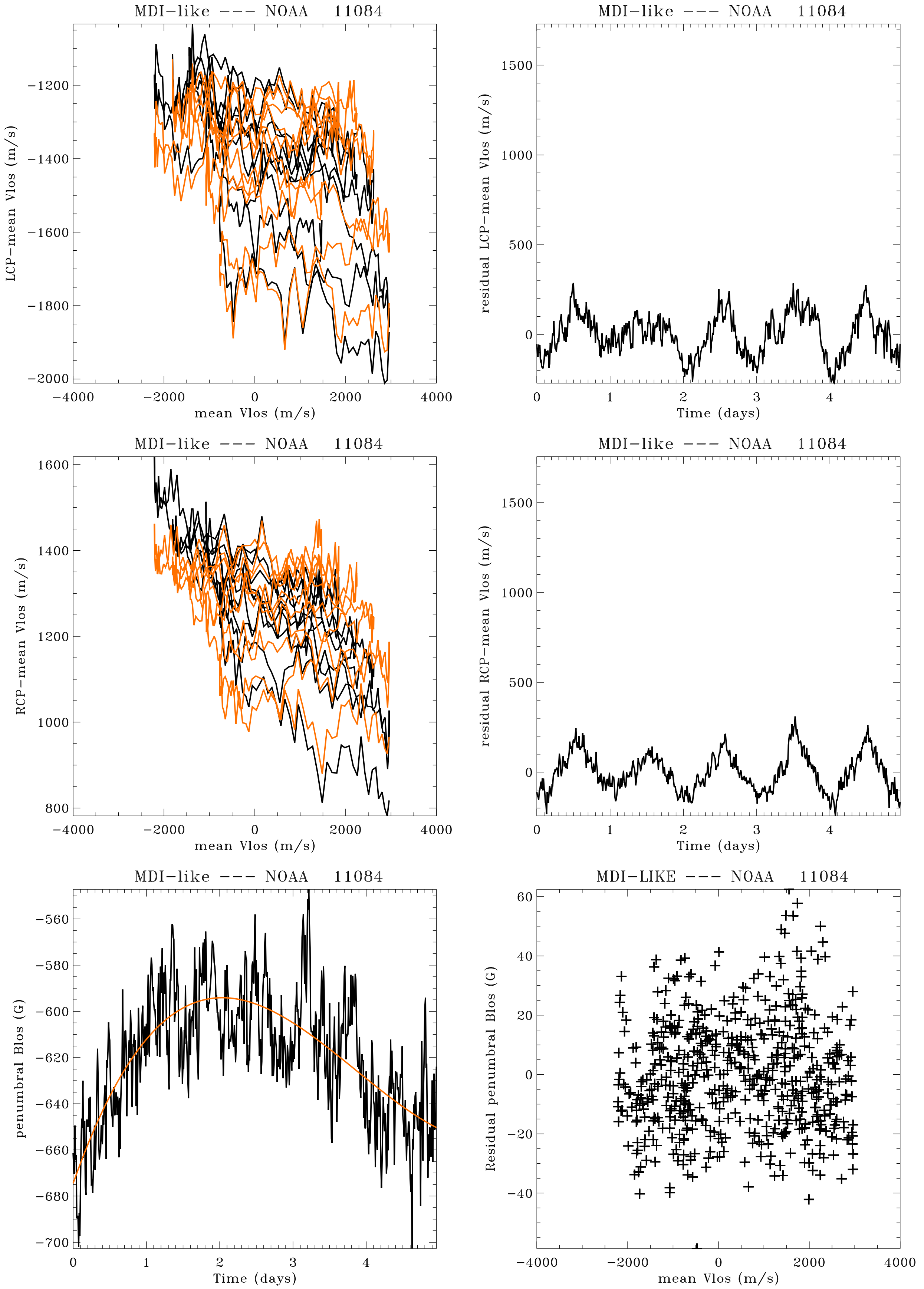

Fig. 3.— LCP and RCP velocities and LOS field strength from LOS algorithm for the penumbra of NOAA 11084. Red curves in the upper and middle left panels are velocities corrected from the oscillations, while in lower left panel it is a polynomial fit of field strength.

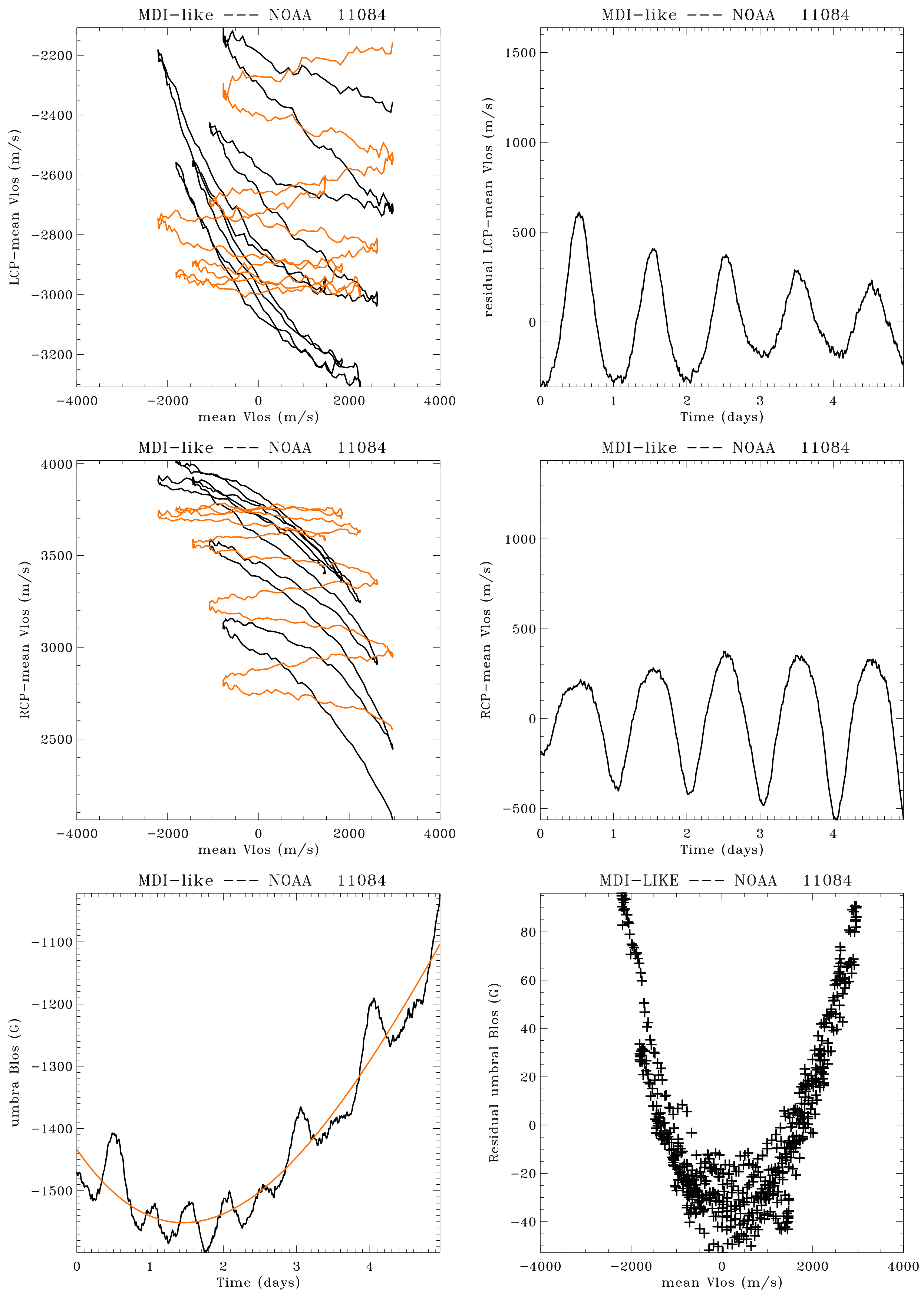

Fig. 4.— Same as Figure 2, but without polynomial correction.

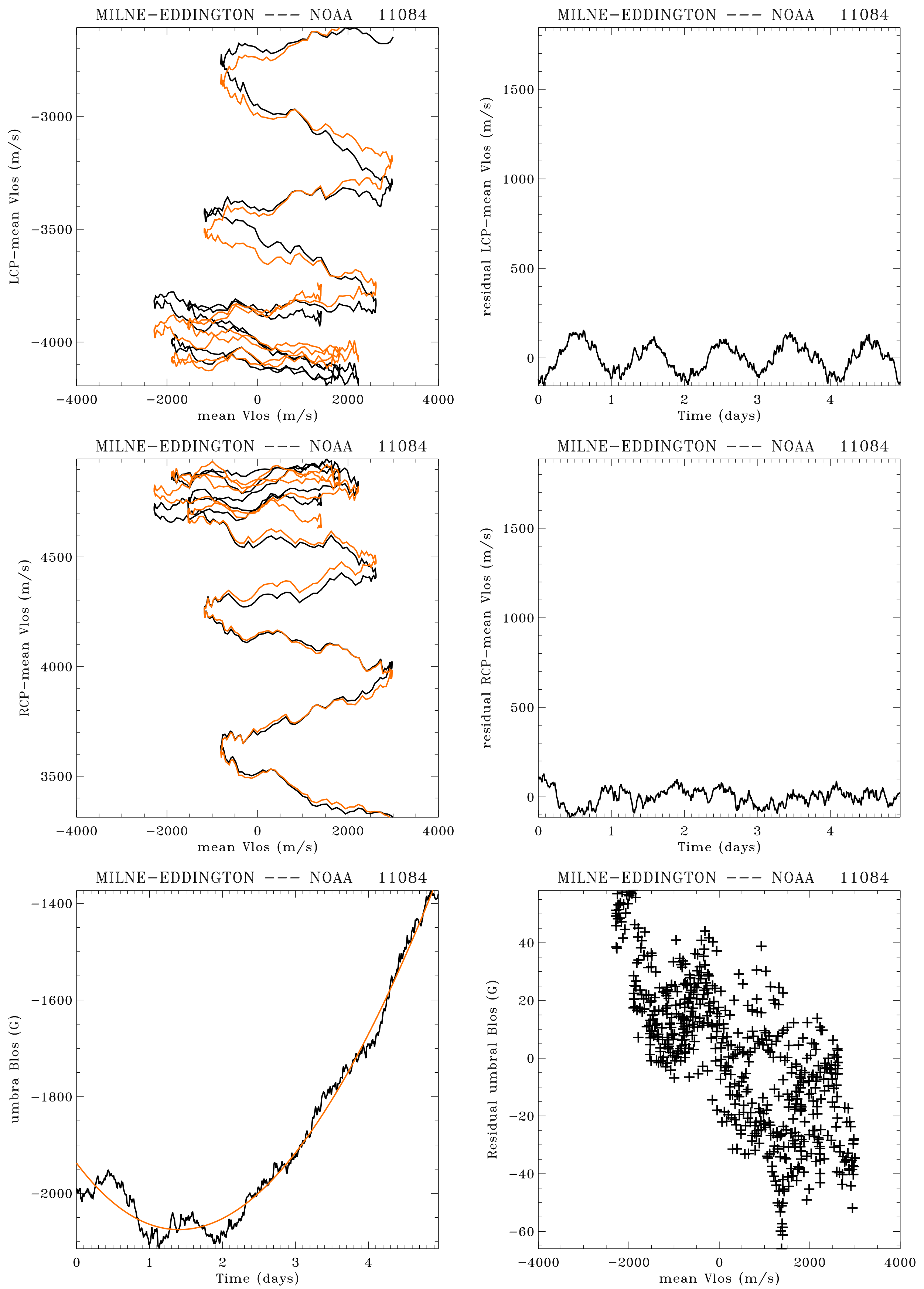

Fig. 5.— LCP and RCP velocities and LOS field strength from ME inversion for the umbra of NOAA 11084. Red curves in the upper and middle left panels are velocities corrected from the oscillations, while in lower left panel it is a polynomial fit of field strength.

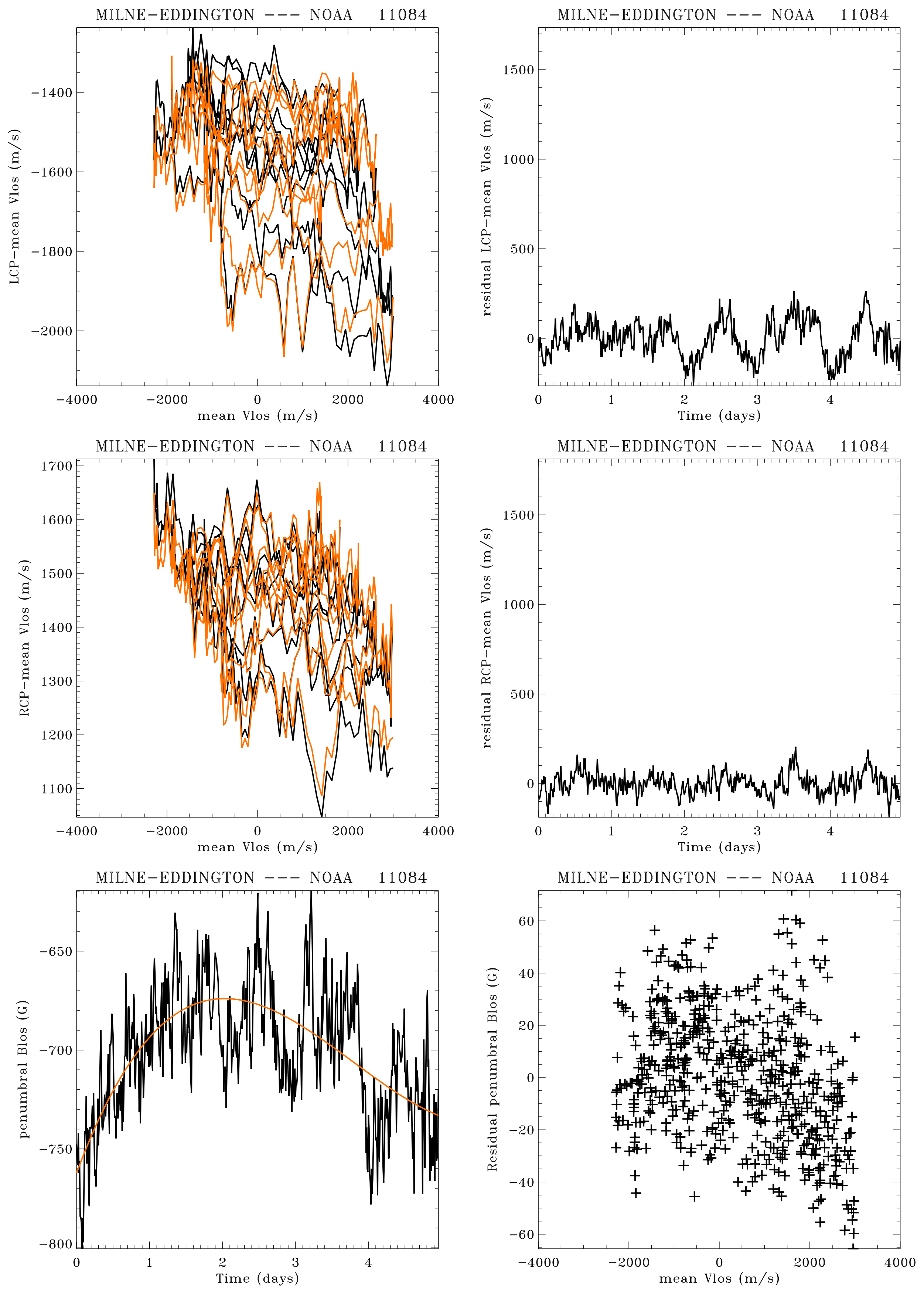

Fig. 6.— LCP and RCP velocities and LOS field strength from ME inversion for the penumbra of NOAA 11084. Red curves in the upper and middle left panels are velocities corrected from the oscillations, while in lower left panel it is a polynomial fit of field strength.

ORIGIN OF THESE OSCILLATIONS

The likely origin of these oscillations is a combination of the large daily variation in SDO orbital velocity (OBS_VR in the range $[-3.5, 3.5]$ km/s) and an error in the Fe I line profile and in the HMI filter transmission profiles used by the observables algorithms. Indeed, the LOS (MDI-like) algorithm assumes that the Fe I line has a Voigt profile, modified by 2 Gaussians to simulate the asymmetry. This profile, valid in the quiet Sun and used to produce the look-up tables, is fixed: width and depth are not adjusted in the presence of magnetic fields (but are adjusted for the center-to-limb distance), unlike the actual Fe I line which is strongly distorted in sunspots (*e.g.* Figure 3 of Norton *et al.*, 2006; Figure 6 of Couvidat *et al.*, 2012). Conversely, the ME inversion code fits for line width and depth, but still assumes that the line profile is a basic Voigt one, thus neglecting any asymmetry. A line profile error is likely to be a larger contributor to the oscillations in the LOS observables than in the ME inversion results.

The HMI filter transmission profiles are derived from calibration sequences using a simple model where only three parameters are used per optical-filter element (a contrast, a phase, and a full spectral range [FSR]): effects like an I-ripple (peak-to-peak variation in intensity with the tuning position) are therefore ignored. Some quantities characterizing the filter elements (like their FSR) are difficult to determine accurately. Overall, it is expected that the filter profiles used in the observables codes have uncertainties of the order of 1%.

Figures 7 and 8 show an example of error in velocity returned by the LOS algorithm for two problems: a random Gaussian error in filter profiles (with $\sigma = 0.01$, roughly equivalent to an I-ripple) and an error in the line profile. With the LOS algorithm, a quadratic error in velocity turns into a linear error in LOS field strength, while a cubic error in velocity produces a quadratic error in field strength. Therefore, the error (residual) observed on the lower right panel of Figure 2 may be explained by a cubic error in velocity, probably originating from the line profile used. Assuming that the behaviour observed with the LOS algorithm applies to the ME inversion, the error in field strength obtained with the ME inversion could be explained by a quadratic error in velocity resulting from errors in the HMI filter profiles.

CAN WE REDUCE OR SUPPRESS THESE OSCILLATIONS?

First, we consider the LOS field strength returned by the MDI-like algorithm. A computationally inexpensive way of correcting this field strength would be to apply a polynomial correction based on fits of the field residual. On Figure 9 we plotted the result of a fit of the residuals in sunspot umbrae and penumbrae, as a function of daily mean field strength in the structure considered. As previously

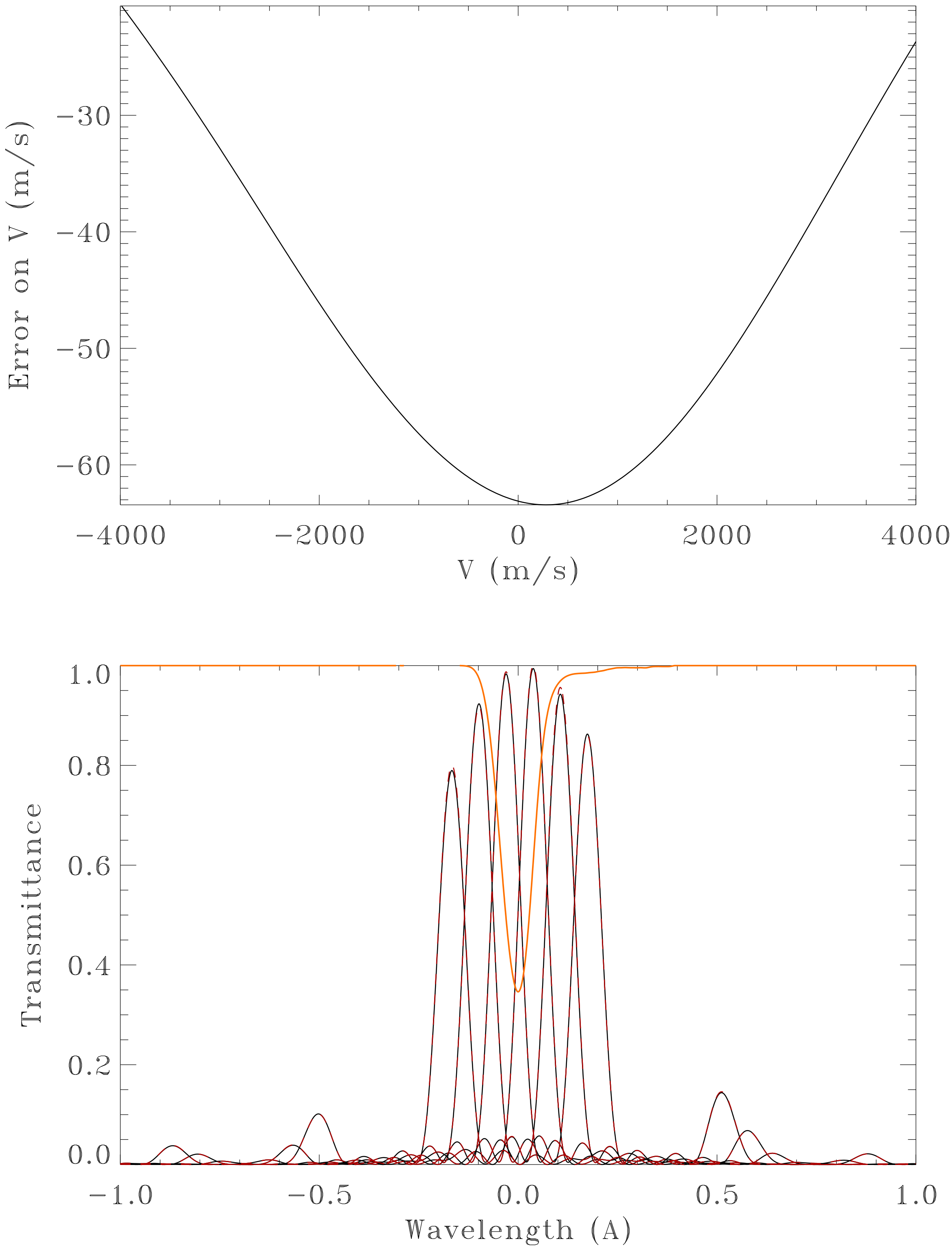

Fig. 7.— Example of impact of a random Gaussian error with $\sigma = 1\%$ in the HMI filter profiles on the velocity returned by the MDI-like algorithm (upper panel). The lower panel shows the Fe I line profile and filter profiles used for this study (dash red lines are the incorrect filter profiles, while the solid lines are for the correct profiles).

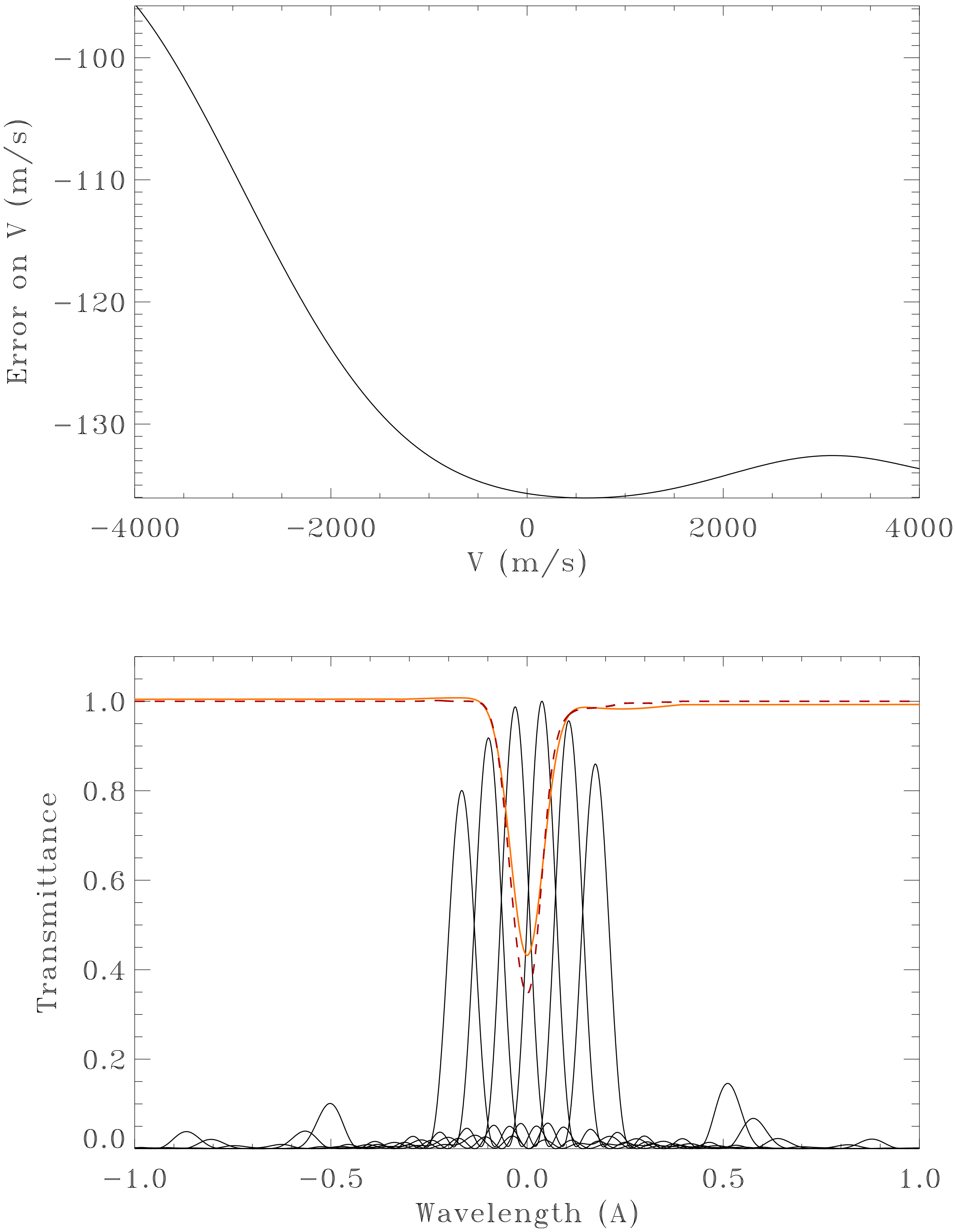

Fig. 8.— Example of impact of an error on Fe I line profile on the velocity returned by the MDI-like algorithm (upper panel). On the lower panel, the solid orange line shows the line profile used to produce the look-up tables, while the dashed red line is the actual line profile.

shown, with the MDI-like algorithm (and in an umbra) the residual has a quadratic dependence on velocity. Also, a 2nd order polynomial was fitted at each 24-hour long interval for 19 sunspots tracked for 4 to 6 days, and the resulting coefficients are plotted as a function of the daily mean field strength. When measuring the mean field and computing the residuals, we were careful not to mix magnetic polarities to avoid flux cancellation. On Figure 10 we used the ME-inverted LOS field strength: because the ME field residual varies linearly with velocity, we did a linear fit to the residuals and plotted the coefficients as a function of mean field strength.

A larger sample of sunspots is necessary to draw firm conclusions, but these preliminary results show a significant scatter in the data points, both on Figure 9 and 10. This means that fitting the LOS field residual as a function of a single parameter (here the field strength) is insufficient for an accurate correction, and other parameters might be needed. We tested linewidth, linedepth, and intensity contrast measured by the LOS algorithm: none of these parameters provides a satisfactory correction.

CONCLUSION

Observables obtained with the HMI pipeline exhibit 12h and 24h period oscillations, both with the LOS algorithm and the ME inversion code. The peak-to-peak amplitude of these oscillations is larger on the Doppler velocity and field strength returned by the MDI-like

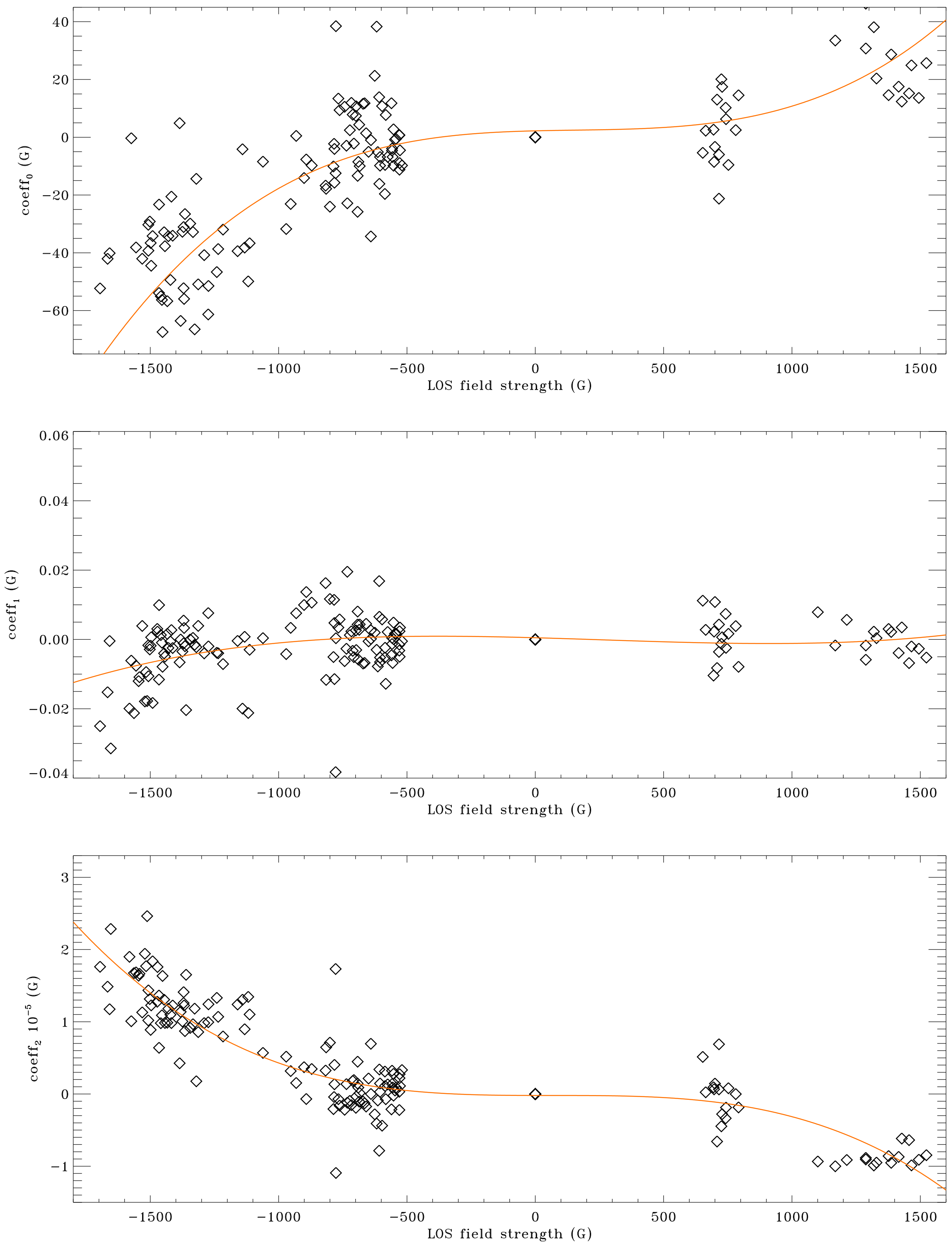

Fig. 9.— Coefficients of a 3rd-order polynomial fit to the residuals of the LOS field strength returned by the MDI-like algorithm, as a function of this field strength. Umbral and penumbral data were included. The red lines are 3rd-order polynomial fits. The point (0,0) was added.

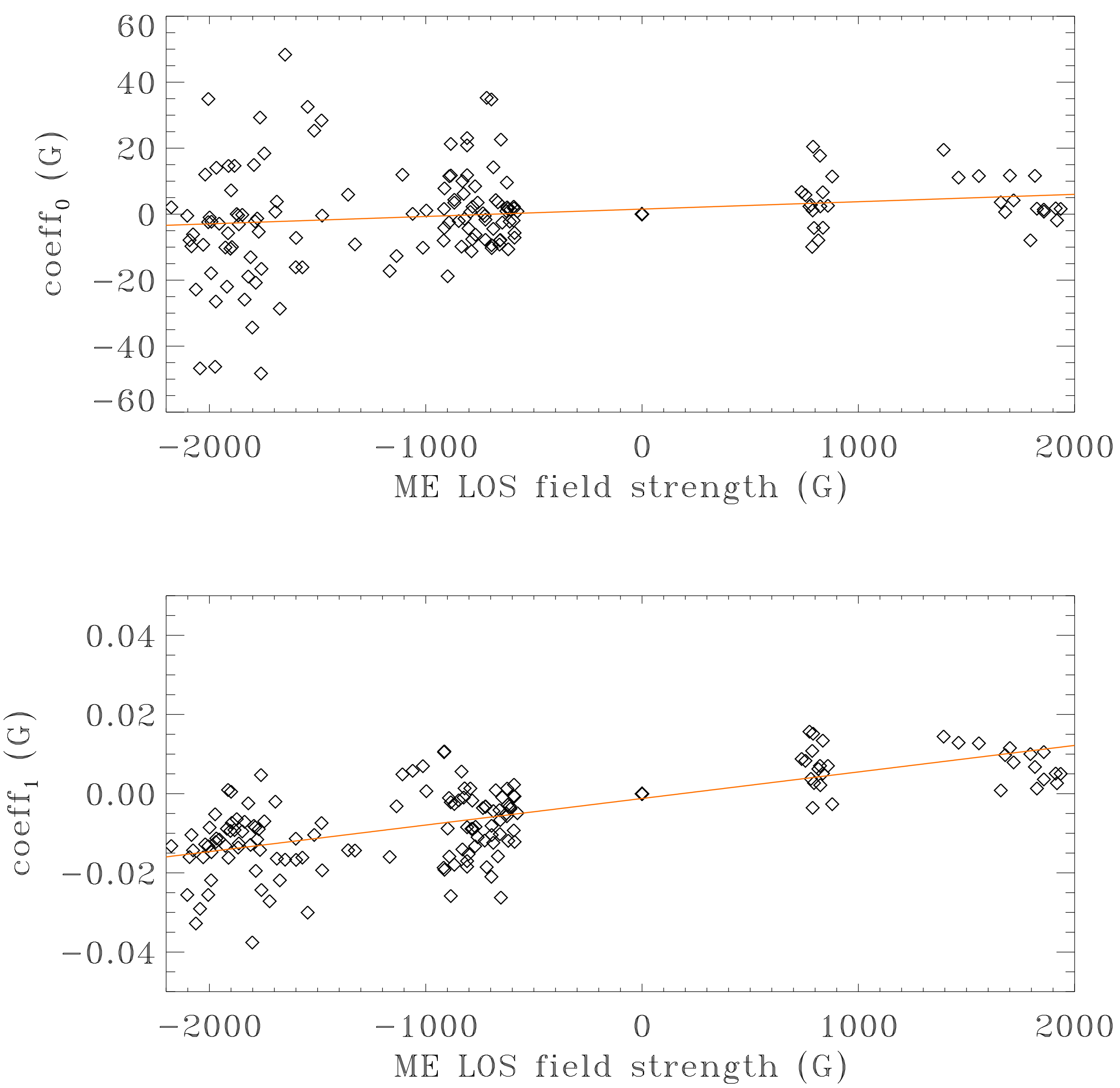

Fig. 10.— Coefficients of a 2rd-order polynomial fit to the residuals of the LOS field strength returned by the ME inversion, as a function of this field strength. Umbral and penumbral data were included. The red lines are linear fits. The point (0,0) was added.

algorithm than by the ME inversion code VFISV. Moreover, the error in field strength obtained with LOS algorithm has a quadratic dependence on the velocity, while the error returned by the ME inversion has a linear dependence. We believe the main contributors to these oscillations are errors in the Fe I line profile used to produce the look-up tables (for the LOS algorithm), and errors of the order of 1% in the HMI filter profiles (for the ME inversion). Correcting these issues will be challenging, as the Fe I line shape varies greatly in sunspots, both as a function of field strength and field inclination, and improving the HMI filter transmission profiles is also difficult. However, the LOS algorithm could be improved by replacing the MDI-like algorithm with a least-squares fit of the Fe I line profile: fitting for the width and depth of this line should provide field strengths and velocities with 12h and 24h oscillations whose amplitudes are closer to the ones obtained with the ME inversion.

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