The Helios Faraday Rotation Data Archive

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Abstract. The Helios Faraday Rotation (FR) Experiment, a passive radio science investigation requiring no on-board hardware other than the existing spacecraft radio subsystem, was designed to study the dynamic and quiescent structure of the magnetic fields and electron density in the solar corona. Measurements of coronal Faraday rotation were derived from the linearly polarized S-band downlink carrier signal, which probed otherwise inaccessible regions of the corona in the radial range from 2 to 15 solar radii during the regularly recurring solar conjunctions. More than 1250 hours of Helios FR data were recorded over the duration of the Helios 1 (1974-84) and Helios 2 (1976-80) missions. The time scales of FR variations provide information on various physical phenomena: (a) slowly-varying rise and fall associated with the changing ray path offset, combined with the rotation of the quasi-static corona; (b) ubiquitous random oscillations with higher fluctuation amplitude at smaller solar offset distances, probably caused by coronal Alfvén waves; (c) occasional nearly discontinuous jumps in the polarization angle, most likely caused by transient events such as coronal mass ejections (CMEs). The Helios FR data, aspects of which have been reported in more than forty publications to date, have now been systematically collected in a data archive for public dissemination. A brief review of the main results of the Helios FR Experiment are presented, together with some suggestions for possible use of the archive for continued solar wind research.

INTRODUCTION

The primary goal of the Helios Faraday Rotation experiment was to investigate the magnetic field $\mathbf{B}$ in the solar corona (Volland et al., 1977, 1984; Levy et al., 1980; Bird and Edenhofer, 1990). The passive radio science experiment required no on-board hardware other than the existing spacecraft radio communications subsystem. Helios polarization angle (FR) data, recorded using the linearly polarized S-band downlink carrier signal during times of superior conjunction, have been made available in an online archive. Selected results gleaned from the unique Helios FR data set with relevance for the coronal magnetic field and MHD-wave environment, as well as some possible future uses of the archive, are presented.

EXPERIMENT DESCRIPTION

A significant component of linear polarization is necessary for recording FR measurements with spacecraft radio signals. Only Pioneers 6 and 9 had been used for this purpose prior to Helios (Levy et al., 1969; Stelzried et al., 1970). In the more recent era, the Galileo spacecraft was optimally equipped with dual-frequency linear polarization (Howard et al., 1990), but prospects for conducting FR experiments were dashed prior to solar conjunction when the high gain antenna could not be deployed. The Helios FR data volume thus remains the largest collection of radio sounding data sensitive to the coronal magnetic field in the region of the solar wind transition to supersonic velocities.

Linear polarized electromagnetic waves propagating through a magnetized plasma undergo ‘Faraday rotation’ of their plane of polarization, which can be used to deduce the magnetic structure of the propagation medium. For the case of the cylindrical despun Helios antenna, the electric vector of the transmitted linearly polarized carrier signal was oriented perpendicular to the ecliptic. Measurements of the coronal contribution to signal Faraday rotation ($\Omega$) were obtained by tracking the received signal polarization angle $q$, referenced to the local horizon, and transforming this value back to the ecliptic frame from the known parallactic angle $p$, as shown schematically in Fig. 1. Coronal FR is related to the longitudinal component of the magnetic field along the ray path $B_s = \mathbf{B} \cdot \hat{s}$ and electron density $N_e$ by

$$\Omega = \frac{K}{f^2} \int_{H}^{\oplus} N_e(s) B_s(s) \, ds \text{ radians} \quad (1)$$

where $K = 2.36 \times 10^4$ in both MKS and cgs units, $f$ is the radio frequency (2.296 GHz), and the integral in Eq. (1)
is taken along the ray path from Helios (H) to the ground station on Earth (G), assumed to be along a straight line. The quantity $\Omega$ can be plus or minus depending on the integrated product of electron density and component of magnetic field along the ray path (quasi-longitudinal approximation). The direction of rotation is called positive (counterclockwise) when the magnetic field points toward the observer, as sketched in Fig. 1, and negative (clockwise) when directed away from the observer.

The short-period, zero-inclination, heliocentric orbits of the two identical Helios spacecraft were ideally designed for conducting radio science investigations of the solar corona during the recurring solar occultations. Helios 1, with an original design lifetime of 18 months, was launched 10 Dec 1974 and underwent a total of 10 solar conjunctions before its demise in 1985. The official end of mission (EOM) was declared as 15 Mar 1986.

Fig. 2 shows an ecliptic plane view of the Helios 1 orbit in a Sun/Earth fixed system during the first year after launch (left panel) and for all orbits through the end of September 1981 (right panel). The shaded wedge-shaped area denotes the region of space where interplanetary spacecraft attain a solar elongation within $3^\circ$, roughly the region where coronal Faraday rotation of an S-band radio signal becomes measurable. Dots are placed at 10 day intervals along the trajectory. Although most solar occultations proceeded diametrically along a solar radial from West to East limb, an occultation near spacecraft aphelion, such as the very first solar conjunction shown in Fig. 2 (left panel), could extend over several weeks.

The counterpart of Fig. 1 for Helios 2 is very similar, except that the orbital perihelion was lowered to 0.29 AU from the 0.31 AU of Helios 1. The associated change in the orbital period caused the clockwise orbital precession rate to decrease from $\sim 14^\circ$ per year (Fig. 1, right) to $\sim 6^\circ$ per year for Helios 2. From its launch on 15 Jan 1976, Helios 2 was tracked regularly until it ceased operating on 3 Mar 1980 (formal EOM: 8 Jan 1981).

AREAS OF INVESTIGATION

The time scales of FR variations, observed during virtually all occultations, provide information on various physical phenomena in the solar corona:

**Slowly-varying background.** The slow rise and fall in FR is associated with the changing ray path offset, combined with the rotation of the quasi-static corona. Fig. 3 shows such slow FR variations observed at solar offsets $R \approx 3 \, \text{R}_\odot$ near and during the overlap interval of two tracking stations (Volland et al., 1977). Pätzold et al. (1987) utilized the absolute FR measurements from 1975-76 for a determination of the mean coronal magnetic field $B(R)$ during solar minimum. A more general study using all FR data to study $B(R)$ at other solar cycle phases would be a valuable extension of this work.

**Random oscillations.** This ubiquitous phenomenon, with higher FR fluctuation amplitude at smaller solar offset distances, is probably caused by coronal Alfvén waves (Hollweg et al., 1982; Efimov et al., 1993, 2000; Andreev et al., 1996, 1997a,b). Fig. 4 shows simultaneous recordings at two tracking stations during an interval of quite obvious wavelike FR fluctuations. A preliminary study determined that ca. 30% of the velocities determined from two-station cross correlations were directed radially inward toward the Sun (Bird et al., 1992). A more exhaustive study using the entire FR data set should be undertaken to confirm these results.

**FR discontinuities.** These occasional abrupt jumps in the polarization angle are assumed to be caused by transient events such as coronal mass ejections (CMEs). A search for white-light CMEs during the 1979 Helios solar conjunctions yielded 5 distinct events which produced obvious abrupt FB signatures associated with their passage through the signal ray path (Bird et al., 1985). These ‘FR transients’ were first seen at solar maximum (Levy et al., 1969), even before their optical counterparts were widely publicized from the Skylab observations. Not restricted to epochs of solar activity maximum, an example from 1976 presented by Bird et al. (1977) is shown in Fig. 5. Some recent work has associated the FR transients with interplanetary sector boundaries (Woo, 1997), rather than CMEs (Pätzold and Bird, 1998). The Helios FR archive offers by far the largest data source for pursuit of this controversy.

In summary, the Helios Faraday rotation experiment provided valuable clues about the quiet and disturbed magnetic structure of the solar corona in the critical
radial range $2 R_{\odot} < R < 15 R_{\odot}$. The unexpectedly long lifetime of the Helios probes enabled studies to extend from deepest solar activity minimum into the following maximum and beyond.

**FR DATA ARCHIVE STRUCTURE**

The FR data consist of ground-received, time-tagged measurements of the locally referenced polarization angle using automatic tracking polarimeters. This angle is transformed to the ecliptic plane (see Fig. 1) to determine the coronal Faraday rotation given by Eq. (1) as a function of $(R, \Theta, \Phi)$, the heliocentric spherical coordinates of the ray path’s point of solar closest approach (the “solar offset”). Significant coronal FR at levels easily distinguishable from the diurnal variation of the Earth’s ionosphere is typically obtained for $R < 15R_{\odot}$. It is important to continually monitor the FR during an occultation (see Fig. 3), avoiding gaps between ground station transitions. This is because any isolated measurement of polarization angle is known only to modulo $180^\circ$. It follows that the actual value of coronal FR can become ambiguous by $\pm n \times 180^\circ$ if the tracking is interrupted too long. This condition was actually realized on a number of occasions during the many solar conjunctions (e.g., Fig. 5).

Helios FR data exist for the years 1975-1984 during most of the periods when the ray path offset was below $15 R_{\odot}$. Only the large Goldstone station (DSS 14) of the...
NASA Deep Space Network (DSN) and the 100 m Effelsberg Radio Telescope were used during the first Helios mission years. The experiment could be conducted on a global basis starting in 1977 when the DSN added automatic tracking polarimeters at the 64-m stations in Canberra (DSS 43) and Madrid (DSS 63). These polarimeters were removed from the DSN ground stations in 1984, effectively ending the Helios FR experiment a few months before Helios 1 operations were terminated.

Data from the Helios FR archive, comprised of 227 tracking passes with 1277 hours of FR data as well as short statistical summaries of each tracking pass, are now available for downloading at the following URL:

http://www.astro.uni-bonn.de/~mbird/helios_html/

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