Can We Measure the Coronal Magnetic Field?

A. Ruzmaikin
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

A talk prepared for the International Conference on solar physics "Structure and Dynamics of the Solar Corona", dedicated to memory of Professor G.M.Nikolsky
Moscow, October 5-7, 1999

Short title: CORONAL MAGNETIC FIELD

Abstract. In this talk a proposal to use the Faraday rotation of the linear polarized radio signals to determine the magnetic field of the solar corona will be discussed. For this purpose a spacecraft positioned behind the Sun is required [Ruzmaikin et al., 1997]. Coronal sounding is provided by the spacecraft dual-frequency radio downlink. To avoid the damping of radio signals in the corona near the Sun, the use of X and Ka band frequencies is suggested. The speed of density and magnetic inhomogeneities can also be determined from reception of the spacecraft signals at multiple radioastronomical antennas.

Simultaneous optical observations of magnetic fields on the photosphere and Faraday rotations in the corona can greatly facilitate finding the coronal magnetic field by deconvolution of the Faraday rotation data. The expected Faraday rotations are calculated from 3-D MHD models of the corona based on the photospheric fields measured the same day. The required coronal electron density and magnetic field are routinely obtained from such models. Comparisons between the observed and expected Faraday rotations will then be used in an iterative fashion to obtain the best magnetic field intensities fit.

Knowledge of coronal magnetic fields is crucial for understanding the origin of the solar wind, coronal heating and coronal mass ejections. Meanwhile our abilities to measure the fields directly, for example using the Hanle polarization effect, the Zeeman effect in infrared lines or radio gyro lines are limited and target mainly the regions in the low corona.

It is possible, however, to derive the magnetic field and its variations from simultaneous Faraday rotation and electron density observations. The technique to accomplish this objective is based on the Faraday rotation and associated electron density measurements at two frequencies. The coronal magnetic field rotates the polarization plane of a linear polarized radio signal by the angle

$$FR = Cf^{-2}\int n_e \mathbf{Bdl}, \tag{1}$$

where n_e is the electron density, f is the frequency, $\mathbf{B}$ is the magnetic field, and $C = 2.36 \times 10^4 m^2 s^{-2} T^{-1}$. The integral is taken along the path from the spacecraft to the Earth (Figure 1).

The absolute value of FR is expected to increase as the radio path is closer to the Sun (Figure 2). Then the removal of $\pm n\pi$ angle ambiguity becomes important. This ambiguity, which severely limited the previous single-frequency measurements, is resolved using the dual-frequency downlink and calculating the differential $FR(= FR_x - (f_x^2/f_{Ka}^2)FR_{Ka})$, where indices refer to X- and Ka- band frequencies.

Previous Faraday Rotation measurements in the corona were performed during Pioneer-6, Pioneer-9 missions (in 1968 and 1970) [Stelzried et al., 1970]) and more extensively with the Helios spacecraft (1975-1984) [Bird et al., 1982; Pätzold et al., 1987] during their solar conjunctions. They used a single S band frequency and observed significant FR between $10R_\odot$ and $4R_\odot$. The signal at this frequency is damped for solar offsets less than $4R_\odot$. The higher frequencies, X and Ka-band, allow us to pass radio signal closer to the solar surface. When the spacecraft is approaching solar occultation, it can measure Faraday rotation of the radio signal passing through previously unexplored regions of inner corona, $(1.1 - 4)R_{\odot}$. Specifically we can use an X-band (7.1 GHz) uplink, and a coherent dual-frequency downlink at X band (8.4 GHz) and Ka-band (32 GHz). The gyrofrequency, plasma frequency, and critical penetration frequency f_c arising due to the radio wave diffraction in the corona and particle collisions are lower than the sounding frequencies for all distances from the Sun.

Faraday rotation of natural radio sources have also been observed [Sakurai and Spangler, 1994; Mancuso and Spangler, 1999]. However, natural sources are difficult to use for sounding the inner corona because their intensity decreases toward the high frequencies and they have a low intrinsic polarization. Also, a time to observe a natural radio source is very limited, often to hours. A spacecraft signal from the orbit behind the Sun can be used for a year or longer.

Electron density and its fluctuations and the speed of density and magnetic inhomogeneities will be derived. The techniques are well developed and have been successfully used in previous spacecraft experiments at solar conjunctions (Pioneer, Mariners, Voyagers, Magellan, Helios, and Ulysses; see for example [Pätzold et al., 1995]. The total electron content (the integrated electron density along the radio ray path) is derived by measuring the propagation time delay at two frequencies. Density fluctuations will be derived by measuring the frequency shift (dispersive Doppler) induced by changes in the phase velocity. The velocity estimation is made by measuring the scintillation pattern caused by density fluctuations in the solar wind with two spaced antennas closely aligned with the flow velocity vector [Grall et al., 1996]. The time delay between the two antennas is estimated from a correlation analysis. The velocity is the observation interval divided by the scale time. With a spacecraft on the farside we can measure and cross-correlate the intensity, because it has a small spatial scale (of the order of 50 km). This is very important because the scintillation is a stochastic process and the correlations can only be estimated with an error that is of the order of the square root of the number of independent samples.

The radio sounding also gives the electron density essential for interpretation of Faraday rotation data and distinguish between several solar wind models such as the jet and wave- driven models. The density fluctuations themselves may be a signature of dissipation mechanisms. The feasibility of this approach was demonstrated by detecting Faraday rotation fluctuations in the S-band signal from Helios spacecraft. The fluctuations were interpreted as Alfvén wavesi.e., caused mainly by variations of magnetic field and not of density [Hollweg et al., 1982]. The power spectra of the fluctuations help to distinguish between different models. Thus, the cascade model (Hollweg and Johnson, 1988) predicts a Kolmogorov spectrum, at least at small spatial scales. In contrast, the ion-cyclotron model Tu and Marsch, 1997) requires substantial wave power at high frequencies.

According to Hollweg, even small coronal magnetic field fluctuations produce easily detected Faraday rotation fluctuations (FRFs). FRFs can be likened to a random walk as the spacecraft signal passes through a large number of locally coherent elements. The FRF produced by one element is proportional to the length, s, of that element along the ray path. The number of elements along the ray path is proportional to s^{-1}. The rms FRF accumulates as the square root of the number of elements, multiplied by the FRF produced by one element i.e., it scales as $s^{1/2}$. The length s is determined by the distance between the photospheric magnetic flux tubes (38,000 km at $3R_{\odot}$). Smaller correlation scales yield smaller FRFs. For example, if the Sun launches ion cyclotron waves, we might expect s to be of the order of the wavelengthi.e., about 30 km if the Alfvén speed is 3000 km/s and the frequency is 100 Hz. This value of s reduces the expected rms FRF by a factor of 35. Deeper regions in the corona can be reached with a better signal-to-noise ratio than before because we use higher frequencies at which the solar noise is lower.

The coronal magnetic field is then derived from these and simultaneous electron density measurements with the assistance of modeling based on full-Sun boundary conditions [Ruzmaikin et al., 1998]. The full-Sun boundary conditions are needed to validate the coronal magnetic field deduced from the Faraday Rotation measurements. At present, the lack of simultaneous full-Sun photospheric magnetic fields as internal boundary conditions is a limiting factor in coronal/solar wind modeling. To provide these conditions, synoptic maps are used. They are made by pasting together 27 days (a solar rotation) of fields seen at central meridian. However, the field shown in a synoptic map is not the field the Sun has at any one time. Moreover, synoptic maps do not even use the fields observed at a single time on the visible disk of the Sun! This approach would be satisfactory if the magnetic field were static or quasi-stationary, but unfortunately this is not the case. Basing magnetohydrodynamic (MHD) coronal models on the full-Sun boundary conditions is necessary because of the rapid changes on the global scale.

In recent years coronal modeling has developed, motivated significantly by the availability of high-resolution solar observations (Yohkoh, Ulysses, and SOHO) and the increasing power of supercomputers. Figure 3 illustrate the results that can be obtained with 3-D MHD models of the solar corona which use full-Sun boundary conditions [Mikic and Linker, 1996]. The full-Sun photospheric fields obtained from optical magnetic imaging from the farside of the Sun and Earthside observations (SOHO/MDI or ground-based) will enable further development in coronal modeling. Data for solar longitudes of the Sun that cannot be well observed (due to proximity of the solar limb) will be filled in using the most up-to-date observations available.

In the Mikic and Linker MHD model, the self-consistent interaction of magnetic, plasma, and solar gravity forces, including the effects of the solar wind, rigid or differential solar rotation, finite plasma resistivity, and a polytropic energy equation are simulated. The improved model will include the effects of coronal heating, thermal conduction, radiation, and Alfvén wave propagation. The coronal plasma is required to satisfy the equilibrium equations, subject to boundary conditions at the solar surface. The key boundary condition is the magnetic field. With the model we calculate the expected polarization brightness and Faraday rotation (see Figure 4) that can be compared with the radio sounding from the farside of the Sun. Thus we can (in an iterative manner) deconvolve the coronal magnetic field.

Acknowledgments. This work was supported by the Jet Propulsion Laboratory of the California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

References

Bird, M. K., H. Volland, *The Faraday rotation experiment of the Helios mission,* Radioastron. Institute of the University of Bonn, 1982.

Grall, R., W. Coles, M. Kinglesmith, A.R. Breen, P. J. S. Willams, J. Markkanen, and R. Esser, *Nature*, **379**, 429, 1996.

Hollweg, J. V., M. K. Bird, H. Volland, P. Edenhofer, C. T. Stelzried, and B. L. Seidel, *J. Geophys. Res.,* **87**, 1–8, 1982.

Mikic Z., and J. Linker, in *Solar Wind Eight*, ed. by D. Winterhalter, J. Gosling, S. Habbal, W. Kurth, and M. Neugebauer, AIP Press, N.Y., p.104, 1996.

Mancuso, S., and S. R. Spangler, *Astrophys. J.*, **522**, 373, 1999.

Pätzold, M., M.K. Bird, and H. Volland, *Solar Phys.*, **109**, 91, 1987.

Pätzold, M., M.K. Bird, P. Edenhofer, S.W. Asmar and T.P. McElrath, *Geophys. Res. Lett.*, **22**, 3313-3316, 1995.

Ruzmaikin, A., and MagSonas Team, A spacecraft going behind the Sun will support SOHO, in Fifth SOHO Workshop The corona and solar wind near minimum of solar activity, ed. by O. Kjeldson-Moe and A. Wilson, ESA publs., SP-404, 1997.

Ruzmaikin, A., J. Feynman, K. Harvey and J. Harvey, Enhanced synoptic observations: A spacecraft on the other side of the Sun, in Synoptic Physics, ed. by K. Balasubramaniam and J. Harvey, Astron. Soc. Pacific, 1998.

Sakurai, T., and S. R. Spangler, *Astrophys. J.*, **434**, 773, 1994.

Stelzried, C. T., G. S. Levy, T. Sato, W.V.T. Rusch, J. E. Ohlson, K. H. Schatten, and J. M. Wilcox, *Solar Phys.*, **14**, 440, 1970.

Received ______________________

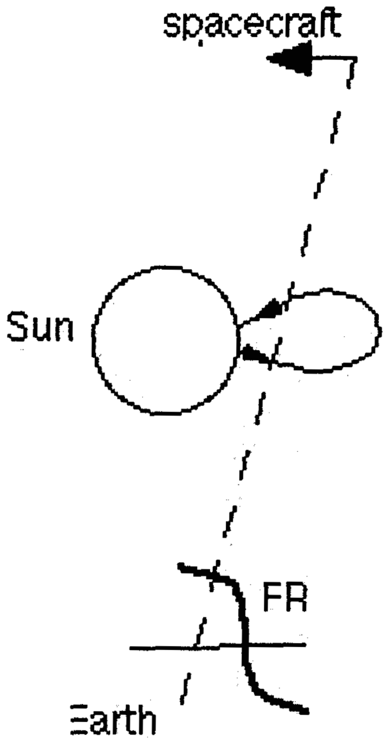

Figure 1. The use of the dual-frequency linearly polarized signal opens a unique opportunity to measure Faraday rotations in the inner corona. Schematic of Faraday rotation for a scan of a magnetic loop is shown.

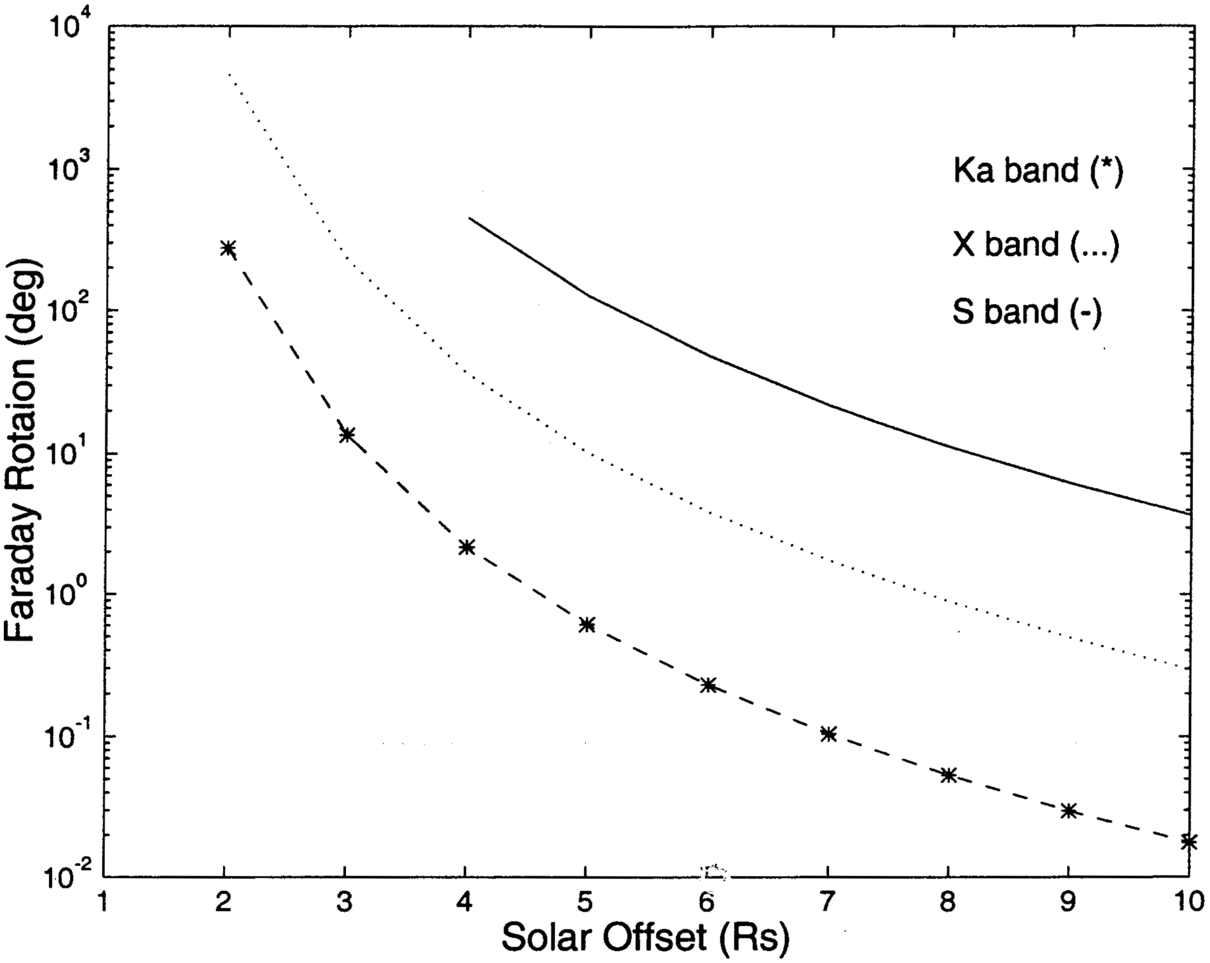

Figure 2. Faraday rotation at X- and Ka-band becomes measurable as spacecraft-Earth line- of-sight passes close to the Sun, permitting radio sounding of the inner corona. Estimated maximum rotation at X, Ka- and S- bands (for comparison) using power-low radial profiles for electron density and magnetic fields.

Figure 3. Magnetic field in the corona calculated using MHD model and synoptic maps on Jan. 30- Feb. 26, 1997 to predict the total solar eclipse on March 9, 1997 [36]. This kind of prediction would be improved by the availability of observations of the magnetic field on the back side of the Sun, as proposed in the MagSonas mission. Such observations are essential at solar maximum.

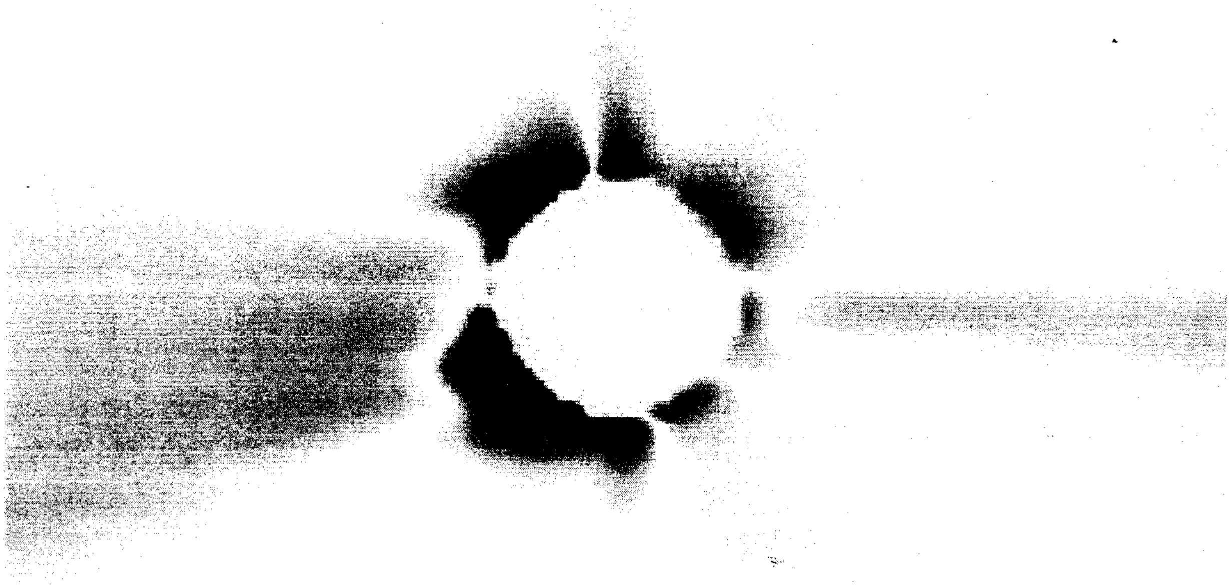

Figure 4. Images of the line-of-sight integral of the magnetic field will be used in reconstruction of the coronal magnetic field. This image shows a distribution of Faraday rotations for the field configuration presented in Figure 1.1.4-2. Red (blue) regions correspond to negative (positive) Faraday rotations.