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Coronal Radio Occultation Experiments with the *Helios* Solar Probes: Correlation/Spectral Analysis of Faraday Rotation Fluctuations

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Abstract The coronal Faraday rotation (FR) experiments using the linearly polarized signals of the *Helios-1* and *Helios-2* interplanetary probes remain a unique investigation of the magnetic field of the solar corona and its aperiodic and quasi-periodic variations. The unexpectedly long lifetime of these spacecraft (1974–1986) enabled studies from very deep solar-activity minimum (1975–1976) into the strong activity maximum (1979). Important experimental data were also obtained for the rising (1977–1978) and declining (1980–1984) branches of the solar-activity cycle. Previous publications have presented results of the initial experimental data only for coronal-sounding experiments performed during individual solar-conjunction opportunities. This report is a more detailed analysis of the *Helios* FR measurements for the entire period 1975–1984. Radial profiles of the FR fluctuation (FRF) intensity recorded during the deepest solar-activity minimum in 1975–1976 are shown to differ distinctly from those during the strong solar-activity maximum in 1979. In particular, the decrease of the FRF intensity with solar-offset distance is substantially steeper in 1979 than in 1975/1976. In all cases, however, the FR data reveal quasi-periodic wave-like fluctuations in addition to the random background with a power-law spectrum. The dominant period of these fluctuations, recorded during 35 % of the total measurement time, is found to be close to five minutes. Large-scale FR variations at considerably longer periods (1.1–2.7 hours) were observed during 20 % of the measurement time. Knowing the intrinsic motion of the radio ray path from spacecraft to Earth and making a reasonable assumption about the solar-wind velocity, FRF observations at widely spaced ground stations have been used to estimate the velocity of coronal Alfvén waves. The velocity values

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range between 290 and 550 km s^{-1} at heliocentric distances between 3.5 and 4.5 R$_\odot$ and are marginally lower (150 – 450 km s^{-1}) at distances between 5.5 and 6.5 R$_\odot$. Occasional FR variations with a period near 160 minutes and harmonics with periods 60, 30, and 20 minutes were also observed.

Keywords Solar corona · Faraday rotation · Radio sounding

1. Introduction

Alfvén waves, generated near the solar surface and propagating into interplanetary space, have been proposed as one of the primary mechanisms for heating the solar corona and acceleration of the solar wind (Chashei, 1989). Direct observations of these waves are quite difficult (Parker, 1987). Alfvénic fluctuations have been measured *in situ* as close to the Sun as 62 R$_\odot$ with the *Helios* solar probes (Schwenn, 1990). Remote-sensing observations in the inner corona, however, are possible using radio-sounding experiments.

Faraday rotation (FR) observations of radio sources near solar conjunction yield information on the coronal magnetic field at heliocentric distances not reached by *in-situ* exploration. The most extensive campaign of coronal radio-sounding polarization measurements using a spacecraft was the *Helios Faraday Rotation Experiment*, conducted over the duration of the *Helios-1* (1975 – 1984) and *Helios-2* (1976 – 1980) missions. FR fluctuations (FRF) provided information on various physical phenomena at different time scales (Bird and Edenhofer, 1990; Efimov *et al.*, 1997; Bird, 2007):

 i) Slow variations are associated with the motion of the radio ray path and gradual evolution of outer coronal structures, primarily due to coronal rotation.
 ii) Random oscillations probably arise from a rich spectrum of Alfvén waves.
iii) Quasi-periodic pulsations connected with Alfvén waves of the five-minute band and longer periods (up to a few hours).

An early analysis of the *Helios* FRF by Hollweg *et al.* (1982) concluded that the observations could not be attributed solely to electron-density fluctuations. It was further suggested that most of the variance was produced by the fluctuating magnetic field of coronal Alfvén waves. More recent work has provided additional evidence that the energy density of the long-period magnetic-field fluctuations detected with the *Helios* FRF measurements is sufficient for extended coronal heating and acceleration of the solar wind (Hollweg, Cranmer, and Chandran, 2010).

In a number of cases, FR measurements could be recorded simultaneously from two widely separated ground stations. Whereas measurements from at least three stations are required for a complete determination of the plane-of-sky velocity of these waves, two lines of sight can still be applied to determine speeds and directions of coronal velocities in a statistical sense.

The FR experiments performed with *Helios-1* and *Helios-2* remain unique both in volume and quality. Similar, single experiments were performed with the *Cassini* spacecraft in 2002 (Jensen *et al.*, 2005) and *MErcury Surface, Space ENvironment, GEochemistry, and Rangin* (MESSENGER) in 2009 (Jensen *et al.*, 2013).

In this article we describe FR measurements with *Helios* carried out at different levels of solar activity (1975 – 1977, 1979, 1981, 1983, and 1984). The FR measurements were generally recorded at a sampling time of one second. The ground stations used for this work include the 100 m radio telescope of the Max-Planck-Institute for Radioastronomy in Effelsberg (also called DSS 69 when used for support of spacecraft tracking) and the three 64 m (70 m at present) NASA Deep Space Network (DSN) tracking stations: DSS 14 in

Goldstone (California), DSS 43 in Canberra, Australia, and DSS 63 in Madrid, Spain. All of the measurements were made for ray-path offset distances from the Sun in the range from 2 to 20 $R_\odot$.

2. FRF Correlation Analysis

The quantity measured during the *Helios Faraday Rotation Experiment* was the change of the polarization plane of the linearly polarized carrier signal at 2.295 GHz (S-band) during its propagation from spacecraft to ground station. The change of the signal polarization angle, the Faraday rotation [Φ], is a function of the electron density [N] and the component of the magnetic field [B_ℓ] along the ray path through the corona

$$\Phi = \frac{A_\Phi}{f^2} \int N(\ell) B_\ell(\ell) \mathrm{d}\ell, \tag{1}$$

where Φ is expressed in degrees when the radio wave frequency [f] is expressed in MHz, $\mathrm{d}\ell$ is the ray-path element along the propagation direction [cm], B_ℓ is the component of the magnetic field along the radio ray path from spacecraft to Earth [G], and $A_\Phi = 1.35 \times 10^{-6}$ [cgs]. FRF data recorded simultaneously at several widely spaced ground stations provide the possibility of investigating Alfvén-wave propagation in the solar corona. Although the distance between radio ray paths in the region of their closest approach to the Sun was more than 1000 km, the temporal spectra of the FRF for different ground stations were very similar to each other. Because the cross-correlation of the FRF was rather strong, it is possible to determine the radial component of the magnetic-field irregularities velocity [V_C] across the radio ray paths with high accuracy.

The value of V_C determined from a cross-correlation analysis consists of three components:

  i) velocity of the solar-wind flow [V_{SW}], which always moves away from the Sun in the radial direction,
 ii) velocity of the quasi-periodic fluctuations [V_A], presumed to be Alfvén waves propagating along the magnetic field in the rest frame moving with the solar wind, and
iii) velocity of the radio ray path from spacecraft to Earth [V_R], relative to the Sun. This is directed antiparallel to the solar-wind direction during solar conjunction ingress and parallel to the solar-wind direction during solar conjunction egress.

From earlier coronal-sounding experiments it is known that the solar-wind velocity for the heliocentric distance interval between 3 and 6 $R_\odot$ rarely exceeds 80 km s^{-1} (Efimov, 1994). The velocity of Alfvén waves at these distances is estimated to lie in the range from $400-600$ km s^{-1} (*e.g.* Ogilvie, 1978).

To a first approximation, it may be assumed that $V_C = V_{SW} + V_A + V_R$ during the ingress phase, while $V_C = V_{SW} + V_A - V_R$ during the egress phase. Because the cross-correlation time lag of the fluctuations is inversely proportional to the total velocity of the irregularities motion across the radio ray path, the radial dependence of the FRF correlation time lag may be asymmetric between ingress and egress. This may be described by an asymmetry coefficient [ξ] defined as

$$\xi = (V_{SW} + V_A + V_R)/(V_{SW} + V_A - V_R). \tag{2}$$

For example, typical values at a heliocentric distance $R = 5$ $R_\odot$ are $V_{SW} = 75$ km s^{-1} for the solar-wind velocity, and $V_A = 400$ km s^{-1}. Assuming the velocity of the ray-path motion

relative to the Sun is $V_R = 42 \, \text{km s}^{-1}$ (typical for the coronal-sounding experiments of 1981), the asymmetry coefficient from Equation (2) is $\xi = 1.21$. If $V_A = 350 \, \text{km s}^{-1}$, then $\xi = 1.24$. The coefficient ξ is thus sensitive to the cross-correlation velocity of the irregularities. If the solar-wind velocity can be found by any independent technique, it is possible to find the Alfvén-wave velocity from the relation

$$V_A = \frac{\xi + 1}{\xi - 1} V_R - V_{SW}. \tag{3}$$

The measurements used for performing the cross-correlation analysis and estimating the Alfvén-wave velocity are the FR time series $[\Phi(t)]$, recorded at widely spaced ground stations at a sampling time of one second. Values of FRF, denoted below by $\psi(t)$, were determined as the difference between the measured values $[\Phi]$ from a slowly changing trend, approximated by a first- or second-degree polynomial fit to the observation segment subjected to processing.

The cross-correlation function $[K(\tau)]$ is calculated according to the relation

$$K(\tau) = \frac{\langle \psi_1(t) \psi_2(t + \tau) \rangle}{\sigma_1 \sigma_2}, \tag{4}$$

where τ is the time delay, ψ_1 and ψ_2 are values of the FRF measured at ground stations 1 and 2, and σ_1, σ_2 are RMS values of the FRF.

A clearly defined maximum of the cross-correlation function implies ordered motion of the irregularities across the radio ray paths. Using the delay time of the maximum of the cross-correlation function $[\tau_m]$ and the distance $[\Delta R]$ between radio ray paths in the region of their closest approach to the Sun, it possible to find the component of the irregularities velocity across the radio link:

$$V_C = \Delta R / \tau_m. \tag{5}$$

The absolute distances between the two rays at their proximate points to the Sun are typically $\Delta R \approx 1300$ to $2100 \, \text{km}$.

It is possible to find a simple connection between the velocity $[V_C]$ and the Alfvén velocity $[V_A]$ in the case when V_R can be neglected. For the case of isotropic turbulence, the argument of the cross-correlation function of FRF measurements at two widely spaced ground stations can be assumed to depend on τ according to

$$\left[\Delta R - (V_{SW} \pm V_{AR})\tau \right]^2 + \left[\Delta y - (\pm V_{Ay})\tau \right]^2, \tag{6}$$

where V_{AR} and V_{Ay} are the two components of the Alfvén velocity perpendicular to the line of sight: V_{AR} is the radial component, and V_{Ay} is the component perpendicular to the radial direction and to the line of sight. Δy is the distance between radio ray paths along the y-direction in the region of their closest approach to the Sun.

The position of the maximum can be determined from the condition $dK/d\tau = 0$:

$$\tau_m = \frac{\Delta R(V \pm V_{AR}) + \Delta y(\pm V_{Ay})}{(V \pm V_{AR})^2 + V_{Ay}^2}. \tag{7}$$

From Equations (5) and (7) it follows that

$$V_C = \frac{\Delta R}{\tau_m} = \frac{(V_{SW} \pm V_{AR})[1 + V_{ay}^2(V_{SW} \pm V_{AR})^2]}{1 + (\Delta y/\Delta R)[\pm V_{Ay}/(V_{SW} \pm V_{AR})^2]}. \tag{8}$$

Figure 1 Cross-correlation function [$K(\tau)$] (solid curve) and autocorrelation function [$A(\tau)$] (dotted curve) of the Faraday rotation fluctuations recorded on 22 December 1981 at the Goldstone and Canberra ground stations.
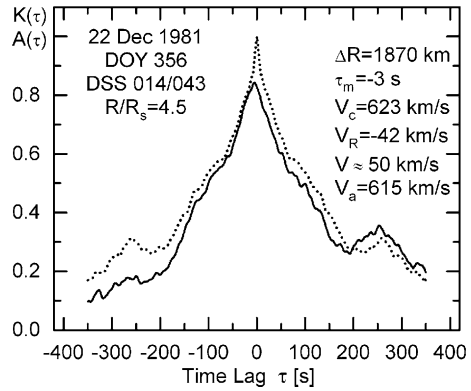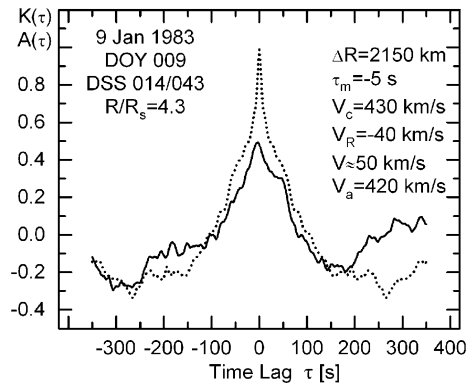

Figure 2 Cross-correlation function [$K(\tau)$] (solid curve) and auto-correlation function [$A(\tau)$] (dotted curve) of the Faraday rotation fluctuations recorded on 9 January 1983 at the Goldstone and Canberra ground stations.

Determination of the Alfvén velocity from Equation (8), derived from simultaneous observations of the FRF at widely spaced ground stations, is possible if the direction of the magnetic-field vector is known. Generally, this is not the case. However, if $V_{Ay} = 0$, in Equation (8), then $V_C = V_{SW} \pm V_{AR}$, and if the solar-wind velocity can be neglected, then the experimental data provide an estimate of the radial component of the Alfvén velocity. If the solar-wind velocity [V_{SW}] and ray-path velocity [V_R] are comparable with the Alfvén velocity, then these components should be taken into account for the estimate of V_A obtained from the cross-correlation analysis.

Figure 1 presents the cross-correlation function [$K(\tau)$] and autocorrelation function [$A(\tau)$] recorded on 22 December 1981 at the Goldstone and Canberra ground stations. In this example the short time lag ($\tau_m = -3$ seconds) yields a rather high value for the irregularities velocity: $V_C = \Delta R/\tau_m = 623$ km s^{-1}. By convention, for the case of observations on the solar east limb (egress), the time lag is negative when the measured velocity of the irregularities is away from the Sun. The directions of the solar-wind velocity ($V_{SW} \approx 50$ km s^{-1}) and of the velocity of the ray-path motion ($V_R = 42$ km s^{-1}) at this solar offset are nearly antiparallel. In this case, the measured cross-correlation velocity [V_C] essentially coincides with the Alfvén velocity: $V_A \approx 615$ km s^{-1}.

A similar case is shown in Figure 2 for FR measurements at the Goldstone and Canberra ground stations on 9 January 1983. The measured velocity is again approximately equal to the Alfvén velocity: $V_C \approx V_A \approx 420$ km s^{-1}. The results of the cross-correlation processing of all data obtained during the four hours of the coronal-sounding experiment carried out on
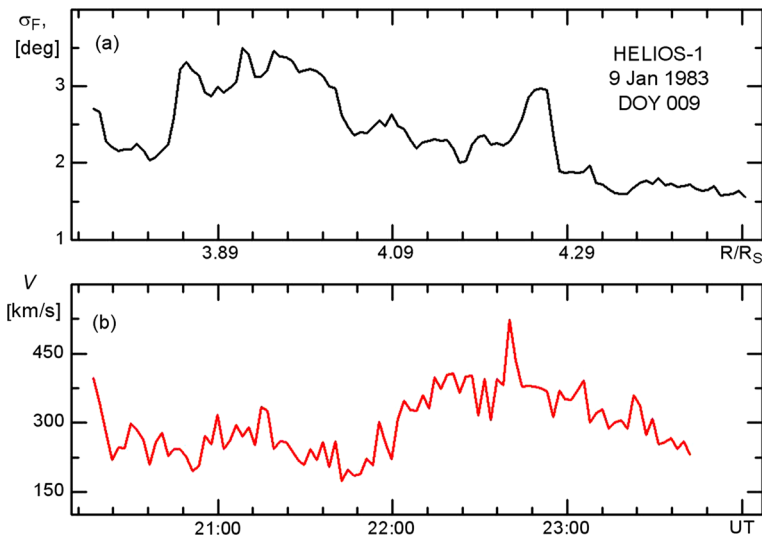
Figure 3 Running averages of the RMS Faraday rotation fluctuation $[\langle\sigma_F\rangle]$ (a) and the irregularities velocity $[V_C]$ derived from two-station cross correlations (b).

9 January 1983 are presented in Figure 3. The cross-correlation functions were calculated for successive time segments of 2048 seconds duration. The time shift between adjacent segments was 128 seconds. The heliocentric distances of the solar proximate point at this time ranged from 3.74 to 4.50 $R_\odot$. Figure 3a shows the average values of the mean FRF amplitude for two ground stations $[\langle\sigma_F\rangle = (\sigma_{F14} + \sigma_{F43})/2]$.

There is a tendency for a decrease in $\langle\sigma_F\rangle$ for increasing solar offset. Figure 3b shows the corresponding values of the measured cross-correlation velocity $[V_C]$, which in this case coincides with the Alfvén velocity $[V_A]$. Typical values of the Alfvén velocity at $R = (3.5\ldots4.5)$ $R_\odot$ are $V_A = (300–400)$ km s^{-1}.

If the electron density at these distances has the reasonable value $N \approx 10^5$ cm^{-3} and the magnetic-field induction $B \approx 10^{-1}$ gauss (Bird and Edenhofer, 1990), then the expected value of the Alfvén velocity is $V_A \approx 600$ km s^{-1}. The experimentally derived values of V_C, however, are generally found to be substantially lower than 600 km s^{-1}. One possible explanation for this difference is non-radial wave propagation perpendicular to the radio ray path. The measured velocity $[V_C]$ could also be lower than 600 km s^{-1} for another simple reason. Coronal sounding experiments with *Helios* were conducted for wave propagation in near-equatorial regions of the solar corona, often dominated by a streamer belt. For this reason, the electron density may be higher and the magnetic induction may be lower than their nominally assumed values. Finally, the substantially lower measured velocity $[V_C]$ from the expected velocity $[V_A]$ may also imply that the coronal magnetic-field configuration is not purely radial.

3. FRF Spectral Analysis

Spectral processing of the *Helios* radio-sounding data was performed in the following way. Each record of Faraday rotation angle $[\Phi(t)]$ was divided into segments of 2048 seconds duration. A slowly varying component (trend) $[\Phi_0(t)]$, connected with the effect of the
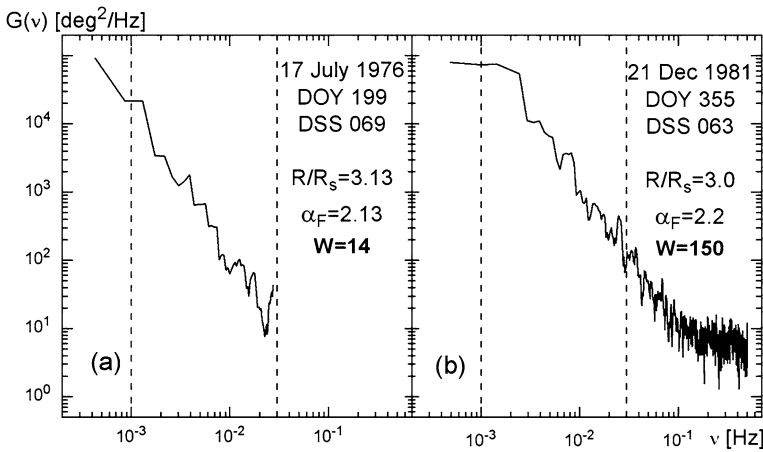
Figure 4 Temporal FRF spectra derived from FR measurements at the Effelsberg ground station on 17 July 1976, $R = 3.1\,R_\odot$ (a) and at the Madrid ground station on 21 December 1981, $R = 3.0\,R_\odot$ (b).

large-scale electron density and magnetic field of the Sun, was subtracted from the measured values. The temporal FRF spectra $[G(\nu)]$, where ν is the fluctuation frequency, were then calculated from the residuals $[\psi(t) = \Phi(t) - \Phi_0(t)]$.

Examples of two spectra are presented in Figures 4a and 4b. These spectra were determined from the measurement data of 17 July 1976 ($R = 3.1\,R_\odot$) and 21 December 1981 ($R = 3.0\,R_\odot$), respectively, *i.e.* at epochs with considerably different solar-activity level. In the first case the sunspot number $[W]$ was very low ($W = 14$), and in the second case, the level of activity was close to solar maximum ($W = 150$).

The temporal FRF spectra in Figure 4 can be described by power-law functions

$$G_{\mathrm{F}}(\nu) = G_{0\mathrm{F}} \nu^{-\alpha_{\mathrm{F}}} \tag{9}$$

for all fluctuation frequencies $[\nu]$ in the interval $\nu_\ell < \nu < \nu_{\mathrm{u}}$, where ν_ℓ and ν_{u} are the lower and upper bounds of the frequency range containing the solar-induced frequency fluctuations; α_{F} is the spectral index of the temporal FRF spectra.

The radial dependence of the FRF spectral index $[\alpha_{\mathrm{F}}]$ is presented in Figure 5. The data in Figure 5 include measurements from the years 1979, 1981, and 1983, which were discussed earlier (Chashei *et al.*, 2000), as well as measurements recorded in 1975 and 1976 using the 100 m Effelsberg antenna. These new data points are denoted in Figure 5 by solid stars.

The data presented in Figure 5 imply that the spectral index $[\alpha_{\mathrm{F}}]$ ranges from 2.0 to 2.4 at small heliocentric distances ($2\ldots3\,R_\odot$), which are values corresponding to a spectral index of the 3D turbulence spectrum $p = 3.0\ldots3.4$. There is a tendency for decreasing spectral index $[\alpha_{\mathrm{F}}]$ with increasing heliocentric distance $[R]$.

Most of the temporal FRF spectra (*e.g.* Figure 4) can be described by pure power-law functions. In some 30 % of the cases, however, the spectra contain a quasi-periodic component (Efimov *et al.*, 2000). Typical values of the centroid of the spectral line $[\nu_{\mathrm{max}}]$ are about 4 mHz (fluctuation period $T_{\mathrm{max}} = 1/\nu_{\mathrm{max}} \approx 250$ seconds), which are most likely associated with the known oscillations of the five-minute band observed near the photosphere (Kaplan, Pikel'ner, and Tsytovich, 1977). An analysis of additional data accumulated during the coronal-sounding experiments of 1979 and 1984 is consistent with the earlier work and indicates that the quasi-periodic FRF component exists at different solar-activity levels.

Figure 5 Radial dependence of the spectral index [α_f] of the temporal FRF spectra. The open circles are taken from Chashei *et al.* (2000). Calculations from the present work are indicated by the solid stars.
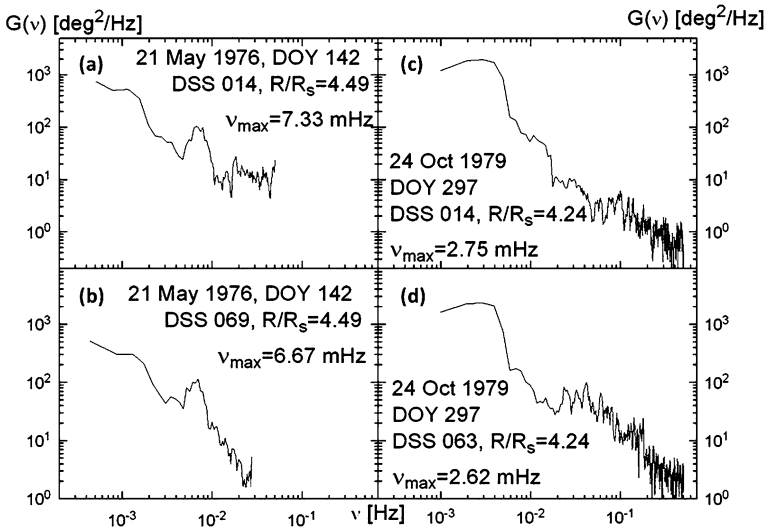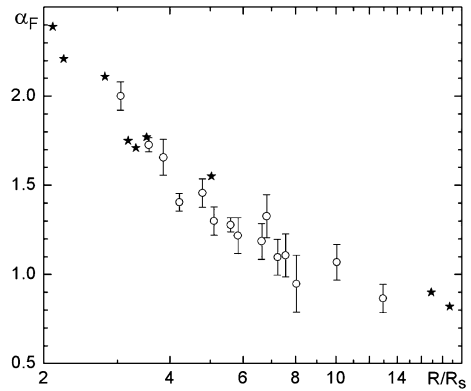

Figure 6 Temporal FRF spectra containing quasi-periodic components from observations at widely spaced ground stations for solar-activity minimum (a, b) and solar-activity maximum (c, d).

Figure 6 presents FRF temporal spectra with a quasi-periodic component obtained from simultaneous measurements on 21 May 1976 at the Goldstone (Figure 6a) and Effelsberg (Figure 6b) ground stations during a period of low solar activity. Figures 6c and 6d show temporal FRF spectra of data recorded on 24 October 1979 at the Goldstone and Madrid ground stations, respectively.

All spectra in Figure 6 have a well-defined quasi-periodic component, which is superimposed on the background spectrum and manifests itself as a relative maximum in spectral density. The background is formed by an ensemble of Alfvén waves with random amplitudes and phases (Efimov *et al.*, 2000). The maxima in the quasi-periodic FRF are interpreted as being produced by quasi-monochromatic Alfvén wave trains. The maximum frequencies ν_{max} are 7.33, 6.67, 2.75, and 2.62 mHz for the spectra shown in Figures 6a, 6b, 6c, and 6d, respectively.

Additional evidence for the quasi-periodic FRF component in the five-minute band is presented in Figure 7, showing overlapping FR measurements recorded on 24 October 1979 at
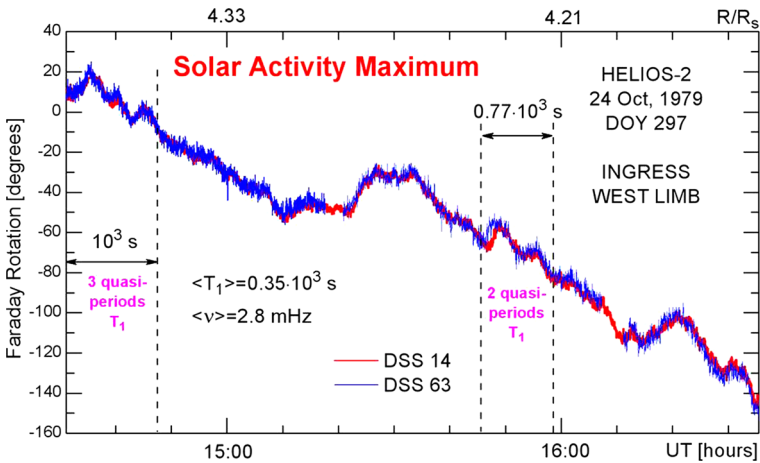
Figure 7 Quasi-periodic FR fluctuations in the five-minute band observed at the Goldstone and Canberra ground stations on 24 October 1979.
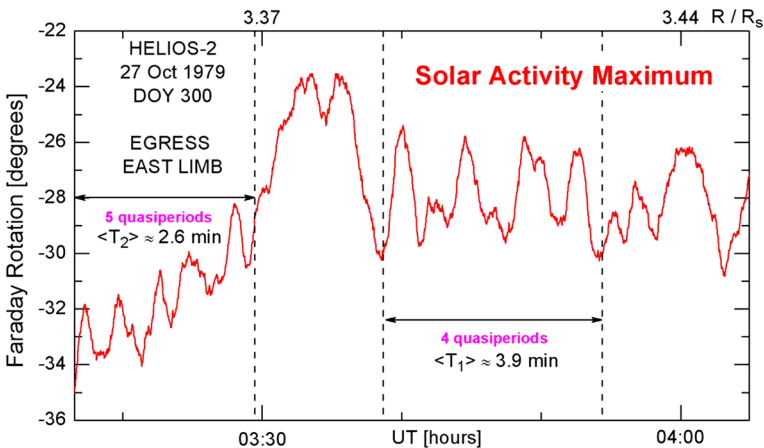

Figure 8 Quasi-periodic FRF trains in the five-minute band observed during solar-activity maximum.

the Goldstone and Madrid ground stations. Two intervals are indicated when quasi-periodic FRF in the five-minute band were observed. The observation time of such fluctuations amounts to 24 % of the total observation time.

Figure 8 presents FR-measurements recorded during the same solar conjunction of *Helios-2* in 1979, but closer to the Sun on the eastern solar limb (egress). Two quasi-periodic FRF trains can be distinguished in Figure 8. One train contains four oscillations with a period $T_1 \approx 3.9$ minutes and amplitude $\pm 2°$; another train contains five oscillations with a period $T_2 \approx 2.6$ minutes and amplitude $\pm 1°$.

Figure 9 shows the continuation of the FR measurements later on the same day when the solar offset moved from 5.05 to 6.72 $R_\odot$. Quasi-periodic FRF components with periods $T_1 \approx 19$ minutes (amplitude: $\pm 18°$) and $T_2 \approx 65$ minutes (amplitude: $\pm 5°$) were observed during the total interval of $\Delta T \approx 11$ hours.
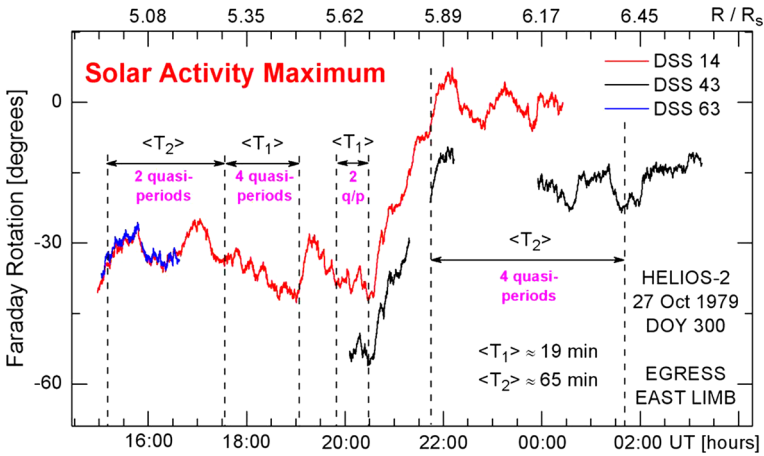
Figure 9 Quasi-periodic FRF in the 20-minute $[T_1]$ and 60-minute $[T_2]$ bands at small heliocentric distances.
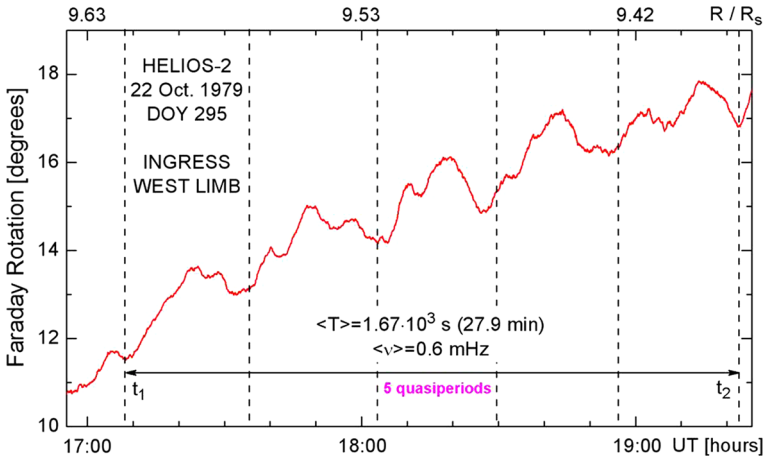

Figure 10 Quasi-periodic FRF in the 30-minute band observed at a relatively large solar offset distance.

An example at the relatively large solar offset distance out to 9.63 $R_\odot$ is presented in Figure 10. Five oscillations of an almost sinusoidally varying FRF train with an average period of $\langle T \rangle = 27.9$ min and amplitude $\pm 0.5°$ were observed.

Figure 11 shows two long-duration FR-measurement intervals (approximately seven hours) recorded during a period of low solar activity on 22 May 1976 (Figure 11a) at solar offset distances in the range between 5.0 and 5.17 $R_\odot$ (occultation egress) and during a period of high solar activity on 24/25 October 1979 (Figure 11b) at solar offset distances from 3.73 to 3.25 $R_\odot$ (occultation ingress). These two examples can be interpreted in terms of quasi-periodic FRF variations with the rather long periods of $\langle T \rangle = (161 \pm 11)$ minutes and $\langle T \rangle = (163 \pm 4)$ minutes, respectively. The amplitudes of the variations differ strongly. While the FRF variation is $\pm 7°$ in the first case (Figure 11a), the oscillation for the second case (Figure 11b) exceeds $\pm 250°$. This discrepancy is probably connected with both the different heliocentric distances and the different solar-activity levels.
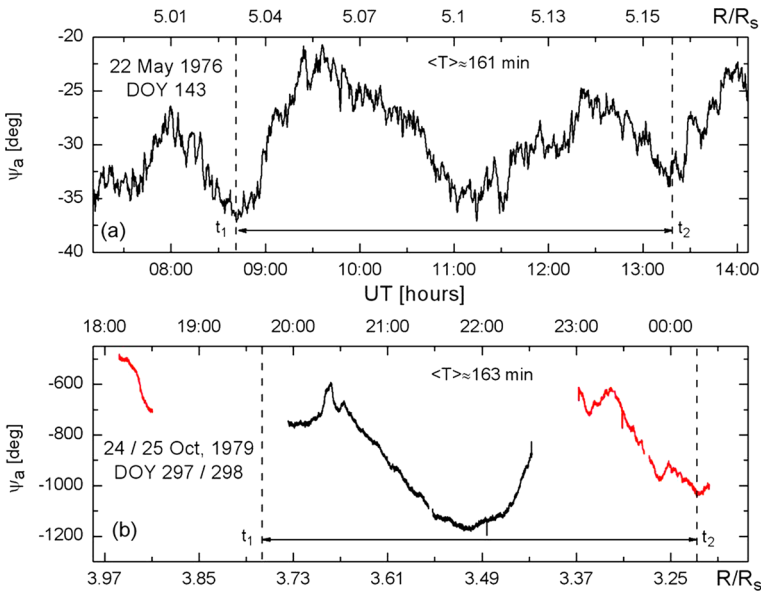
Figure 11 Large-scale quasi-periodic FRF variations in the 160-minute band observed at solar-activity minimum (a) and solar activity maximum (b).

4. Conclusion

A correlation and spectral analysis of Faraday rotation fluctuations in the solar corona has been carried out for polarization measurements recorded with the *Helios* solar probes over approximately one solar cycle.

Cross-correlation processing of simultaneous FRF observations at several widely spaced ground stations was used to estimate the velocity of the fluctuation pattern for heliocentric distances between 3 and 6 $R_\odot$. The derived velocities vary in the range from 250 to 650 km s^{-1} and always exceed the local solar-wind velocity. This provides evidence that the dominant contribution to the FRF must originate from coronal magnetic-field fluctuations (Alfvén waves) rather than from fluctuations of the electron density. As a rule, the measured velocities are lower than the expected Alfvén-wave velocities at a given height in the corona. This discrepancy can be explained by the deviation of the magnetic-field configuration from a purely radial alignment in the near-equatorial region of the corona.

It has been determined that FR-measurements recorded during the coronal-sounding experiments with *Helios-1* and *Helios-2* in 1975–1984 occasionally reveal wave-like structures with periods extending from 2.5 to 160 minutes. The most commonly encountered FRF periods belong to the bands at periods centered near 5, 20, 30, and 60 minutes, all of which can be considered as harmonics of the longest period fluctuations in the 160-minute band. The amplitude of the oscillations is found to be generally proportional to the period.

Disclosure of Potential Conflicts of Interest The authors declare that they have no conflicts of interest.

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