

Measurements of Faraday Rotation Through the Solar Corona During the 2009 Solar Minimum with the MESSENGER Spacecraft

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Abstract Measurements of Faraday rotation through the solar corona were collected using the radio beacon aboard the MESSENGER spacecraft during the longest solar minimum in a century. As MESSENGER entered superior conjunction, the plane of polarization of its radio signal was observed to rotate as it traversed the circularly birefringent plasma of the Sun's atmosphere. On time scales of less than three hours, these uncalibrated plane of polarization observations of Faraday rotation can be used to investigate the dynamic processes

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in the solar plasma, such as magnetohydrodynamic (MHD) waves and coronal mass ejections (CMEs). Here we describe the MESSENGER Faraday rotation experiment, the data processing conducted to obtain the plane of polarization, and the estimation of error.

1. Introduction

Understanding and predicting the Earth's 'space weather' is of increasing importance as our technology becomes more sophisticated. For example, the Corporation of Lloyd's insurance market (Hapgood and Thomson, 2010) has documented that a catastrophic solar storm can cause \$30B in damage to satellites. The solar wind, accelerated and heated plasma originating from the solar corona, strongly affects the Earth's magnetosphere through changes in ram pressure, magnetic field strength, and flow direction. Although the precise mechanism(s) for the transfer of energy to heating the corona and solar wind remain unknown, the Sun's magnetic field is instrumental to dynamic processes on all scales (temporal and spatial). However, outside of active regions (ARs), the magnetic field is "invisible" as it transitions from the base of the corona to a radial distance of 1 AU. Only the technique of Faraday rotation, as described in this paper, can be used to measure the solar magnetic field through this spatial region.

This paper describes measurements of Faraday rotation in the solar corona made with signals received from the *MERcury Surface, Space ENvironment, GEOchemistry, and Ranging* (MESSENGER) spacecraft (Leary *et al.*, 2007). The data in this paper were collected in 2009, following the longest solar minimum in a century. The observations constitute the final dataset (of five) collected over the waning period of Solar Cycle 23. This spacecraft's dataset is the first dataset of Faraday rotation observations collected at equatorial latitudes since 1985. The observation period was part of a worldwide observing campaign of the heliosphere by the radio scintillation community. Other results of that campaign are discussed in an accompanying paper (Jensen *et al.*, 2013).

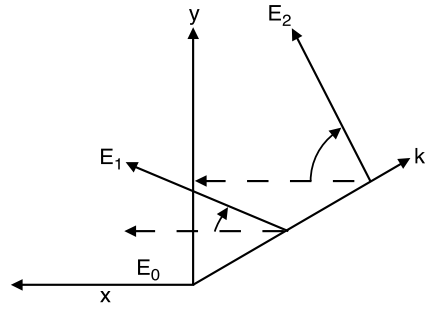
2. Background

During 8–11 November 2009, the MESSENGER spacecraft *en route* to insertion into orbit about Mercury was in superior conjunction. While located on the opposite side of the Sun from Earth, the radio-frequency transmissions from MESSENGER traversed the circularly birefringent medium of the solar corona to the *Green Bank Telescope* (GBT) in Green Bank, West Virginia, USA. Due to scintillation of the signal in the relatively dense plasma of the solar corona, no data could be transmitted during that time period. However, the greater plasma density allowed the observation of the coronal magnetic field through the Faraday rotation phenomenon.

Faraday rotation is the rotation of the plane of polarization of an electromagnetic (EM) wave as it traverses a circularly birefringent medium (see Figure 1). For this experiment the radio-frequency signal of MESSENGER rotated as it traveled along the line of sight to Earth through the solar corona. The amount of rotation is proportional to the integral along the line of sight of the line-of-sight component of the magnetic field weighted by the electron density:

$$\text{FR} = \frac{A}{f^2} \int_{\text{SC}}^{\oplus} N\mathbf{B} \cdot d\mathbf{s} \quad [\text{radians}]$$

Figure 1 Faraday rotation. The local magnetic field is oriented along the k -direction, which is also the direction of travel of a linearly polarized electromagnetic wave in this example (only the \mathbf{E} is shown at times 0, 1, and 2). As the wave travels under these conditions, its plane of polarization rotates in the right-handed direction around the axis of its direction of travel (as shown in the image).



$$A = \frac{q^3}{8\pi^2\epsilon_0 m_e^2 c} = 2.3648 \times 10^4 \quad [\text{m}^2 \text{rad s}^{-2} \text{T}^{-1}] \tag{1}$$

The frequency of the signal (f) is in Hz, SC is the spacecraft, \oplus is the Earth, N is the electron density in $[\text{m}^{-3}]$, s is the path of the signal in $[\text{m}]$, q is the electron charge in $[\text{C}]$, m_e is the mass of an electron in $[\text{kg}]$, and c is the speed of light in $[\text{m s}^{-1}]$. A positive FR means that the signal rotated in the right-handed sense (*i.e.*, as shown in Figure 1) about the wave vector, the direction of travel of the electromagnetic wave.

In measuring Faraday rotation, it is the calibrated change in the plane of polarization, where the plane of polarization (*i.e.*, the \mathbf{E} shown in Figure 1) is measured from the phase of the right- and left-circularly polarized components of MESSENGER’s radio-frequency signal:

$$\text{PP} = \frac{\phi_{\text{rcp}} + \phi_{\text{lcp}}}{2} \quad [\text{radians}]$$

$$\text{FR} = [M]\text{PP} \quad [\text{radians}] \tag{2}$$

ϕ is the phase angle of the right- and left-circularly polarized waves (rcp and lcp), PP is the plane of polarization, and $[M]$ is the Mueller matrix used to calibrate the PP measurement to give the Faraday rotation FR. Note that the effects of $[M]$ are slow varying over a period of hours and do not exceed 180 degrees. For PP rotations with higher frequency and over a range greater than 180 degrees, $\Delta\text{PP} \cong \Delta\text{FR}$. This paper is focused on documenting the measurement of the plane of polarization PP, its error bars, and comparing ΔPP to modeled ΔFR for the conjunction.

3. Faraday Rotation Modeling

The geometry of the measurements as viewed from above the ecliptic is shown in Figure 2 in Carrington (solar) coordinates (International Astronomical Union). The magnetic field was calculated from the Wilcox Solar Observatory (WSO) potential field source surface (PFSS) model (Hoeksema and Sherrer, 1986; Jensen, 2007). The source surface was set at 2.5 solar radii with the magnetic field configured radially at this boundary. Because the maximum offset distance of the line of sight was less than 3.5 solar radii, the amount of curvature to the magnetic field (non radial) within this region (above the source surface) is assumed to be negligible. As MESSENGER’s radio signal passed through the modeled solar corona to Earth on 8 November, it rotated in the positive direction initially since it was located in a

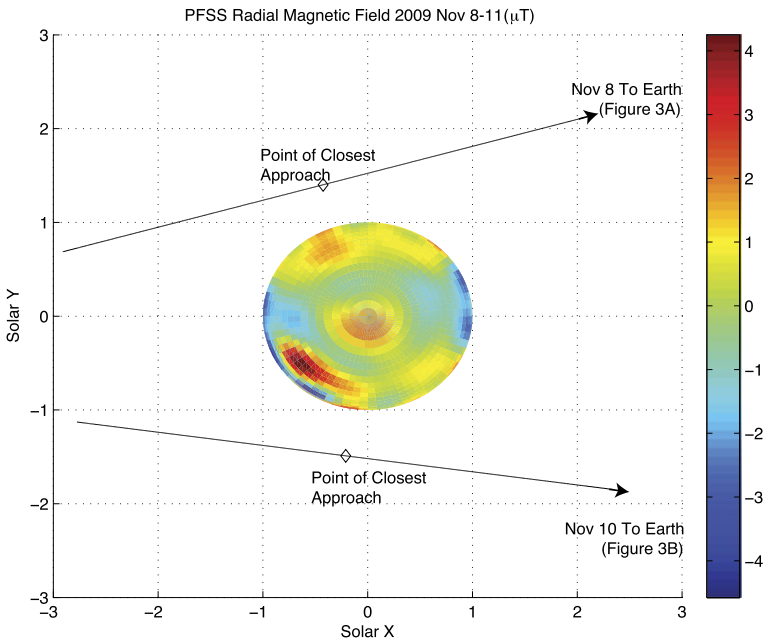


Figure 2 The radial solar magnetic field (shown in color) affecting the MESSENGER radio-frequency signal, according to the WSO PFSS model (2.5 solar radii source surface); note that below 2.5 solar radii, the magnetic field is not purely radial. Shown in Carrington coordinates, two single time periods on 8 and 10 November 2009 are indicated by their trajectories from MESSENGER to Earth. Figure 3 shows the modeled Faraday rotation along those two trajectories.

region of negatively pointing magnetic field (pointing inward towards the Sun). The wave vector then crossed a possible current sheet (the structure between the Sun’s positive and negative magnetic field regions through which the current flows to balance the magnetic pressure gradient) reversing the component of the magnetic field along the line of sight to the outward/antiparallel direction and shifting the Faraday rotation to the negative rotational direction. Then the wave vector crossed the point of closest approach where the outward magnetic field then became parallel to the path of the line of sight causing the Faraday rotation to reverse again into the positive direction. Note that in reality the electron density in each region was different. For this paper we have modeled the electron density using the modified Allen–Baumbach model (Tyler *et al.*, 1977). This electron density model is symmetric in longitude and gives densities that are substantially greater than the actual solar environment in 2009 when the Sun was in an unusual solar minimum.

$$N_e = \left[\left(\frac{2.99}{\rho^{16}} + \frac{1.55}{\rho^6} \right) \times 10^{14} + \frac{3.44}{\rho^2} \times 10^{11} \right] \left(\cos^2 \theta + \frac{1}{64} \sin^2 \theta \right)^{1/2} \quad [\text{m}^{-3}] \quad (3)$$

N_e is the electron density in m^{-3} , θ is solar latitude, and ρ is the offset radius (in solar radii).

The polar plots in Figure 3 illustrate the modeled observation made by the GBT at Earth; it is a single observation of the plane of polarization at that time. If the plane of polarization of MESSENGER was $0^\circ/180^\circ$, then the final plane of polarization at Earth on 8 November 2009 would have been approximately $45^\circ/225^\circ$ according to the model. On 10 November, the final plane of polarization would have been approximately $90^\circ/270^\circ$. Note that there is a 180° ambiguity in the plane-of-polarization observation.

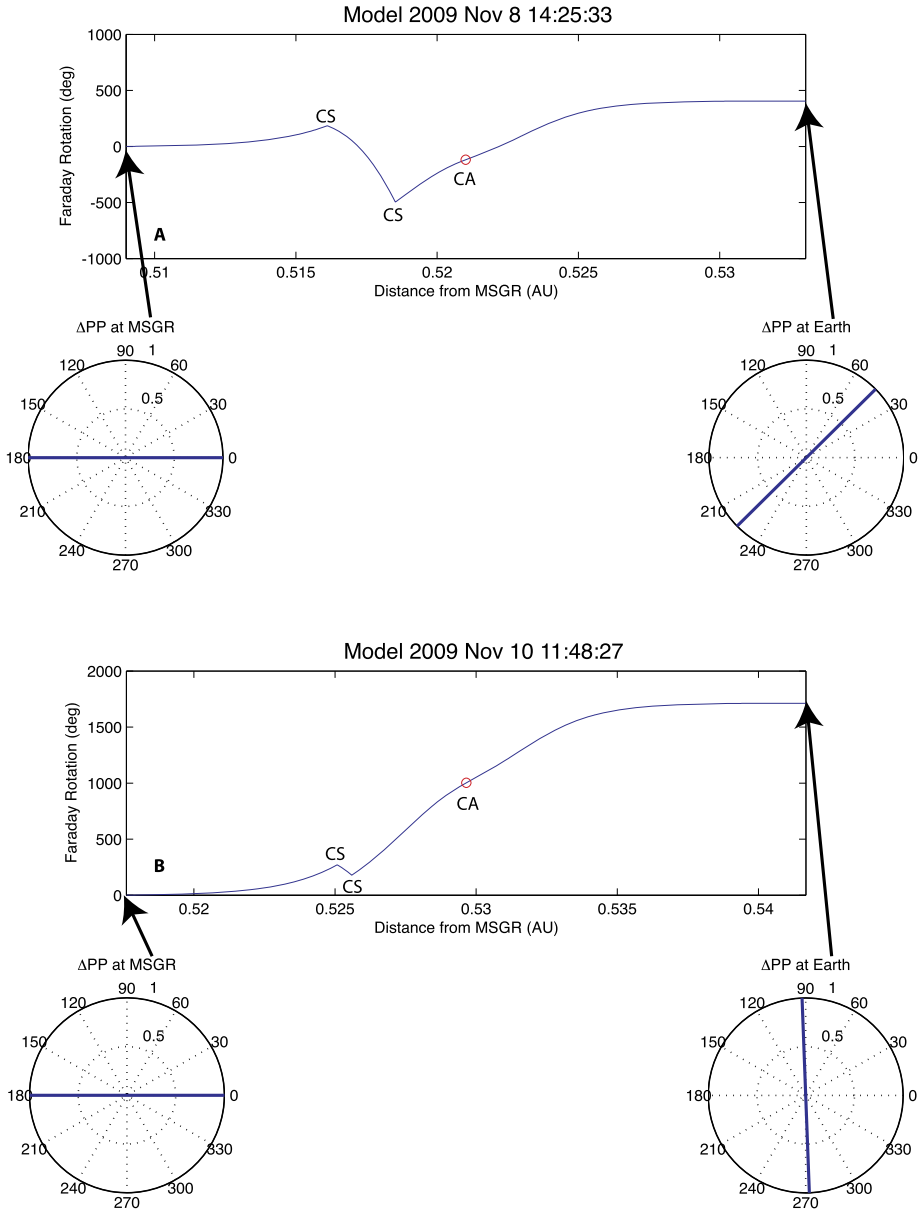


Figure 3 From Figure 2, two single time periods on 8 and 10 November 2009 are illustrated by their trajectories from MESSENGER to Earth. The modeled Faraday rotation along those two trajectories is shown in panel A for 8 November and panel B for 10 November. The change in the plane of polarization using the modified Allen–Baumbach symmetric electron density model is shown for each track. The polar plots illustrate the plane of polarization information as obtained at Earth.

Simple analyses of Faraday rotation observations focus on how the plane of polarization changes. These analyses yield information on the dynamics of the solar corona. Measurements of the plane of polarization at substantial offset distances from the Sun must be taken

to calibrate and remove the effects of the antenna equipment. The calibrated data can then be used to investigate the steady-state solar corona.

The location of the MESSENGER spacecraft relative to the Sun observed using the GBT during the November 2009 superior conjunction is shown in Figure 4. At each point, the MESSENGER signal traversed a slightly different offset path through the solar corona, which allowed the measurement of structure as radius changes. The final plane of polarization measured at Earth for each point was slightly different as a result. Figure 4 (right) shows the modeled results for ideal Faraday rotation at each point that GBT measurement a plane of polarization. The actual measured changes in plane of polarization for these days should be less because of the lower electron densities that were actually present during this extended solar minimum. There are no dynamic fluctuations in this model. The model predicts that on 11 November, the average change in the plane of polarization should have had very little slope. On 10 November, the plane of polarization is predicted to have sloped strongly negative. Because the observation on 8 November was taken close to the solar surface (well below the source surface), we do not know if the PFSS model accurately predicts the magnetic field configuration in the region.

4. Obtaining the Plane of Polarization

We measured the plane of polarization by sampling the right- and left-circularly polarized (RCP and LCP, respectively) components of the MESSENGER signal. If the amplitudes of the RCP and LCP waves are equal, then the signal is linearly polarized (similar to the polar plots shown in Figure 3). The MESSENGER signal was strongly RCP with a small ($\sim 1\%$) leakage of LCP EM radiation (Figure 5). As a result, the signal was circularly polarized with a slight ellipticity, allowing measurement of the plane of polarization and tracking how that polarization changes. Note that the Fourier spectrum of the signal shown in Figure 5 has a positive frequency image. Churchill, Ogar, and Thompson (1981) showed that this outcome can be the effect of the in-phase and quadrature components of the wave having different amplitudes due to slightly different gains. The actual signal is the stronger of the two frequency peaks (the negative frequency peak). As a normal part of the data processing (Jensen and Russell, 2007), the amplitudes of the in-phase and quadrature components of the wave are normalized independently so as to remove this effect.

The 8 GHz signal received by the GBT is ideally down-converted to a few Hz allowing the measurement of the phase of the signal. For MESSENGER, its 8 GHz signal was instead down-converted to approximately 637 kHz, because of a problem in the prediction of its offset frequency. The change in frequency from Doppler motion was appropriately calibrated. This correction is apparent in the consistent ~ 637 -kHz frequency of the signal throughout the observation time periods (see Figure 6).

The MESSENGER signal was sampled by two instruments at GBT, the NRAO spectral processor (SP) and the fast digital sampler (Margot and Giorgini, 2010). The spectral processor takes 32-bit sampled circular polarizations and auto- and cross-correlates them to measure the full Stokes parameters. Unfortunately, the -637 -kHz down-converted MESSENGER signal was outside of the 312.5-kHz bandwidth setting of the SP. Aliased, under-sampled signals were detected within this dataset, but they did not yield a sufficiently good signal-to-noise ratio (SNR) for further analysis.

The fast digital sampler sampled the down-converted MESSENGER signal at a rate of 5 million samples per second. We found that this dataset could not be decimated without degrading the SNR of the ~ 637 -kHz signal. Implementing the technique documented by

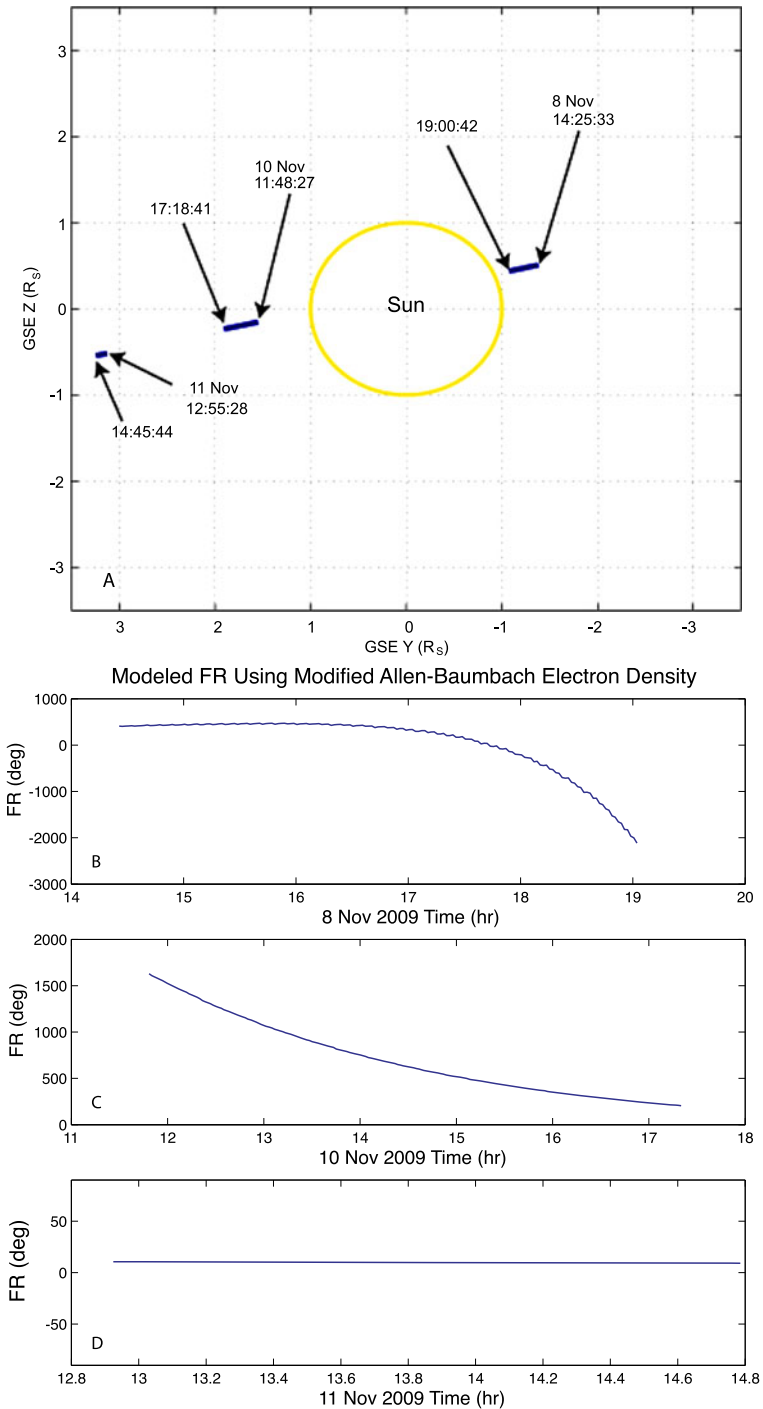


Figure 4 (Panel A) Lines of sight from MESSENGER during superior conjunction. The modeled Faraday rotation (FR) using the WSO PFSS model and the modified Allen–Baumbach model for 8 (B), 10 (C), and 11 (D) November 2009.

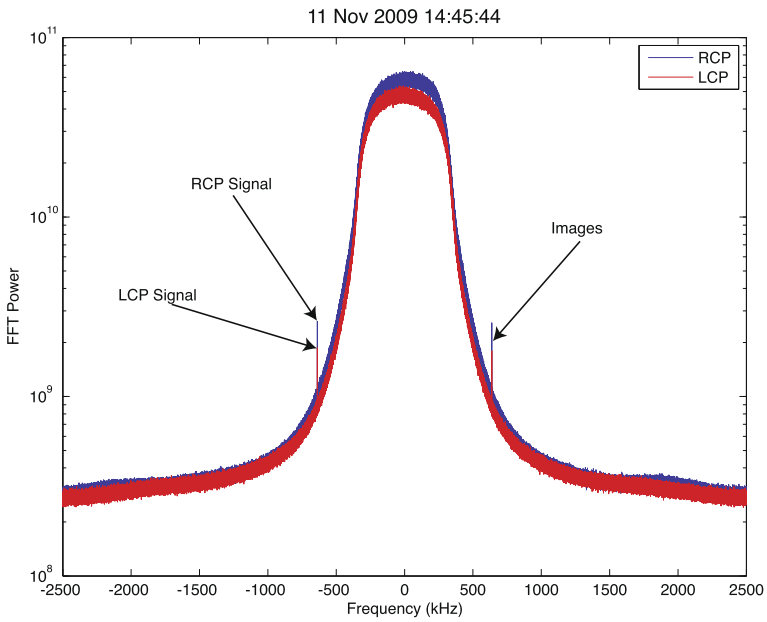


Figure 5 Fourier spectrum of the right-hand (RCP) and left-hand (LCP) circularly polarized components of the MESSENGER signal at the date and time (UT) indicated.

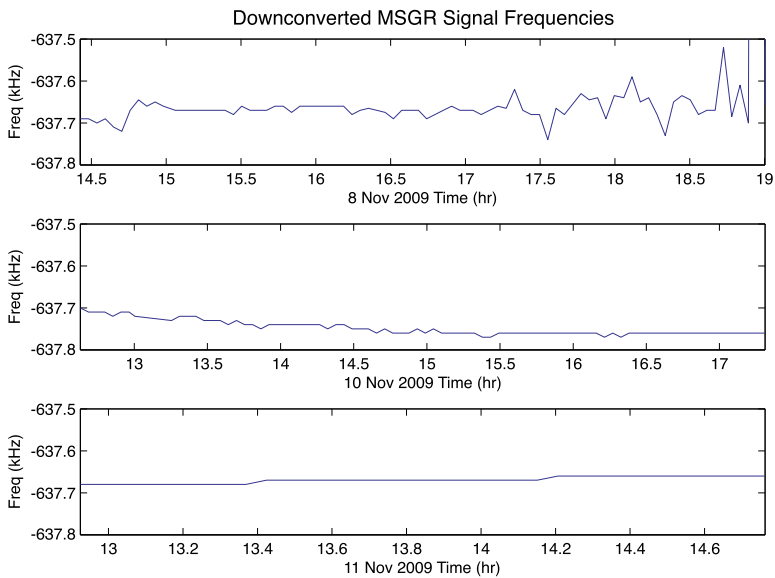


Figure 6 The down-converted frequency of the MESSENGER signal on 8, 10, and 11 November 2009 (top, middle, and bottom panels, respectively). The change in the frequency is due to the change in the path delay from the solar plasma density.

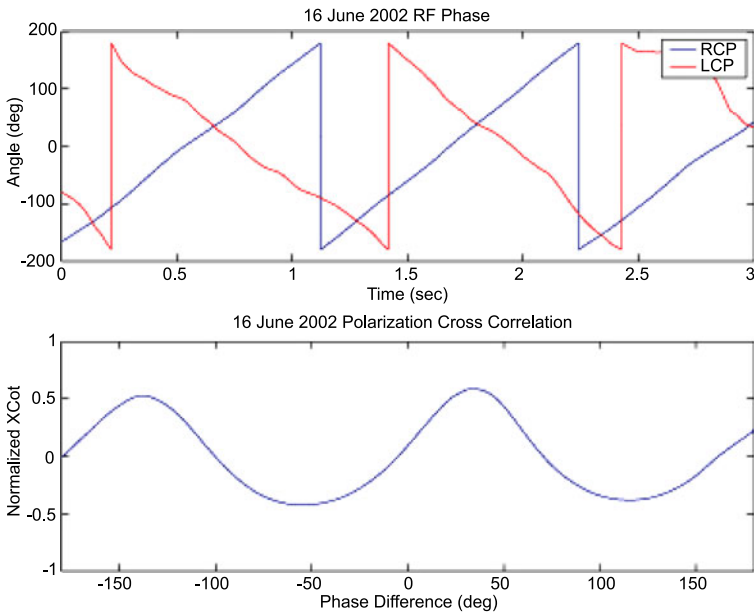


Figure 7 Measurement of the plane of polarization. (Top) Phase angles of the RCP (blue) and LCP (red) waves, which create a saw-tooth wave with time. (Bottom) The cross-correlation of the RCP and negative LCP can be converted to phase lag from the wave's known frequency (see Jensen and Russell, 2007 for details).

Jensen and Russell (2007) to obtain the plane of polarization required moderate modification for this quantity of data (discussed later).

A depiction of how the plane of polarization is measured is shown in Figure 7. The top plot shows the phases of the RCP (blue) and LCP (red) signals intersect near 45° and -135° . According to Equation (2) the plane of polarization is $45^\circ/-135^\circ$ where these intersections occur. If we cross-correlate the RCP and negative LCP phases, the maximum correlations occur where the lags correspond to $45^\circ/-135^\circ$.

The data shown in Figure 7 consist of 100 s of data mixed with a wave to bring the down-converted signal frequency to a fixed frequency (of 1.5 Hz) and bandpass filtered around the 1-Hz bandwidth signal. This procedure was adjusted for the MESSENGER data because of the high sampling rate. The fixed frequency was increased to 3.125 kHz, and the down-converted signal to this mixed frequency was decimated by a factor of 100 (99 points out of every 100 was removed) after filtering. The cross-correlation could then be run successfully on the processed signal. Figures 8, 9 and 10 show the plane of polarization observations for 8, 10, and 11 November 2009.

5. Estimating Error

The plane of polarizations shown in Figures 8, 9, and 10 were determined from the maximum cross-correlation value of the two maxima. Ideally, the cross-correlation maxima should be separated by 180° ; however, this separation occurs only at large offset distances from the Sun (e.g., as shown in the bottom panel of Figure 7). At offset distances closer

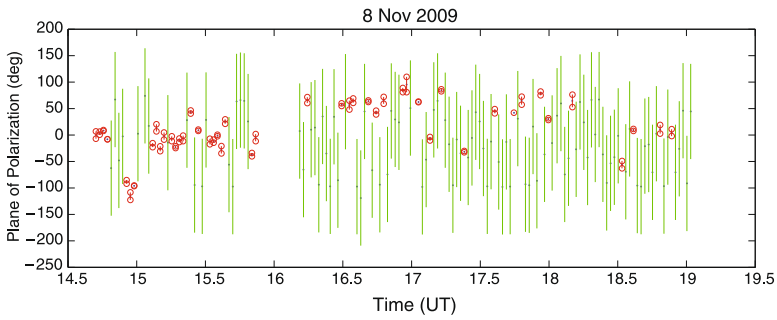


Figure 8 The change in the plane of polarization (blue dots) on 8 November 2009 with determined (red) and undetermined (green) error bars.

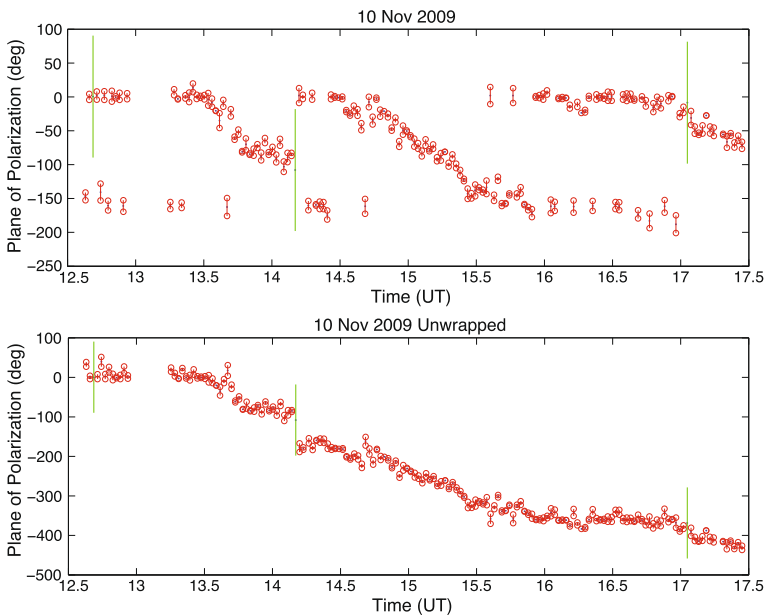


Figure 9 (Top) The change in the plane of polarization (blue dots) on 10 November 2009 with determined (red) and undetermined (green) error bars. (Bottom) The unwrapped change in the plane of polarization values from the figure above with the $\pm 180^\circ$ uncertainty removed. The change in the plane of polarization on 10 November is strongly negative as predicted by the Faraday rotation model.

to the Sun, the separation between the cross-correlation maxima can vary from 180° . This variation introduces an uncertainty to the plane of polarization observation giving an error in determining the plane of polarization.

With higher levels of noise in this dataset than previously encountered (*i.e.*, Jensen and Russell, 2007), particularly on 8 November, it was determined that the error should be carefully calibrated. A fixed plane of polarization tone was synthesized and passed through the algorithm described above with varying levels of noise mixed in. Signals mixed with 40–70 % noise required larger error bars. The size of the adjusted error bar varied with the cross-correlation value of the observation. Figure 11 shows that the error bar adjustment

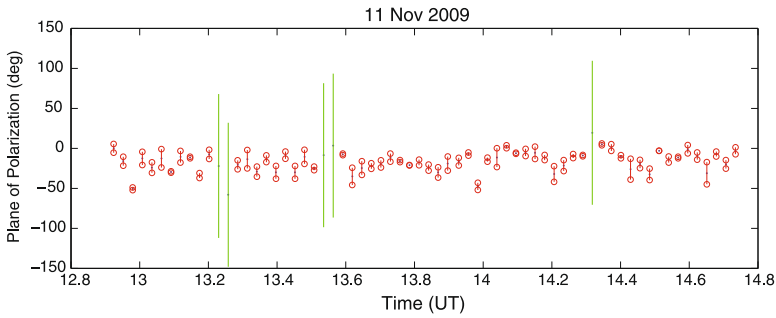


Figure 10 The change in the plane of polarization (blue dots) on 11 November 2009 with determined (red) and undetermined (green) error bars. The plane of polarization on 11 November has a negligible average slope, similar to the prediction.

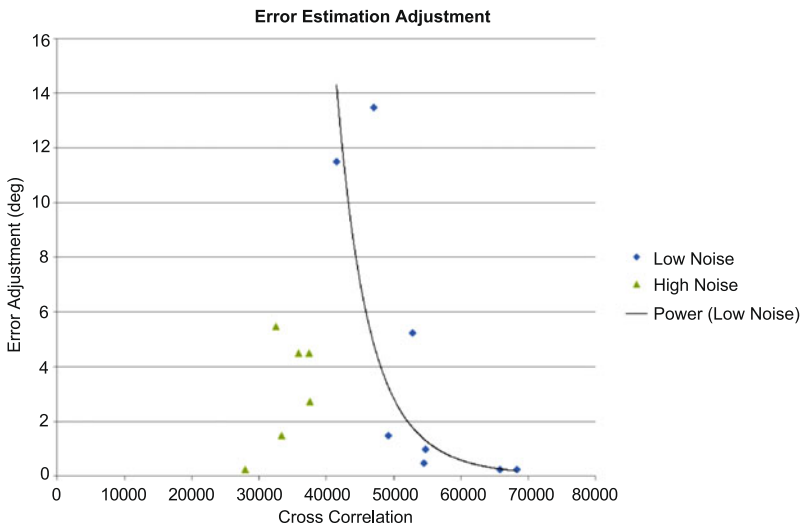


Figure 11 The effect of varying noise on the plane-of-polarization measurement. Low noise tests between 30–50 % (blue) show that the error bars increase with decreasing cross-correlation values. Higher noise tests with noise between 50–70 % are also shown (green). The fitted power-law function reaches 90° around an average maximum cross-correlation value of 40 000. The equation shown is $1.58 \times 10^{41} \langle X_{\text{corrMax}} \rangle^{-8.67}$.

follows an approximate power-law fall-off with increasing value of the average of the cross-correlation maxima. Around an average cross-correlation maximum value of 40k, the adjustment becomes large enough that the error bar spans ± 90 degrees: the plane of polarization is unknown.

6. Results

The observations collected on 8 November 2009 were significantly noisy. Figure 8 shows that, as the offset distance from the signal decreased while MESSENGER moved closer to conjunction on ingress, the times when plane of polarization values could be determined with small error bars occurred with less frequency. A semi-continuous series of observations

are required to unwrap the rotation of the signal (as shown in Figure 9), so these plane of polarization values from 8 November could not be unwrapped.

In creating Figure 9 (Bottom) for 10 November 2009, the plane of polarization shown on top was unwrapped. The distribution of points around 0° and 180° illustrates the $\pm 180^\circ$ uncertainty in the plane of polarization. Because we are looking at the change in the plane of polarization through the observing time period, these values were adjusted accordingly. The approximately 180° per hour rotation rate is clearly visible in the time series.

Although Figure 10 on average has no significant slope (as predicted), the time series fluctuates about this slope strongly. An accompanying paper (Jensen *et al.*, 2013) presents an analysis of the fluctuations present on 10 and 11 November.

As shown in Figure 4, the modeled Faraday rotation decreases during the observing time. This change in the plane of polarization with time is similarly observed in Figure 9. These similar behaviors indicate that the magnetic field configuration from the PFSS model was accurate, while the electron density model was significantly greater. Because these observations were taken during the longest solar minimum in a century, this result is expected.

7. Conclusion

In November 2009, towards the end of the longest solar minimum in a century, the MESSENGER spacecraft was in superior conjunction, a geometry that allowed the measurement of the solar magnetic field using Faraday rotation, *i.e.*, the rotation in the plane of polarization in proportion to the component of the magnetic field parallel to the line of sight weighted by the electron density. We effectively modeled this effect using the Wilcox Solar Observatory potential field source surface model and the modified Allen–Baumbach electron density model as described earlier. We found that the change in the plane of polarization behaved similarly to predictions on 10 and 11 November 2009, but the change in the plane of polarization on 8 November, at a location near the base of the solar corona, was very noisy.

This paper describes in detail the MESSENGER Faraday rotation experiment and the data processing performed on the observations. The resulting change in the plane of polarization measurements are analyzed in the accompanying paper (Jensen *et al.*, 2013).

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