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The coronal-sounding experiment

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Abstract. — The main science objective of the Ulysses Solar Corona Experiment is to derive the plasma parameters of the solar atmosphere using established coronal-sounding techniques. Applying appropriate model assumptions, the 3-D electron density distribution will be determined from dual-frequency ranging and Doppler measurements recorded at the NASA Deep Space Network during the solar conjunctions. Multi-station observations will be used to derive the plasma bulk velocity at solar distances where the solar wind is expected to undergo its greatest acceleration. As a secondary objective profiting from the favorable geometry during Jupiter encounter, radio-sounding measurements will yield a unique cross-scan of the electron density in the Io Plasma Torus.

Key words: interplanetary medium, solar corona.

1. Introduction.

The Ulysses (ULS) spacecraft assumes a position favorable for radio-sounding experiments at a number of times during its mission. Such investigations exploit the spacecraft's radio communications links with earth to extract information on the structure of otherwise virtually inaccessible media throughout the heliosphere. As appropriate for the emphasis on heliospheric studies conceived for the ULS mission, the Solar Corona Experiment (SCE) will perform coronal-sounding measurements during solar conjunctions. The scientific objectives for coronal sounding remain basically unchanged from an earlier description of the investigation based on the 1986 launch (Volland *et al.*, 1983). Contemporary coronal-sounding measurements have also been scheduled for the Galileo (GLL) spacecraft during its extended interplanetary cruise phase (Howard *et al.*, 1991). The Gravitational Wave Experiment (GWE), another ULS radio-science investigation described in this same volume (Bertotti *et al.*, 1992), will concentrate its search for general relativistic perturbations on coherent Doppler measurements during the ULS oppositions.

SCE will use dual-frequency Doppler and ranging data recorded at the NASA Deep Space Network (DSN) to determine the density, velocity and turbulence spectrum of the Sun's atmosphere, hopefully to distances well below 10 $R_\odot$. In contrast to previous ***in situ*** exploration of interplanetary space (minimum solar distance: 0.29 AU), radio-sounding observations are thus sensitive to plasma parameters in the main acceleration regime of the solar wind. An opportunity for electron content measurements of the Io Plasma Torus (IPT) occurs during the ULS flyby at Jupiter. A description of the scientific goals, a timetable for the radio-sounding experiments, and a brief description of the SCE "Instrument" are presented here together with an example of the quality of the data recorded during the ULS radio-science calibration period at the first opposition O_1.

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2. Scientific objectives and opportunities.

A timetable of the radio-sounding events during the ULS mission is presented in Table 1. The primary data recording phase will be the August 1991 solar conjunction C_1. The results of this first opportunity and the health of the spacecraft will provide the basis for the decision to repeat the experiment at the subsequent conjunctions. A somewhat different experimental approach must be applied for the IPT occultation at Jupiter encounter. Investigative plans for these two objectives are treated here separately.

2.1. Solar corona.

A solar disk view of the ULS solar conjunctions in solar ecliptic coordinates is shown in Figure 1. The dots repre-

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1992A&AS...92..425B

sent the virtual position of the ULS spacecraft at 0 hours UT on each day. The small circle is the size of the photosphere; the dashed circle has a radius of 10 $R_\odot$. The axes are marked in units of 2 $R_\odot$.

The best opportunity for coronal sounding is the pre-Jupiter conjunction C_1. The second conjunction C_2 will not be as useful, because the coronal signature becomes increasingly weaker at the much larger ray path impact parameters. The geometry is especially poor at C_3 (September 1993), which is not shown in either Figure 1 or Table 1. The final conjunction C_4 occurs just before the ULS spacecraft passes through the ecliptic plane in its journey from the south to the north solar poles. The ray path will move through all solar latitudes in the SW solar quadrant within about 20 days - an unprecedented geometry that will be especially sensitive to the latitudinal structure of the corona. Hopefully the ULS power budget will still permit dual-frequency transmission at that late stage of the mission.

The SCE ranging and Doppler data products will be used to derive the 3-D distribution of the coronal electron density, one of the main scientific goals of this investigation. The large-scale structure can be inferred from the total electron content I obtained from dual-frequency ranging. The dual-frequency Doppler observations cannot provide an absolute value for I, but are about 100 times more sensitive to relative changes δI (see e.g. Bird & Edenhofer, 1990). Previous spacecraft providing radio signals used to derive the large-scale coronal electron density distribution at various phases of the solar cycle were Mariner (Muhleman *et al.*, 1977), Helios (Esposito *et al.*, 1980), Viking (Tyler *et al.*, 1977; Muhleman & Anderson, 1981), and Voyager (Anderson *et al.*, 1987).

In addition to the quasi-static structure of the outer corona, the dual-frequency Doppler data will be used to characterize the level and spectral index of coronal turbulence. Recent studies have shown that turbulence dissipation moves from smaller to larger scales as the solar distance increases, eventually relaxing to an isotropic spectrum with index -11/3 (Kolmogorov) in interplanetary space (Woo & Armstrong, 1979; Armand *et al.*, 1987). The radial and latitudinal dependence of this transition is not well known, but it is most certainly associated with the same coronal conditions that govern the flow speed and mass flux of the asymptotic solar wind. The SCE sensitivity to plasma and the high temporal resolution of the DSN "open-loop" receivers (see Section 3.2) are adequate to provide valuable additional data for this analysis.

Another plasma parameter obtained from radio sounding is the velocity. The most reliable measurements of this type are obtained from cross correlation of radio scintillations using multiple signal ray paths. Most previous efforts have used intensity scintillations (e.g. Armstrong & Woo, 1981), but there are reasons to expand the analysis to phase (or frequency) scintillations, because these are not subject to scale-size limitations from the Fresnel filtering effect (e.g. see Bird & Edenhofer, 1990). Intercontinental DSN two-station overlap tracking has been explicitly required for SCE. Special efforts will also be made in the European view periods to engage additional smaller ground stations for ULS Doppler tracking in a "listen-only" capacity.

Finally, it is anticipated that the interplanetary vestiges of a Coronal Mass Ejection (CME) will be occasionally detected as a significant perturbation in the ranging and Doppler data. Examples of these were described by Edenhofer *et al.* (1977) and by Woo & Armstrong (1981). The plasma structure and speed of these dynamic phenomena can be inferred from radio sounding observations as they traverse the signal ray path.

2.2. Io PLASMA TORUS.

Most of our knowledge of the IPT was obtained during the Jupiter encounter of Voyager 1, which actually passed through the torus while approaching to within 0.3 R_J of Io on 5 March 1979. Dual-frequency Doppler measurements recorded on this occasion represent the only successful radio-sounding detection of the IPT to date (Levy *et al.*, 1981; Campbell & Synnott, 1985). The Pioneers 10 and 11 were occulted by the IPT, but both lacked the dual-frequency capability necessary to achieve the required sensitivity. Voyager 2 encountered Jupiter when the SEP angle was only 25°, a geometry quite unfavorable for discriminating between the IPT and random interplanetary fluctuations in electron content.

The Voyager 1 electron content profile of the IPT, which reached peak values of some 50-100 Hexems (1 Hexem $= 1 \times 10^{16}$ el m^{-2}), was compared with models based on the *in situ* observations. The IPT could be inferred to have peak electron densities of 3-6 $\times 10^9$ el m^{-2}, and a typical thickness of ca. 2 R_J. The striking differences in the IPT profiles at ingress and egress suggested that the IPT may exhibit considerable azimuthal asymmetry.

The ULS flyby at Jupiter on 8 February 1992 thus represents the second opportunity to measure the electron content of the IPT. An isometric view of the occultation geometry in a coordinate system fixed to the IPT is shown in Figure 2. Since the IPT (located near Jupiter's "centrifugal equator") actually wobbles $\simeq \pm 7°$ at the Jovian rotation period of 10 hours (see e.g. Bagenal & Sullivan, 1981), the sheet formed by the locus of ray paths in Figure 2 is noticeably warped. The IPT occultation is expected to begin about 3 hours after JCA (Jupiter Closest Approach targetted at 12:04 UT) and will last for about 3-4 hours. Jupiter is fortuitously close to opposition, so that interplanetary and ionospheric electron content contamination of the IPT profile is expected to be minimal. The ULS/Earth ray path cuts cleanly through the torus first on the sunward lobe in front of Jupiter and then

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1992A&AS...92..425B

the nightside lobe closer to the ULS spacecraft. The next such opportunity for IPT occultation studies will not occur until after the GLL spacecraft begins its orbital tour of Jupiter in December 1995.

3. The SCE instrument.

3.1. ULS spacecraft radio telecommunications subsystem.

The SCE instrumentation consists of the same equipment on the spacecraft and in the ground stations that is used for radio communications; i.e. command, telemetry, and navigation. During SCE data recording intervals the telecommunications subsystem is configured to receive an S-band signal from the ground station and transmit S- and X-band signals coherent with the received signal. The coherence ratio (transponder multiplier from S-band up to S-band down) is 240/221. The ratio of the two downlink frequencies, X-band to S-band, is 11/3. The parameters of the ULS telecommunications subsystem of significance for SCE are given in Table 2.

The signals are transmitted to the ground station via a dual-feed high gain antenna (HGA) with a diameter of 1.653 meters. This parabolic antenna is aligned with the spin axis of the spacecraft. Continual earth-point during cruise is maintained by regular attitude maneuvers. The attitude control system uses two references, one from a sun sensor and the other from CONSCAN processing of the uplink radio signal. The CONSCAN capability is achieved by deliberately offsetting the S-band boresight from the nominal spin axis by 1.8°.

Each of the two redundant transponders on board the ULS spacecraft contains an S-Band receiver, a modulator, an S-band power amplifier and an X-band exciter. In order to achieve coherency with the received S-band uplink, the ULS telecommunications subsystem is designed to allow either S-band receiver, selected by command, to drive the downlinks from either or both transponders. When it drives both downlinks, the S-band and X-band downlinks must be generated from different transponders. The output of either X-band exciter is routed to either of two redundant traveling wave tube amplifiers that boost the RF output to 20 W. The S-band power amplifier produces a 5 W signal. All ULS radio links are designed to be right-hand circularly polarized (RCP). Due to the asymmetrical design of the S-band feed for CONSCAN, however, the S-band downlink is actually elliptically polarized with an axial ratio of ca. 2. Since the two downlink frequencies are generated through different transponders, the phase delay through the separate sets of electronics is expected to be slightly different. The delay difference should be invariable over the course of the mission, however, so that differential phase measurements will remain uneffected.

3.2. The DSN radio science system.

Routine cruise tracking of the ULS spacecraft is performed with the standard 34-m subnet of NASA's DSN. During the critical mission phases such as conjunctions, oppositions and Jupiter flyby, however, most of tracking is assumed by the three largest (70-m) stations. Being an integral part of the SCE radio science instrument, the network's performance and proper calibration directly determine the accuracy of the experimental data. With the exception of the 34-m station (DSS 12) in Goldstone, California, all DSN antennas are equipped with both "closed-loop" and "open-loop" receivers. These receivers are supplied with frequency and timing reference signals from a highly stable hydrogen maser frequency standard.

As part of each station's receiver-exciter subsystem, the closed-loop receiver acquires and tracks the spacecraft carrier signal using a phase-locked loop feedback scheme. The tracking subsystem estimates and reports the Doppler shift after comparing the phase-locked loop frequency output with a reference from the station's frequency standard, which is also used to generate the uplink signal. In addition to the Doppler measurements, the spacecraft's range can be determined using the sequential ranging assembly. Modulated with range code, the S-band uplink signal is transmitted to the spacecraft where it is detected and transponded back to the station. The round-trip light time, directly related to the spacecraft's distance, is computed in the ground station by comparing the received code with the transmitted code.

Used primarily for Radio Science experiments and VLBI, the open-loop receiver, tuned by frequency predictions, downconverts the filtered carrier signal to baseband where it is digitized and recorded on magnetic tapes. The receivers at the 70-m stations have four channels, thereby enabling simultaneous recording of both S- and X-band downlinks in both polarizations, LCP and RCP. Data can be recorded at rates as high as 50 kHz for special events such as comet encounters (e.g. Giotto), but are routinely recorded at 200 Hz for most of the SCE intervals. A higher rate is foreseen during the IPT occultation at Jupiter encounter. Displays of the received carrier signal spectrum and system noise temperature can be made available for real-time control of the receiver parameters.

4. Instrument calibration during first ULS opposition.

The first ULS opposition O_1 occurred only 85 days after launch and provided an excellent opportunity for SCE to conduct an end-to-end radio science test before scientific data is recorded during the first conjunction C_1 in August 1991. Some key radio-science activities exercised at O_1 included uplink planning, real-time monitoring and acquisition, validation, delivery and analysis of all radio

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1992A&AS...92..425B

science data types. Besides the radio-science investigators, these activities involved coordinated interactions between the Radio Science Support Team, the ULS Spacecraft Operations Team and DSN personnel at the ground stations.

The ULS radio science system for both SCE and GWE was calibrated during a series of tests between 3 December 1990 and 5 January 1991. These tests took advantage of the close range and favorable geometry at O_1. When the spacecraft is relatively close to the extension of the Sun-Earth line, group and phase delays due to solar plasma wind scintillations are at an absolute minimum, thereby offering ideal conditions for assessing the radio system's accuracy and stability. The following SCE test objectives were achieved during this period:

- Characterize the ULS flight transponder Doppler stability and differential ranging delay
- Calibrate the closed-loop receivers and tracking system, acquiring Doppler and ranging data from all participating DSN stations
- Calibrate the open-loop receivers and Signal Processing Assembly (together called the Radio Science System), acquiring data at each participating DSN station

Figure 3 shows an example of ULS dual-frequency Doppler data, recorded at DSS 12 on 4 December 1990 (DOY 338). During this pass the spacecraft was located 0.36 AU from earth at a solar elongation angle of $SEP = 145°$. The large-scale fluctuations, one of which reaches an amplitude of 0.5 Hexem, arise from clumps of interplanetary plasma passing in and out of the signal ray path. While the nighttime ionospheric electron content is only of the order of a few Hexems, the total interplanetary electron content during these measurements is estimated to be about 40 Hexems. The level of sensitivity for the ULS S/X-band radio-sounding experiments, reflected by the thickness of the trace in Figure 3, is most certainly less than 0.1 Hexem.

The calibrated precision for SCE measurements may thus be slightly less than that expected from the theoretical specifications of the ULS S/X-band radio-sounding instrument (Volland *et al.*, 1983), which was estimated at 0.02 Hexem. Although the noise level at the upcoming occultations will be much higher than at O_1, it is anticipated that fine scale plasma structures in the corona and in the IPT will still be clearly detected.

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1992A&AS...92..425B

TABLE 1. *Timetable of ULS radio-sounding opportunities.*

Event	Event[a] Date	*SEP*[b] [deg]	Mean Daily[c] Motion [$R_\odot$/d]	DSN Coverage Intervals[d] I = Ingress; E = Egress	Geocentric Range [AU]	Heliocentric Range [AU]
O_1	30 Dec 1990	174.6	—	24 Dec - 07 Jan 1991 (14 days)	0.59	1.57
				I_1 : 23 May - 21 Jul (60 days)		
				I_2 : 22 Jul - 05 Aug (15 days)		
				I_3 : 06 Aug - LOS ($\simeq$ 11 days)		
C_1	20 Aug 1991	1.15 N	2.65	—	4.98	3.96
				E_3 : ROS - 05 Sep ($\simeq$ 8 days)		
				E_2 : 06 Sep - 20 Sep (15 days)		
				E_1 : 21 Sep - 19 Nov (60 days)		
JCA	08 Feb 1992	157.1	—	±12 hours about JCA (8.503 Feb)	4.48	5.40
O_2	27 Feb 1992	179.4	—	13 Feb - 12 Mar (28 days)	4.41	5.40
C_2	02 Sep 1992	7.78 S	3.02	I_1/E_1 : 04 Jun - 01 Dec (180 days)	6.27	5.27
C_4	05 Mar 1995	6.21 S	2.48	to be defined	2.33	1.36

[a]Event timing based on actual Ulysses orbit (J.L. Pojman, Ulysses Reference Trajectory Characteristics, JPL Doc. 628-53, Rev. E, 29 Nov 1990)

[b](N/S) = North/South pole crossing

[c]$1° \simeq 3.74\ R_\odot$ at the Sun

[d]Daily average DSN coverage requirements for SCE:

I_1/E_1 = 2 hours (70-m or 34-m)
I_2/E_2 = 8 hours (70-m)
I_3/E_3 = 12 hours (70-m); 2 hours (2 × 70-m simultaneous)

TABLE 2. *Parameters of the ULS telecommunications subsystem.*

Radio link	S-band up	S-band down	X-band down
Frequency [MHz]	2112	2293	8408
Wavelength [cm]	14.2	13.1	3.6
RF transmit power [W]	—	5	20
Carrier transmit phase noise [deg]	—	5	14
Carrier receive threshold [dBm]	-146	—	—
1.6 m antenna gain [dBi]	24.9	24.1	40.3
3 dB beamwidth [deg]	5.5	5.1	1.4
Boresight offset [deg]	1.8	1.8	< 0.1
Polarization	RCP	RCP	RCP

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1992A&AS...92..425B

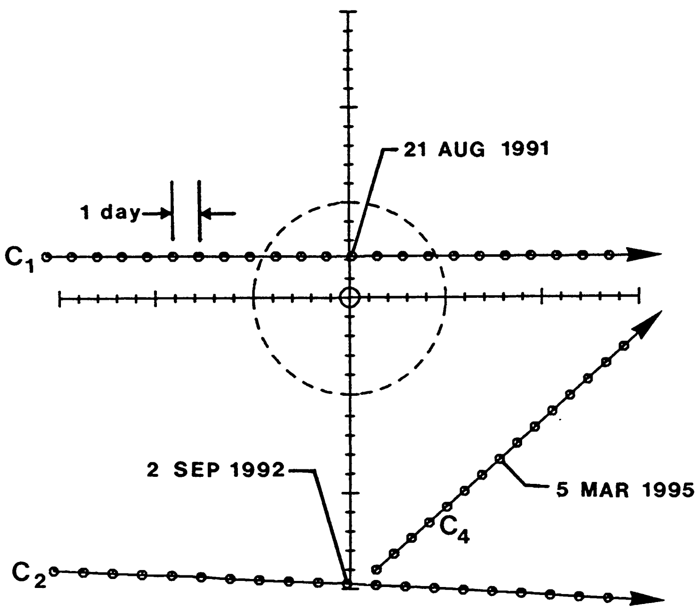

FIGURE 1. Solar disk view of the ULS solar conjunctions.

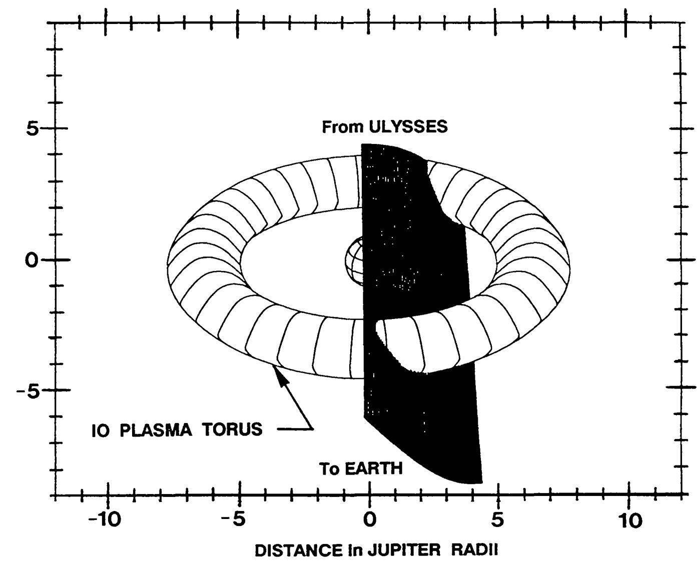

FIGURE 2. ULS signal ray path penetration through the IPT during Jupiter encounter (courtesy of R. Sunseri, JPL).

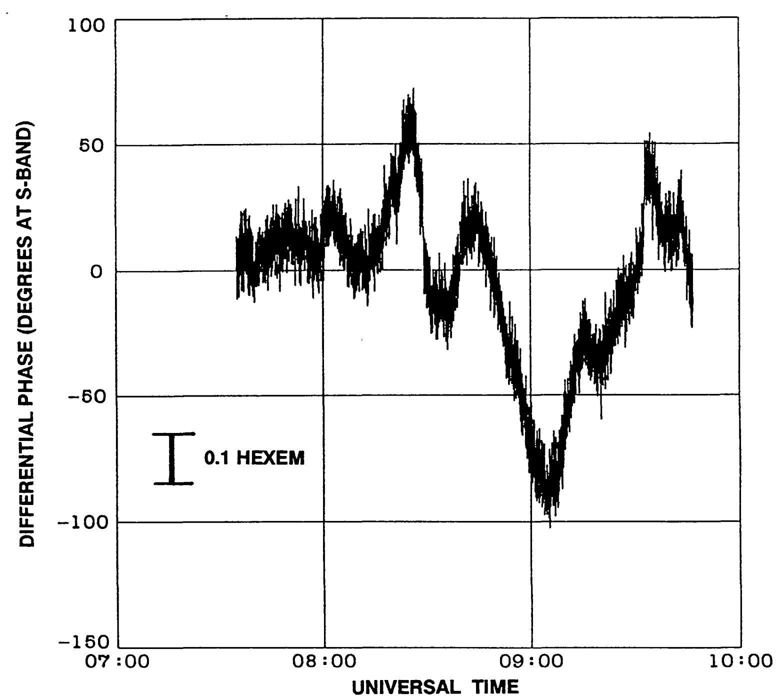

FIGURE 3. ULS differential Doppler measurements recorded during the radio-science calibration period near first opposition.

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