Design requirements of space-based radio instrument at L4-L5 for space-weather monitoring

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Abstract

Faraday rotation (FR) measurements provide information on plasma density and magnetic fields of the medium through which a polarized signal propagates. In the inner heliosphere, large-scale magnetic structures such as coronal mass ejections (CMEs), corotating interaction regions (CIRs), and the solar wind itself can be probed using the FR phenomenon. In this study, we discuss the design requirements of a space-based quad-line-of-sight radio instrument, which can be used to determine the line-of-sight magnetic field and total electron content in coronal and heliospheric structures.

1. Introduction

Faraday rotation (FR) measurements have been well-established as a method for determining the strength and structure of the coronal magnetic field[1]. When a linearly polarized radio wave propagates through a highly magnetized plasma medium, the polarization plane of the radio wave rotates due to the magnetic field strength and electron density, caused by different phase velocities for left- and right-hand circularly polarized (LCP and RCP, respectively) waves. FR allows us to measure an average of the magnetic field parallel to the line of sight, weighted by the electron density.

In general, the coronal magnetic fields (B) play an essential role in the formation, evolution, and dynamics of the small and large-scale structures in the solar corona[2]. With respect to extreme events, Coronal mass ejections (CMEs) are large eruptions of magnetized plasma from the solar corona[3]. The knowledge of the magnetic field evolution and its structure at the earliest time in the CMEs trajectory is important for space weather prediction[4]. FR measurements at 1 AU have shown to be an excellent tool for inferring the magnetic field of the solar corona, including CMEs and the background solar wind[5].

The Faraday Effect Tracker of Coronal and Heliospheric Structures (FETCH) is a new instrument concept for the proposed next-generation multi-spacecraft comprehensive mission, called the Multiview Observatory for Solar-Terrestrial Science (MOST)[6,7]. The MOST mission consists of four spacecraft (S/C), two located at L4 and L5; two drifting ahead of L4 and behind L5 (see figure 1). These S/C will be carrying a range of instruments to perform several in situ and remote sensing measurements. While most of the instruments to be onboard the MOST mission are at high technology readiness level, the FETCH's instrument capabilities are yet to be tested, characterized and demonstrated. FETCH aims to reconstruct the geometry, orientation, and intensity of magnetic field associated with the coronal and heliospheric plasma structures by measuring the FR effect on radio waves propagating through these structures along multiple paths.

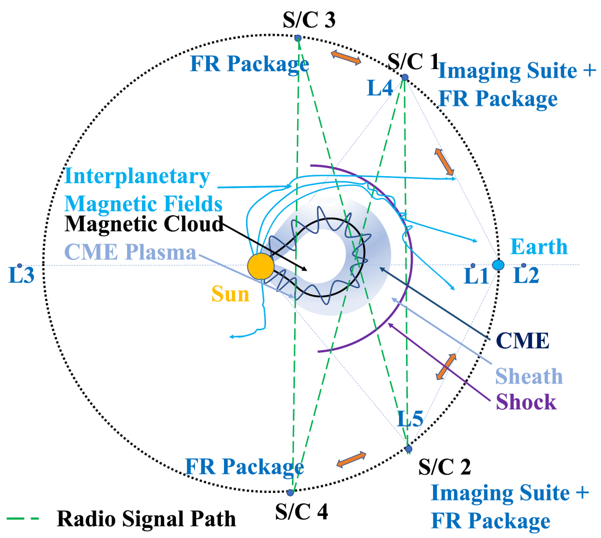

Figure 1. A schematic showing the four spacecraft positions in the multi-spacecraft MOST mission concept. The 'green' dashed lines show the radio signal path along which the FR measurements are proposed using FETCH between 0.3-1 AU (adapted from [7]).

2. Effect of Noise on Polarization properties

To understand the impact of Signal-to-Noise Ratio (SNR) on the uncertainty of the polarization plane and polarization fraction recovery in FR measurements, specifically in the context of spacecraft-based radio observations, we need to understand how the noise can affect the transmitted signal. The accuracy in the rotation measure observations would decide the accuracy of the inferred magnetic field and geometry of the plasma in the coronal/heliospheric domain. For high precision polarization measurements, one needs to have knowledge of the noise properties. Any transmitted wave electric field vector (**E**), when received at the receiver, can be affected by a total noise electric field represented by **δE**. For a totally random noise, the direction of the transmitted wave electric field upon reception can become uncertain by a cone angle $\delta\theta/2$ (see figure 2).

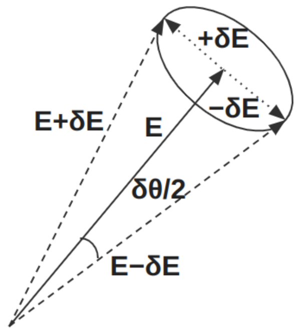

Figure 2. The observed signal plane shows the noise uncertainty at the receiver end. [9]

Consider the two orthogonal electric field components of a plane-polarized electromagnetic wave received by a crossed dipole antenna on axis at a point in space (with $E_z = 0$), so they can be represented as:

$$E_x(t) \ = \ E_{0x}(t)cos[\omega t \ + \ \delta_x(t)] \qquad (1)$$

$$E_y(t) \ = \ E_{0y}(t)cos[\omega t \ + \ \delta_y(t)] \qquad (2)$$

where E_{0x}(t) and E_{0y}(t) are the instantaneous amplitudes, ω is the instantaneous angular frequency, and $\delta_x(t)$ and $\delta_y(t)$ are the instantaneous phase factors.

All the four Stokes parameters, which can express any state of polarized light, can be expressed as[8]:

$$S0 \ = E_x E_x {}^* + \ E_y E_y {}^* \qquad (3)$$

$$S1 \ = E_x E_x {}^* - \ E_y E_y {}^* \qquad (5)$$

$$S2 \ = E_x E_y {}^* \ E_y E_x {}^* \qquad (6)$$

$$S3 \ = i(E_x E_y {}^* - E_y E_x {}^*) \qquad (7)$$

The polarization fraction (p) and plane of polarization angle (ψ) can be obtained from Stokes parameters as follows:

$$p \ = \ \frac{\sqrt{S1^2 + S2^2 + S3^2}}{S0} \qquad (8)$$

$$\psi = \frac{1}{2} atan\left(\frac{S2}{S1}\right) \qquad (9)$$

Using these sets of equations, we simulated the instruments response and studied the effect of noise on the received signals.

3. Monte Carlo Simulations

We employed the Monte Carlo simulation technique to comprehensively analyze how various noise sources affect the polarization properties of a linearly polarized signal as might be expected in signals transmitted and received between MOST spacecraft. We evaluate the impact of different noise sources on the polarization characteristics of a linearly polarized signal transmitted at 165 MHz between spacecraft located at Lagrange points L4 and L5—the originally planned positions for two of the FETCH-hosting spacecraft. The preliminary findings offer valuable insights into the system's performance in realistic noise conditions, facilitating the determination of acceptable SNR thresholds crucial for designing the FETCH Link budget.

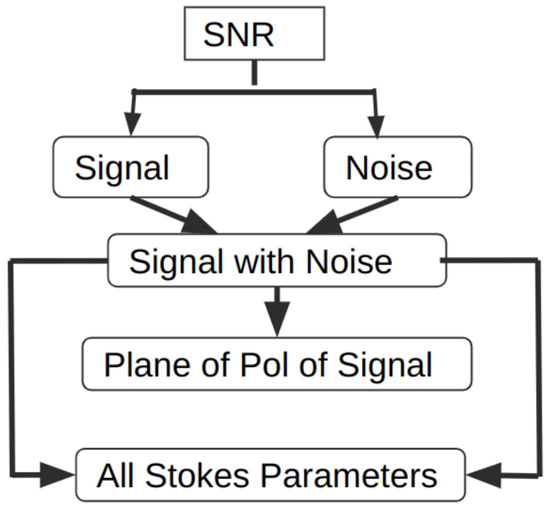

Figure 3. The flowchart of the Monte Carlo simulations for FETCH.

The simulation involved the generation of a linearly polarized continuous-wave (CW) signal at 165 MHz and transmission between spacecraft, and downconverted to a lower frequency for ease of calculations. All Stokes parameters and the plane of polarization were meticulously calculated for this signal. Subsequently, two types of noise were introduced into the system: the system noise, representing random and uncorrelated noise inherent in the receiving system, and the galactic noise, signifying weakly correlated noise emanating from the galactic background.

To assess the impact of these noise sources, various polarization properties of the received signal were estimated. These include evaluating the SNR after the addition of noise, examining Probability Density Functions (PDFs) of signal amplitudes, and determining the Stokes parameters (I, Q, U, V) for both polarizations. These analyses collectively provide valuable insights into the polarization characteristics of the received signal and inform the design considerations for the FETCH system under realistic operational conditions.

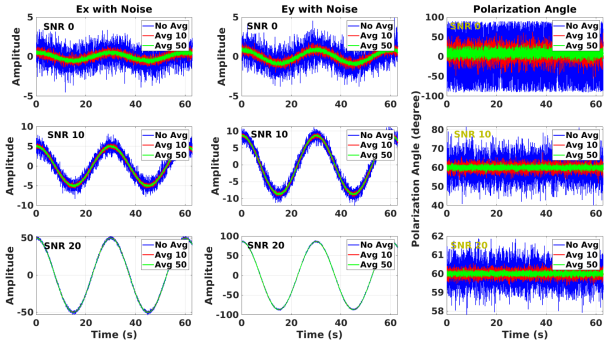

Figure 4. Left and Middle Columns show the transmitted signal (plane of polarization 60º) after adding uncorrelated noise for different SNR values (0, 10, 20 dB). Right column shows the recovered plane of polarization angles. Blue, Red and Green colors represent the effect of averaging ψ on the reconstructed signal.

In figure 4, the simulated transmitted signal has a plane of polarization 60º, following the addition of uncorrelated noise for varying SNR values between 0-30 dB. The right column illustrates the recovered plane of polarization angles, where different colors represent the impact of ψ signal averaging on the reconstructed signal. In the top left and middle panels, the plots show the effect of low SNR, where the signal is predominantly dominated by noise. Notably, the rightmost panel shows the retrieved plane of polarization angles using Eq 9. An increment is observed as SNRs increase in steps of 10 dB in the middle and last rows. Further, transmitting signals with different planes of polarization (0-180º at intervals of 5º) were also done to check if the results had repeatability. The results indicate that the plane of polarization can be reliably retrieved when the SNR > 7.

Each iteration involved simulating the signal under the influence of both system (uncorrelated) and galactic noise (weakly correlated), which was used for computation of noise effects on the received signal and variations in the plane of polarization at different SNRs.

In figure 5, the mean and standard deviation in the plane of polarization of the received signal, respectively, subsequent to the addition of uncorrelated noise at different SNR levels. The original transmitted signal's plane of polarization was set at 60º. The different colors signify the impact of signal averaging on the reconstructed signal, while the red dashed lines indicate the acceptable error bars for scientific analysis. This highlights the significance of both the retrieved mean polarization angle and standard deviation (std) in the retrieved values. Notably, a small number of sample averages can provide an approximation of the transmitted polarization angle. However, the accuracy can only be ensured when the standard deviation is within an acceptable range. As shown in Figure 5, the plane of polarization can be accurately retrieved if the SNR exceeds 7, underscoring the importance of considering both mean and standard deviation for precise reconstructions.

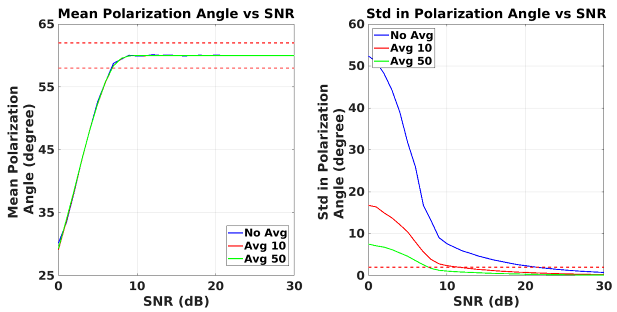

Figure 5. Left and right Columns show the mean and standard deviation in the plane of polarization of the received signal after adding uncorrelated noise for different SNR values, respectively. The original transmitted signal plane of polarization was 60º. Blue, red and green colors represent the effect of averaging on the reconstructed signal. The red dashed lines show the error bars (~ 2º).

5. Results and Discussions

We found that with an averaging of ~50 time samples of the received signals is sufficient to reconstruct the polarization plane of the transmitted signal. We also demonstrated how noise affects the polarization properties of the received signal. The plane of polarization can be recovered with input SNR > 7 dB, which may also depend on the plane of polarization of the transmitted signal.

For the purpose of evaluating this uncertainty calculation, the 2015 Solar Terrestrial Relationship Observatory (STEREO) radio frequency beacon polarized radio data was analyzed. Initial results suggest that an SNR of 6 or greater is required for a post- processing integration that increases the SNR > 30, which supports the preliminary simulation results discussed here.

In summary, we used Monte Carlo simulations as a tool for evaluating the noise effects in FETCH systems. By mimicking realistic noise conditions and quantifying the influence of noise on signal polarization, these simulations provide crucial guidance for the design of the FETCH Link budget. The findings enhance our understanding of the system's performance under varying

SNR conditions, offering valuable insights for optimizing FETCH system design in real-world scenarios.

6. Acknowledgements

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