ANALYSIS OF GALILEO DOPPLER MEASUREMENTS DURING THE SOLAR OCCULTATIONS IN 1994 AND 1995

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Abstract. Measurements of S-band downlink frequency (Doppler) shift were collected for intervals of about 3(I clays during the 1994 and 1995 solar conjunctions of the Galileo spacecraft. The occultation geometries enabled coronal radio sounding of the heliographic equatoral region over a heliocentric range from about 5 to 20 R_S (solar radii) for the 1994 conjunction and from about 4 to 35 R_S for the 1995 conjunction. Spectral analysis was carried out with the S-band Doppler scintillations to determine the strength and spectral distribution of coronal electron density fluctuations. Cross correlations of the Galileo downlink signals received simultaneously at two ground stations were computed to obtain the propagation velocity of plasma disturbances crossing tile ray paths.

Introduction

The Galileo Solar Corona Experiment (SCE) was performed during the spacecraft's superior conjunctions in December 1994 and December 1995. Doppler measurements of the spacecraft's S-band downlink signal were recorded for intervals of about 30 days using the 70-111 antennas of the NASA Deep Space Network (DSN) at Goldstone (California), Canberra

(Australia.) and Madrid (Spain). During these periods the radio ray path from Galileo to Earth moved essentially parallel to the solar equator, sounding the circumsolar plasma at low heliographic latitudes during solar minimum conditions. Measurements of the residua l Doppler shift at S-band (f_0 = 2.3 GHz) are analyzed in this paper to determine the radial dependence of coronal plasma parameters such as the electron density fluctuations and propagation velocities.

Basedon assumptions similar to those applied fOr derivation Of a coronal electron density model [3], the radial dependence of the electron density fluctuations is determined. Frequency fluctuation spectra arc computed and used to obtain the spectral index of the three-dimensional wavenumber spectrum of the electron density fluctuations. The propagation velocity of plasma inhomogeneities is derived from a cross-correlation analysis of simultaneous overlapping measurements at two different ground stations. Similar analyses have been performed for the Venera-10 and Venera-15/16 experiments [4, 8], as well as for the Viking [1] and Ulysses [6] radio science investigations.

Coronal Radio Sounding with Galileo

The radio equipment on Galileo was designed to operate in two different radio science modes. In the two-way mode the downlink frequencies were controlled by the coherent turnaround of an uplink signal. Alternatively, a one-way mode could be used, where the downlink signal was derived from an onboard ultrastable oscillator (USO). Due to the failure to deploy the High Gain Antenna (HGA), the one-way mode at S-baud was used for most of the Doppler measurements during the solar conjunctions in 1994 and 1995. Only sporadic two-way measurements could be performed because of the difficulty to maintain a two-way radio link with the low signal strengths available via the spacecraft's Low Gaiu Antenna (LGA). In spite of this reduced radio science capability, analyses of the data have demonstrated that a large part of the originally proposed scientific objectives of the Galileo SCE [5] could be achieved.

Characteristic parameters of radio waves such as the phase and group velocity will be altered during propagation through an ionized medium. Any change in the electron density of the coronal plasma along the propagation path between spacecraft and Earth will produce a change in the phase of the received carrier signal, corresponding to a Doppler shift in signal frequency [2]. The Doppler shift observed at the ground station is thus not ouly proportional to the relative motion between spacecraft aud ground antenna, but also promotional to the time derivative of the electron density integrated along the propagation path (electron content). The Doppler shift also contains a term due to frequency deviations from the instabilities of the onboard USO.

Coronal Electron Density Fluctuations

The standard deviations of Doppler fluctuations for the ingress and egress phases of the Galileo solar occultations in 1994 (upper panel) and 1995 (lower panel) are shown in Fig. 1. Due to the HGA failure, the measurements were performed in one-way mode using the onboard USO. The horizontal dashed lines indicate the inherent stability of this USO, as defined by the square root of the Allan-variance at 1 s sampling time $\sigma_{USO}/f_0 \simeq 3 \times 10^{-11}$ [5]. This converts to frequency fluctuations of $\sigma_{USO} \simeq 0.07$ Hz at S-band. The flattening of the curves at larger solar offset distances is a result of the limited USO stability. Scientific analysis of coronal plasma fluctuations is thus restricted to fluctuation amplitudes above the dashed lines.

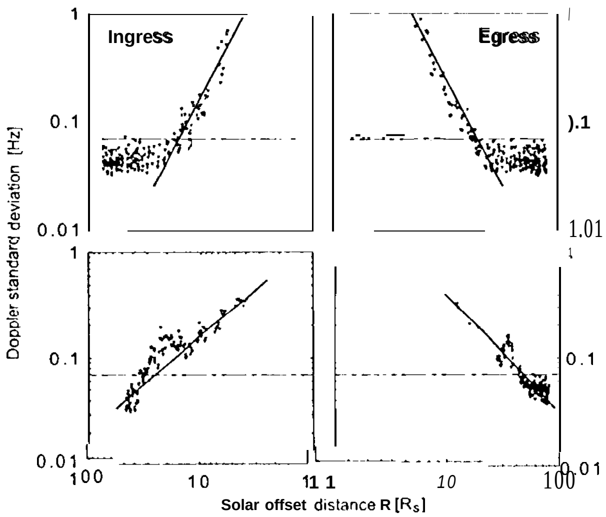

Figure 1. Doppler standard deviation versus solar offset distance for the occultations in 1994 (upper panel) and 1995 (lower panel)

As mentioned earlier, the Galileo/Earth line-of-sight moved essentially parallel to the solar equator during these solar occultations, sounding the solar corona at low heliographic latitudes. Neglecting any latitudinal dependence, the coronal electron density can thus be described as a function of solar distance by a single power law throughout region probed by the

Galileo line-of-sight [3]:

$$N(R) = N_B \cdot \left(\frac{R_S}{R}\right)^{\alpha} \quad \text{for } R > 4\ R_S \tag{1}$$

Ranging measurements, which could have provided information about the electron density distribution, were not performed during the Galileo SCE due to the restricted radio science capability. As a result, only information about electron density fluctuations levels could be derived from the available Doppler measurements.

In analogy with the approach to an electron density model, a log-log linear least-squares fit was computed for the Doppler standard deviations and plotted in each panel of Fig. 1. A purely radial model was employed for the electron density fluctuation level:

$$\sigma_N(R) = \sigma_{NB}\left(\frac{R_S}{R}\right)^{\beta} \tag{2}$$

Using this formula for the coronal electron density fluctuations, the radial dependence of the mean Doppler fluctuation can be approximated by a single power law in R:

$$\sigma_f(R) = \frac{A}{c \cdot f_0} \cdot \sqrt{\pi} \cdot (\beta - 1) \cdot K(\beta) \cdot u \cdot \sigma_{NB} \cdot \left(\frac{R_S}{R}\right)^{\beta} \tag{3}$$

where c is the speed of light, f_0 is the signal frequency, $A = 40.3\ \mathrm{m}^3/\mathrm{s}^2$ is a constant, $u = dR/dt$ is the transverse speed of the line-of-sight in the plasma and

$$K(\beta) = \frac{\Gamma[(\beta-1)/2]}{\Gamma(\beta/2)} \tag{4}$$

with Γ representing the Gamma function. The Doppler fluctuation levels approximated by Eq. (3) for the ingress aud egress phases of the 1994 and 1995 solar occultations are shown in Fig. 2. It can be seen that the Doppler fluctuation level for the egress phases (line-of-sight is moving away from the Sun) are greater for R < 10 R_S than for the ingress phases (line-of-sight approaching the Sun). A steeper decrease with increasing solar offset distances is obtained for the data in 1994. The values of the least-scluarcs fit parameters σ_{NB} and β for the electron density fluctuation levels are given in Table 1. Parameters determined for the Galileo occultations during a period of low solar activity are compared to those derived for the Ulysses occultation in August 1991, a period of remarkably higher solar activity. As expected, the mean coronal density fluctuations at times of low solar activity are significantly lower thau the fluctuation levels at times of high solar activity.

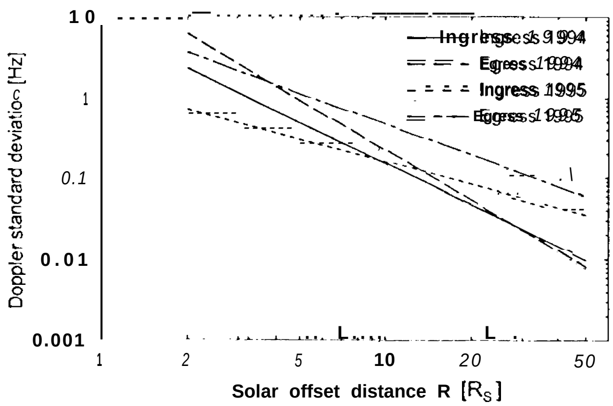

Figure 2. Mean Doppler fluctuation level versus solar offset distance

TABLE 1. Radial Fit Parameters for Three Solar Conjunctions

Conjunction		Ingress phase σ_{NB} [cm^3]	Ingress phase β	Egress phase σ_{NB} [cm^3]	Egress phase β
Ulysses	1991	$1.01\pm0.35\times10^6$	2.47 ± 0.11	$0.77\pm0.25\times10^6$	2.41 ± 0.10
Galileo	1994	$2.07\pm0.66\times10^4$	1.74 ± 0.11	$5.28\pm1.03\times10^4$	2.02 ± 0.07
Galileo	1995	$0.54\pm0.07\times10^4$	0.98 ± 0.06	$1.77\pm0.69\times10^4$	1.13 ± 0.09

An additional investigation was carried out to derive the spectral index of the three-dimensional wavenumber spectrum of the electron density fluctuations. Assuming a single power law for the three-dimensional electron density spectrum with spectral index p and applying the Rytov approximation, the power spectrum of the frequency fluctuations can be described as follows [9]:

$$\Phi_f(\omega) = 0.234 \cdot \pi^2 \cdot k^2 \cdot L_e \cdot c_\mu^2(R) \cdot v^{p-2} \cdot K(p) \cdot \omega^{3-p} \quad (5)$$

where k is the wavenumber, L_e is the effective thickness of the plasma layer causing the fluctuations, c_μ is a radially dependent structure constant and v is the solar wind speed. The power spectrum in Eq. (5) falls off with w according to the exponent (spectral index) $m_f = p - 3$. Temporal power spectra were computed from a data interval of 4096 frequency samples using a standard FFT algorithm. The spectral index m_f was obtained by applying a power law fit to the data in the frequency range from 5 to 50 mHz. The electron density fluctuation spectral index for the ingress and egress phases of the Galileo 1995 solar occultation is shown in Fig. 3 as a function of solar offset distance. The spectral index was determined for data from each tracking pass of sufficient length. The dashed line denotes the Kolmogorov value for isotropic turbulence ($m_f = p - 3 = 2/3$). The mean spectral index for the ingress phase is $\bar{p} = 3.60$ and for the egress phase $\bar{p} = 3.61$, respectively, which are close to the Kolmogorov value.

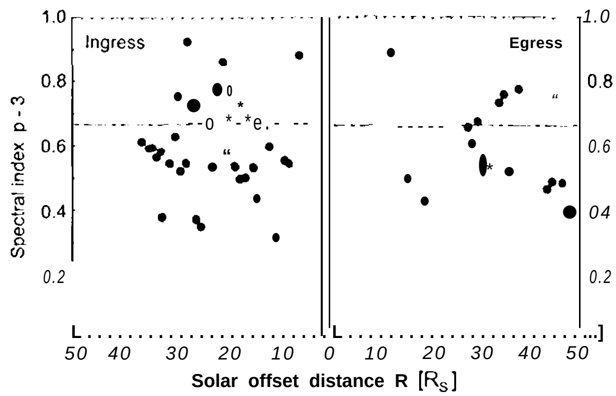

Figure 3. Spectral index p-3 versus solar offset distance

Plasma Propagation Velocities

The propagation velocity of plasma inhomogeneities in the solar corona was determined by computing the cross correlation of Doppler measurements recorded simultaneously at widely-spaced ground stations. Plasma inhomogeneities moving outward from the Sun will intersect the two ray paths, spatially separated in the corona by a distance d, at different times. By computing the cross correlation of simultaneously recorded Doppler measurements, the time lag τ_m needed to transit across both radio ray paths can be obtained from the maximum in the cross-correlation function. Using the time lag and the spatial separation of the ray paths, the apparent plasma propagation speed is then derived from [6]:

$$v_{pl} = \frac{d}{\tau_m} \tag{6}$$

Such cross-correlation methods can be used for evaluation of plasma propagation velocities whenever two radio links, either two downlinks to different ground stations or uplink/downlink to one ground station, are available simultaneously. Due to the reduced radio science capability (one-way mode, only S-band), no uplink/downlink cross correlations [7] could be performed during the Galileo solar conjunctions. In contrast to the uplink/downlink method, where only one ground station is required, the two-station cross-correlation analysis requires two ground-based receivers.

The calculated propagation velocities of the plasma inhomogeneities are shown in Fig. 4 as a function of solar offset distance. No propagation velocities could be obtained for egress 1995 because only one ground station (DSS 14, Goldstone) was available for recording the Doppler data.

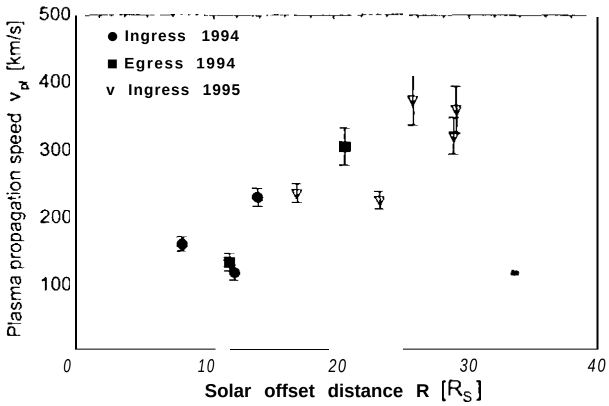

Figure 4. Plasma propagation velocities versus solar offset distance

Significant correlation maxima (correlation coefficients greater than 0.1) were obtained over the range of solar offset distances from about 8 to 20 R_S for the 1994 conjunction and from about 15 to 30 Rs for the 1995 conjunction. The inferred propagation velocities increase with increasing solar offset distances from about 120 km/s (8 R_S) up to 350 km/s (30 R_S).

Conclusion

In view of the generally good quality of these preliminary scientific results, the Galileo Solar Corona Experiment during the 1994/95 solar occultations can be proclaimed a success in spite of the loss of the Galileo HGA. S-band Doppler measurements were used to determine the level and spectral index of coronal electron density fluctuations. Corresponding to the lower solar activity in December 1994 and December 1995, significantly lower fluctuation levels were obtained during the Galileo occultations than during the Ulysses occultation in August 1991. A cross-correlation analysis of two-station measurements was performed to determine the propagation velocity of plasma disturbances in the coronal plasma. Significant correlation maxima were found at heliocentric distances from about 8 to 30 R_S. The propagation speed of inhomogenieties in the solar corona shows au increase over this heliocentric range from about 120 km/s up to 350 km/s.

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