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The Ulysses Mission

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Abstract. -- The Ulysses mission is unique in the history of the exploration of our solar system by spacecraft. The path followed by Ulysses will enable us, for the first time, to explore the heliosphere within a few astronomical units of the Sun over the full range of heliographic latitudes, thereby providing the first characterisation of the uncharted third heliospheric dimension. Advanced scientific instrumentation carried on board the spacecraft is designed to measure the properties of the heliospheric magnetic field, the solar wind, the Sun/wind interface, solar radio bursts and plasma waves, solar energetic particles and galactic cosmic rays, solar X-rays, and interplanetary/interstellar neutral gas and dust. Ulysses will also be used to detect cosmic gamma-ray bursts and search for gravitational waves. The mission, a collaboration between ESA and NASA, was launched in October 1990 and employs a Jupiter gravity-assist to achieve the trajectory extending to high solar latitudes. Ulysses will spend a total of 234 days, equivalent to about 8 solar rotations, at latitudes in excess of 70°. The purpose of this paper is to describe the characteristics of the Ulysses mission in order to establish a framework within which to better understand the objectives and goals of the scientific investigations which are described in subsequent papers.

Key words: interplanetary medium -- solar system: general -- space vehicles -- Sun (the): general.

1. Introduction.

Despite the general acceptance that the heliosphere -- the vast region of space dominated by the radial outflow of the solar wind plasma from the Sun -- is intrinsically three-dimensional in nature, our current understanding of the physical processes occurring within this environment is essentially based on observations made by spacecraft located close to the plane of the ecliptic. In terms of heliographic latitude, these spacecraft are only able to sample a narrow belt extending 7.25° above and below the heliographic equator. To date, only two spacecraft have escaped the confines of the ecliptic, Pioneer 11 and Voyager 1, climbing to 16° and 30° latitude, respectively. Following the Neptune encounter in 1989, Voyager 2 is slowly heading south of the ecliptic in the outer heliosphere.

The global, three-dimensional structure of the heliosphere clearly does not possess a simple symmetry. Our belief that the inner heliosphere is not symmetric is based on, for example, eclipse pictures, sunspot belt location (butterfly diagram), coronal hole positioning, solar wind velocity differences measured by interplanetary scintillation and Lyman alpha scattering, charged particle gradients between Voyager 1 and the ecliptic, a warped current sheet varying with sun-spot cycle, the inability to explain cosmic ray modulation by measurements made in the ecliptic. The foregoing clearly underlines the need for extreme caution when extrapolating physical conditions encountered in the essentially two-dimensional world of the ecliptic to the fully three-dimensional heliosphere as a whole (Marsden 1986).

The importance of comprehensive, in-situ measurements of the heliosphere covering the full range of heliographic latitudes has long been recognised (eg. Simpson *et al.* 1959). The Ulysses mission (Page 1975; Wenzel 1980; Wenzel *et al.* 1983; Marsden *et al.* 1986; Simpson 1989; Wenzel *et al.* 1989; Smith *et al.* 1991), having as its primary objective the study of the inner heliosphere in three dimensions, will provide the first important step toward achieving this goal. The instruments on board Ulysses will make measurements of the heliospheric properties between the ecliptic and the polar regions of the Sun in three latitudinal scans.

The Ulysses spacecraft will be placed in a high-inclination, heliocentric orbit by means of a Jupiter gravity-assist manoeuvre. Following its launch by the Space Shuttle Discovery on 6 October 1990, the combined two-stage IUS/PAM-S upper stage solid rocket motors injected the spacecraft into an ecliptic transfer orbit en-route to Jupiter. In February 1992 the Jovian gravitational field will deflect the spacecraft into the desired high-inclination orbit, directing it south of the ecliptic plane. Shown in schematic form in Figure 1 this elliptical orbit, with aphelion at 5.4 AU and perihelion at 1.3 AU, will place the spacecraft over the southern solar pole at a distance of 2.3 AU below the ecliptic in mid-1994. The subsequent pole-to-pole segment of the trajectory will be traversed relatively quickly and the second (northern) polar passage will occur in mid-1995. In total, the spacecraft will spend 234 days at heliographic latitudes in excess of 70° and reach a maximum latitude in excess of 80°.

This exploratory mission, formerly known as the International Solar Polar Mission, is being carried out jointly by ESA and NASA. Within the cooperative programme, ESA provides the spacecraft and is responsible for its operation, while NASA provides the spacecraft power supply, the launch vehicles, the Mission Operations Centre at the Jet Propulsion Laboratory (JPL) and tracking via the Deep Space Network (DSN). The scientific instruments were developed by European and American scientists.

Originally conceived and approved as a two-spacecraft mission in 1977/78, the project suffered a number of setbacks during its development: the spacecraft NASA was to have provided was cancelled in 1981, owing to budgetary constraints; the launch, originally planned for February 1983, was first delayed by 3 years to May 1986 and later, following the Challenger accident, by another $4^1/_2$ years.

This paper, giving an overview of the mission, is organised as follows: after this introduction, Section 2 contains a summary of the scientific objectives of the Ulysses investigations which are presented in Section 3. A description of the trajectory design, including mission constraints, is given in Section 4. The Ulysses spacecraft is discussed in detail in Section 5, followed in Section 6 by an outline of mission operations. The Ulysses Common Data File is described in Section 7. Finally, Section 8 contains an overview of the Jupiter flyby.

2. Scientific objectives.

The Primary scientific aim of the Ulysses mission is to gain definitive knowledge, by means of in-situ observations, of conditions and processes occuring in the inner heliosphere in three dimensions. The investigations carried out on board the Ulysses spacecraft address problems encompassing the heliospheric magnetic field, the properties of the solar wind, the structure of the Sun/Wind interface and solar radio bursts and plasma waves, the origin, composition and propagation of solar energetic particles and galactic cosmic rays, solar X-ray emission, and the properties of interstellar neutral gas and dust in the heliosphere, all as a function of solar latitude.

Specific objectives of the Ulysses scientific investigations are:

- to assess the global three-dimensional properties of the interplanetary magnetic field and the solar wind
- to study the origin of the solar wind by measuring the composition of the solar-wind plasma at different heliographic latitudes
- to increase our knowledge of waves, shocks and other discontinuities in the solar wind by sampling plasma conditions that are expected to be different from those available near the ecliptic
- to study the acceleration of energetic particles in solar flares by observing the X-ray and particle emission from active solar regions
- to improve our understanding of galactic cosmic rays by sampling these particles over the solar poles, where low-energy cosmic rays may have easier access to the inner solar system than near the ecliptic plane
- to advance our knowledge of the neutral component of interstellar gas that enters the heliosphere by measuring its properties as a function of heliographic latitude
- to improve our understanding of interplanetary dust by measuring its properties as a function latitude.

Secondary objectives of the mission include interplanetary physics investigations during the in-ecliptic Earth/Jupiter phase and measurements in the Jovian magnetosphere during the Jupiter flyby phase. Signals arriving at Ulysses from distant sources in the galaxy will also be detected. Ulysses will search for gamma-ray burst sources and, in conjunction with observations from other spacecraft, contribute to their identification with known celestial objects. An additional objective is the search for low-frequency gravitational waves by using the spacecraft's radio communication link.

3. Scientific investigations.

The scientific payload carried by the Ulysses spacecraft (Wenzel *et al.* 1983) comprises nine instruments that will obtain the data needed to address the science objectives described above. The investigations and associated instrumentation are summarised in Table 1. The payload contains two magnetometers, two solar-wind plasma instruments, a unified radio/plasma wave instrument, three energetic charged particle instruments covering a wide range of energies and species, an interstellar neutral gas sensor, a solar X-ray/cosmic gamma-ray burst instrument and a cosmic dust sensor.

Ulysses also includes two radio-science investigations (see Tab. 2) which make use of spacecraft and ground communication systems at specific periods in the mission to study the solar corona and search for gravitational waves.

The payload instruments and radio-science investigations are described in detail in the other articles contained in this volume.

The Ulysses on-board investigations are complemented by two interdisciplinary investigations which will combine data from several instruments to address specific problems of heliospheric science (see Tab. 2).

4. The trajectory.

Ulysses will be the first spacecraft to venture into the unexplored regions above the solar poles. Since no combination of available launch vehicles exists to achieve a high-inclination solar orbit directly, a gravity-assist at Jupiter will be employed to change the orbital plane of the Ulysses space probe such that it will reach high solar latitudes.

The prime scientific requirement for the Ulysses trajectory design was to maximise the time the spacecraft will spend at high heliographic latitudes. As a convenient, but somewhat arbitrary, criterion the total observation time at latitudes greater than 70° was introduced. A minimum period of 150 days during the two polar passes was specified. Maximum solar latitude was a secondary consideration. Additional constraints on the mission design were:

-the perihelion distance shall not be less than 1.28 AU for thermal reasons

- the heliocentric radius at maximum latitude shall not be larger than 2.3 AU for scientific reasons
- the Sun-probe-Earth angle shall not exceed 60° (excluding the first 30 days of the mission) to comply with the instrument design
- the Jupiter closest approach shall be greater than 6.0 Jupiter radii to avoid radiation damage to instruments
- the Jupiter closest approach shall be at such longitude (time) to minimise radiation fluence.

The injection accuracy attained by the upper stage motors was extremely high. As a result only two small orbit adjustments were required to target the spacecraft to a position slightly north of Jupiter. These were executed 10 and 30 days after launch. One small further trajectory correction was performed on 8 July 1991. It was possible to use some of the fuel budgeted for the first trajectory correction manoeuvre (TCM-1) to slightly improve the mission performance. As a result, Ulysses will be able to spend a total of 234 days above 70° solar latitude and achieve a maximum heliographic latitude of 80.1°.

Table 3 lists the main trajectory characteristics and Table 4 provides a timeline of mission events.

After crossing over the north polar region of the Sun in 1995, the nominal Ulysses mission will have been completed. The spacecraft will, of course, remain in its elliptical, high-inclination orbit and it is hoped that scientific data will continue to be taken for some time. However, the gradually diminishing output from the power supply precludes indefinite continuation of the mission even if the various experiments and spacecraft subsystems remain in good working condition. The probable duration of an extended mission obtaining valuable results will not exceed a further five years.

5. Spacecraft description.

5.1. SYSTEM CONFIGURATION.

The Ulysses spacecraft (Wenzel 1983, Eaton 1990) is shown in its operational configuration in Figure 2. Dictated by the long distances from the Earth and the Sun at which the spacecraft operates, the configuration of the spinning spacecraft (5 rpm) is dominated by the large diameter (1.65 m), Earth-pointing High-Gain Antenna (HGA) providing the communication link and by the Radioisotope Thermoelectric Generator (RTG) supplying the spacecraft's electrical power. Experiment requirements for electromagnetic cleanliness (EMC) and for minimisation of the RTG radiation environment resulted in a 5.6 m long radial boom which carries several experiment sensors and is mounted on the opposite side of the spacecraft to the RTG. A 72.5 m tip-to-tip dipole wire boom and a 7.5 m axial boom serve as electrical antennas for the Unified Radio and Plasma Wave Experiment (Stone *et al.* 1992). Most of the scientific instruments are mounted on the main body, as far as possible removed from the RTG, and in compliance with the field-of-view requirements of the experiment sensors (see Fig. 3). The spacecraft mass at launch was 367 kg including 55 kg of payload and 33.5 kg of hydrazine for orbit, attitude and spin rate adjustments.

The HGA meets the radio-link requirement to Earth with 20 W *X*-band and 5 W *S*-band transmitters. The uplink *S*-band carries commands and ranging code. The downlinks in *X*- and *S*-band carry telemetry and turnaround ranging code, respectively. (*S*-band telemetry could only be used in the early orbit phase at close distance to Earth). This simultaneous ranging and telemetry is a basic feature of the spacecraft communication system.

Spacecraft mass properties and balance have been a driver in the spacecraft design to meet the requirements both for the launch configuration and for the deployed boom configuration with the HGA pointing towards Earth. The spin axis of the launch configuration was the geometric centre line. The theoretical spin axis in deployed configuration is aligned with the electrical axis of the HGA.

Near-continuous data throughout the mission is a prime scientific requirement. Since continuous coverage by ground stations is impossible for such a long-duration mission, data are stored on-board and replayed, interleaved with real-time data, during periods of coverage. The nominal tracking coverage is 8 h in every 24 h.

A variety of downlink bit rates up to 8192 bit/s is selectable, which can provide real-time data rates between 128 and 1024 bit/s and stored data rates between 128 and 512 bit/s. The prime data rates are 1024 bit/s for real-time data ("tracking mode") and 512 bit/s for stored data ("storage mode").

A strong scientific requirement was to have an electromagnetically and electrostatically clean spacecraft; EMC considerations have therefore driven the mechanical configuration design. The spacecraft is divided into a "quiet" and a "noisy" zone. The former comprises an electromagnetically shielded compartment of sensitive experiments, whereas the latter contains the less-susceptible but more emissive electrical spacecraft subsystems. The preamplifiers for the wire booms and the axial boom are mounted outside the overall spacecraft compartment, which acts as a Faraday cage against fields generated inside. A unipoint grounding concept has been implemented in which the main platform constitutes an electrical ground reference with only one area which serves as grounding starpoint for the electrical system. All units that produce significant magnetic fields are removed as far as possible from the magnetometers. Low-impedance ground bus bars are isolated from the platform and connected to it only at the starpoint. Strict control of the magnetic properties of all subsystems and experiments was exercised. For example, the RTG was magnetically compensated.

The electrostatic cleanliness requirement for low-energy particle measurements (Bame *et al.* 1992) has been achieved by making all external surfaces of the spacecraft electrically conducting. This measure will also prevent differential charging of parts of the spacecraft in the Jovian magnetosphere.

The Jupiter gravity assist necessitates the spacecraft's passage through the Jovian radiation belts. All subsystems and experiments have therefore been designed to survive this environment and radiation-hardened parts (design dose rate 60 krad) have been used throughout the spacecraft.

The spacecraft also provides autonomous system capabilities for failure-mode detection and for safe spacecraft reconfiguration. This is required during unexpected and/or predicted periods of nontracking and because of the long signal travel time between ground and spacecraft. The preprogrammable functions include search-mode initiation to reacquire the Earth if no command is received after a preselectable time of up to 30 d, switch-over to redundant units, and preprogrammed attitude manoeuvres at superior conjunctions.

5.2. STRUCTURE AND MECHANISMS.

The Ulysses spacecraft has a box-type structure with two overhanging "balconies" (see Fig. 3) and a single aluminium honeycomb equipment platform. All electronics units of the scientific instruments and spacecraft subsystems, most of the sensors and the propellant tank are mounted on this platform. The RTG is mounted on an outrigger structure to minimise its radiation effects and to isolate the main subsystems and the experiments from excess heat.

The two-section radial boom carries the two magnetometer sensors (Balogh *et al.* 1992), the solar X-ray/cosmic gamma-ray burst sensors (Hurley *et al.* 1992) and the magnetic search-coil sensor of the wave experiment (Stone *et al.* 1992). Because of the radiation pattern of the RTG, it was necessary to have the gamma-ray sensor lying as closely as possible along the RTG centre axis. The related boom configuration achieves this whilst maintaining the maximum length of the boom consistent with a two-hinge system and satisfying the requirement for the spacecraft to be balanced in both the stowed and deployed boom configurations. The boom section material is carbon-fibre-reinforced plastic (CFRP) tubing with a 50 mm diameter and 1 mm wall thickness.

The electrical antennae of the wave experiment (Stone *et al.* 1992) consist of a pair of radially extending wire booms in the spin plane and an axial boom deployed along the orbital spin axis. The wire booms consist of 5 mm wide and 0.04 mm thick Cu-Be ribbon stowed during launch on two identical drive units. The wires were deployed to a length of 72.5 m tip-to-tip by centrifugal forces acting on tip masses after the second trajectory correction manoeuvre (TCM-2). Each wire boom has a passive tubular root damper which reduces relative motions between the boom and the spacecraft by natural material damping with a time constant of 3.5 h. The axial boom element is formed by a pre-stressed, coilable elastic Cu-Be tube anchored in the axial-boom drive mechanism located on the rear face of the spacecraft. The boom element was deployed to a length of 7.5 m by a traction force through a set of rollers driven by a stepper motor one day after the wire booms.

Several experiment sensors had protective covers on ground and during launch; these were all successfully opened in the first month of operation.

5.3. THERMAL SUBSYSTEM.

Thermal control of the spacecraft, its subsystems and of most of the experiments is achieved by passive means in conjunction with a commandable internal/external power dump and heater system. This involves an optimised layout of subsystems which avoids hot spots on the spacecraft platform, an efficient thermal-blanket design in order to minimise the solar input, the compensation, by the power dump system, of heat fluxes which are caused by the varying solar input and a heater system for individual critical units. The most stringent requirements on the thermal subsystem are to guarantee a temperature above +5°C at all times for the hydrazine of the Attitude and Orbit Control Subsystem (AOCS) and a temperature below +35°C for all experiment solid-state detectors. All spacecraft walls are covered with thermal multilayer blankets, which are closely fitted around the experiment-sensor apertures. The blankets consist typically of 20 layers of aluminised mylar. The outermost layer is kapton, coated with a transparent conductive coating (Indium Tin Oxide) to provide an electrically conductive outer spacecraft surface. Heat rejection is performed by a thermal radiator, located on the rear of the spacecraft and covered by a 2 mil kapton foil. All units external to the spacecraft (e.g. several experiments) are thermally decoupled from the interior.

5.4. RTG AND POWER SUBSYSTEMS.

Electrical power is provided by the RTG at a level of about 280 W at the begining of the mission, decreasing to about 250 W at nominal mission end. The RTG, which generates 4500 W of thermal energy, has two major components: a heat source and a converter. The General-Purpose Heat Source (GPHS) consists of several elements containing the isotopic fuel 238 Pu, in the form of PuO_2. The radioactive decay energy is absorbed at the heat source-converter interface where heat is produced. The Si-Ge converter contains thermoelectric elements which convert the heat into electrical energy. Power is delivered to the experiments and subsystems at 28V ± 2%.

5.5. COMMUNICATION SUBSYSTEM.

The communication subsystem provides capabilities for telemetry with bit rates up to 8 kbit/s, ranging, telecommand and radio science. It operates in *X*-band (downlink) and *S*-band (up- and downlink). The subsystem includes two redundant transponders (each consisting of an *X*-band exciter, a modulator, an *S*-band receiver and an *S*-band power amplifier), two redundant 20 W *X*-band Travelling-Wave-Tube Amplifiers (TWTA), a TWTA Interface Unit and an *S*-band Radio-Frequency Distribution Unit. A considerable amount of cross -coupling capability exists within the subsystem (Bird *et al.* 1992, Eaton 1990).

The parabolic HGA, with both *X*-band (8.4 GHz) and *S*-band (2.3 GHz) capabilities, is the prime communications link. Telemetry is provided in *X*-band, with a 2° beamwidth (3 dB); downlink *S*-band is used for ranging, and radio-science investigations. *S*- or *X*-band ranging operations can be performed with or without telemetry transmission. Both transponders can be operated simultaneously, one in *X*-band and the other in *S*-band.

A special feature of the HGA is its ability to measure the offset of the spin axis from the direction of the ground station by the CONSCAN (conical scan) system. This is accomplished by a tilt of 1.8° between the *S*-

band antenna pattern and the spin axis which results in a spin modulation in the uplink signal strength as the satellite rotates. Processing within the Attitude and Orbit Control Subsystem (AOCS) gives the offset magnitude and direction which is either transmitted for ground analysis or employed in a closed loop control system to minimise the offset. Attitude adjustments are made by operating hydrazine thrusters (see Sect. 5.7).

5.6. COMMAND AND DATA-HANDLING SUBSYSTEM.

The command and data-handling subsystem provides capabilities for ground commanding, a variety of telemetry formats, on-board data storage, and, in combination with the AOCS, safe automatic manoeuvring.

The telecommand decoder checks commands for validity and distributes them to the experiments and subsystems. There are directly executed commands and memory-load commands. The latter are stored as block commands that are validated prior to execution of critical operations. A command-time-tagging capability over a range of 32 s to 24 d is also available.

The Central Terminal Unit (CTU) processes command messages received from the decoder, provides on-board timing information, and performs formatting and encoding of data to be sent to the ground. It also controls all on-board automatic functions. The CTU contains a provision to auto-check its own functioning and to switch over to the redundant CTU in the event that a failure is detected, assuring that important spacecraft information is maintained.

The CTU contains a master crystal oscillator from which all synchronisation and timing signals for subsystems and payload are derived. 32-bit timing information with a resolution of 2 s is included in every telemetry format, ensuring unambiguous identification of the telemetry data throughout the mission lifetime. A spin reference ("Sun pulse") and spin segment clock (16 384 pulses per spin period) are also supplied by the CTU, based on Sun-sensor data provided by the AOCS subsystem (see Sect. 5.7).

The Data Storage Units consist of two redundant tape recorders for storage of data during those periods when the spacecraft is not in communication with the ground (nontracking periods) for subsequent playback and transmission during the next tracking period. The 45 Mbit capacity of each tape recorder is sufficient to provide continuous storage at 512 bit/s for 22 h or 256 bit/s for 44 h. The telemetry formats and bit rates selectable on the Ulysses spacecraft are shown in Table 5.

Telemetry formats are built up of successive frames. There are three data formats:

- Scientific format consisting of 32 scientific frames
- Interleaved format consisting of a block of 32 frames, interleaving real-time and stored frames with a selectable ratio (1:1, 1:3, 1:7). Formats are played back in reverse time order, but the frames within each format and each individual frame are in forward order
- Engineering format consisting of two frames of spacecraft house-keeping data and containing no scientific data.

Telemetry channels are sampled in a time-ordered fashion and allocated to specific words (8 bit), which are arranged into frames of 128 words. In the scientific and interleaved formats one frame consists of 110 digital science words, nine analogue science words, two subcommutated experiment housekeeping words, four subcommutated spacecraft housekeeping words and three synchronisation and identification words. Analogue channels are sampled and converted into 8-bit words with an accuracy of 1% full scale. There are also datation channels which contain accurate time information on an event with a resolution of 0.488 ms (32 s range) or 3.9 ms (256 c range). Datation channels are used by the gamma ray-burst instrument (high resolution) and by the magnetometer and wave experiments (low resolution).

5.7. ATTITUDE AND ORBIT CONTROL SUBSYSTEM (AOCS).

The primary operational functions of the AOCS are to maintain the spacecraft spin axis Earth-pointing and control the spin rate. Additional operational functions are dictated by trajectory control requirements, nutation damping, and by the measurement of the attitude for scientific reasons.

The spacecraft Earth-pointing attitude is measured and controlled by the CONSCAN system (see Sect. 5.5) with spin-rate, spin-phase and solar-aspect-angle information determined from redundant Sun sensors. The Sun-sensor outputs are processed in the data-handling subsystem to provide the spin reference pulse and the spin segment clock. These signals and the Sun-sensor data are then used in the AOCS electronics to determine the spacecraft spin rate and solar aspect angle for the purpose of closed loop on-board control, failure detection and recovery. Hydrazine thrusters are actuated either by telecommand or automously. These are fed from a single tank, mounted at the launch centre of gravity, and arranged in two blocks of four thrusters each, providing complete redundancy.

Another AOCS operation is the periodic precession manoeuvring for correction of the apparent Earth drift with respect to the spin axis. These can be performed in closed loop on-board or in open loop via time-tagged command.

A special manoeuvre strategy is required for conjunctions, since the proper spacecraft attitude depends on the operation of the Sun sensors with a safe operational limit of the solar aspect angle greater than 1.25°.

The spacecraft carries three nutation dampers containing a fluid whose viscous motion dissipates energy. In the operational spin rate range the nominal damping time constant for nutation cone angles from 2.0° to 0.02° is less than one hour.

The AOCS also includes failure-mode-detection and protection functions which result in fail-safe operation and a reacquisition capability in both automatic and ground-initiated recovery sequence.

5.8. IN-FLIGHT PERFORMANCE.

Following launch and orbit injection of Ulysses on 6 October 1990, the initial flight phase consisted of checking out all spacecraft subsystems (including redundancy), deploying the radial, axial and wire booms and switching on all experiments. The latter were commanded on one-by-one and thoroughly checked over an extended period between 19 October and 16 November 1990. Early in January 1991 the spacecraft was formally declared to be commissioned.

Initial in-orbit results have demonstrated good EMC performance. The DC magnetic requirement for a remnant spacecraft system field of less than 0.1 nT at the position of the outboard vector helium magnetometer has been achieved. Ulysses has set new standards in magnetic cleanliness (Balogh *et al.* 1992). Although background levels in the most sensitive instrument, the wave experiment (URAP), are generally as low as during ground testing, some interference has been observed. When operated, the URAP sounder (Stone *et al.* 1992) affects the data from the DUST experiment (Grün *et al.* 1992). In addition, the *X*-band TWTA (see Sect. 5.5) is seen in the URAP data at 9.6 KHz. None of these interferences will, however, affect the Ulysses scientific results in any significant way.

The only potentially serious problem encountered to date occurred immediately following deployment of the 7.5 metre axial boom on 4 November 1990. About two hours after this event, a small nutation of the spacecraft was observed. This gradually grew until it reached a half-cone angle of 3° with a pronounced periodicity. At that distance from Earth, data transmission was still in *S*-band with its wide-angle beam. If significant nutation had occurred at larger geocentric distance, with the narrowbeam (2° beamwidth) *X*-band system operating, data transmission would have been seriously hampered.

Investigations to find the cause of the nutation and to find ways to reduce and control it showed that the principal, but not the only, cause was solar energy entering the axial boom as the spacecraft rotated at 5 rpm.

This induced a periodic bending of the boom which coupled into the entire spacecraft to cause nutation. As the spacecraft traveled further from the Sun and the solar aspect angle diminished (putting the boom into the shadow of the spacecraft), the effect was reduced and on 17 December 1990 the nutation disappeared completely. In the period when nutation was still active, it was experimentally established that use of the automatic earth seeking attitude control system (closed loop CONSCAN, see Sect. 5.5) was extremely efficacious in keeping nutation at very low levels. Consequently, if the nutation should reappear later in the mission (it is predicted to recur at a reduced level for two periods of a few months each in 1994 and 1995), procedures exist to control it. There is reasonable confidence that nutation, should it return, will not seriously impact the mission.

All experiments have been collecting scientific data since their respective switch on. Regular tape recorder operations have been conducted to provide continuous data coverage as far as possible. Except for a few periods of special spacecraft operations, or ground station problems, about 98% data coverage has been achieved during the first months of routine operations.

6. Mission operations.

Mission operations for Ulysses are conducted from the Mission Operations Centre located at the Jet Propulsion Laboratory (JPL) by a joint ESA/NASA mission operations team. JPL constitutes the focal point of the Deep Space Network (DSN) whose 34-m ground station subnet is used for communications with the Ulysses mission.

Telemetry data from the spacecraft are acquired by the DSN stations at Goldstone in California, Madrid in Spain, and Canberra in Australia. These data are then transmitted via the NASA communications network to the JPL Mission Control and Computing Center. Here the data flow is split, with one path leading to the Ulysses mission control system where data are processed in real-time for spacecraft control and experiment status checks. The other path is to the Data Records System, where the incoming data are processed in non-real time.

The Data Records System puts the Ulysses data in "time-of-generation" order before being sorted by experiment. These data are then written on magnetic tape as Experiment Data Records (EDRs), which is the primary method of transferring data to the Ulysses experiment teams on a regular basis. Data that relate to the trajectory and to the spacecraft attitude are included in a supplementary EDR that is also sent to the experiment teams. Portions of the real time data (not play-back data) are made available to the experiment teams in the form of quick-look EDRs during each tracking path via remote access to Data Records System. The Space Physics Analysis Network (SPAN) is used for this purpose. This method was very successfully used in the early mission phase and is expected to be a prime means to transfer data quickly during the Jupiter encounter phase.

7. Common Data File.

Experience on previous missions, particularly in the International Sun-Earth Explorer (ISEE), Atmospheric Explorer and Dynamics Explorer programmes, has shown that an interdisciplinary approach is essential if the complex interactions between plasmas, magnetic fields and charged particles are to be studied comprehensively. The Ulysses Science Working Team (SWT), which is composed of all Principal Investigators (PI) and chaired by the ESA and NASA Project Scientists, realised early on that interexperiment correlations are of crucial importance in the case of an exploratory mission like Ulysses. The SWT therefore agreed on the provision of a Ulysses Common Data File (CDF) containing key parameters derived from various instruments which provides an overview of the interplanetary conditions as encountered by the spacecraft.

The CDF is a computer-generated file, processed and reduced to physical parameters to yield a time-ordered record of science data. Its purpose is to provide all investigators with evidence of data trends, significant events, etc. and to permit individual investigators to identify interesting time periods for further detailed analysis and correlative studies. The set of CDF parameters is directly derived from the telemetry stream, without human intervention, based on algorithms of moderate complexity provided by the investigators. Each parameter is based on data of one specific instrument only. Since simple algorithms are used, the CDF parameters may not be absolutely accurate; in particular the accuracy may depend on interplanetary conditions or instrument operating modes.

Table 6 lists the parameters included in the CDF. These parameters characterise primarily the interplanetary magnetic field, the solar-wind plasma conditions and the energetic-particle environment encountered by the spacecraft. The CDF also contains information on the occurrence of wave activity and solar X-ray bursts identified in data stream. The CDF science data is complemented by some simplified spacecraft trajectory information.

The SWT has agreed on a general policy for the use of the CDF within the Ulysses community. The main purpose of this policy is to ensure the proprietary data rights of the PI and his team. It is also intended to prevent publication of data that have not been certified by the PI.

The key features of this policy are:

- the CDF is to be used for correlative studies only. The CDF is not to be taken as a source of data for detailed analysis
- studies that use the data from the CDF should, in general, be conducted in collaboration with the appropriate investigator team
- no CDF data are to be published without the permission of the appropriate PI.

There is little doubt that the Ulysses CDF will enhance the scientific return from the mission.

8. Jupiter flyby.

The Ulysses flyby of Jupiter in February 1992 will be the fifth spacecraft encounter with the giant planet. It will occur more than 18 years after the very first flyby by Pioneer 10, 13 years after the two Voyager flybys and 3 1/2 years prior to the arrival of Galileo, the first Jupiter orbiter.

Although the reason for the Ulysses flyby is the need to change the inclination of the spacecraft orbit, the Ulysses payload will perform important measurements during the almost two weeks that the spacecraft will spend in or near the planet's enormous magnetosphere. The instruments will be operated in the Jovian environment in a manner consistent with their design which is optimised for conditions in interplanetary space. Ulysses will be the first spacecraft to cross the dusk side of the Jovian magnetosphere, a region that also Galileo will not access. It will reach higher latitudes than the Pioneers and Voyagers did. It also has novel instrument capabilities. For example, it carries more sensitive and complete wave instrumentation than previous missions to permit a complete determination of the polarisation of the Jovian kilometric radio emission (see Stone *et al.* 1992). The SWICS instrument will provide detailed charge state and species information about the hot and suprathermal components of the plasma in the Jovian environment (Gloeckler *et al.* 1992). Further Jovian science objectives and instrument capabilities can be found in other articles of this volume.

Ulysses will enter the magnetosphere on the dayside near 0900 h local time and traverse the inner magnetosphere at northern magnetic latitudes between about 5° and 50°. The point of closest approach will be at 6.3 Jupiter radii (R_j) and at 31° N magnetic latitude (8 Feb. 1992; 1202 UT). A few hours after closest approach Ulysses will pass through the outer section of the Io plasma torus which will receive spacial attention with *in-situ* (Stone *et al.* 1992) and radio occulation (Bird *et al.* 1992) measurements. The trajectory will then take the spacecraft to southern latitudes around 30° in the dusk sector of the magnetosphere. Continuous ground coverage will be available for approx. 14 d around closest approach (i.e. approx. within

150 R_j from the planet), including one 70 m DSN pass per day.

Shortly after the flyby, Ulysses goes through its second opposition (27 Feb. 1992) which will be the prime period for the search for gravitational waves (Bertotti *et al.* 1992).

9. Concluding remarks.

After many years of waiting, the Ulysses mission is finally under way: the scientific payload is fully operational, data coverage to date is nearly continuous and the spacecraft trajectory has been optimised. In February 1992, following the 16-month in ecliptic measurement phase, Ulysses will begin the most important part of its exploratory voyage when the gravitational pull of Jupiter sends the spacecraft swinging out of the ecliptic on its trajectory towards the poles of the Sun.

The story is told in Dante's Inferno that Ulysses, the legendary Greek hero, King of Ithaca, becoming restless for further adventure, wanted to explore beyond the known world which then ended at Gibraltar. He exhorted his companions "To venture the uncharted distances...of the uninhabited world beyond the Sun...to follow after knowledge and excellence". "Ulysses" therefore seems to be an apt name for man's first adventure into the unexplored and uncharted regions over the Sun's poles.

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TABLE 1. *The Ulysses scientific payload*.

TABLE 2. *The Ulysses radio-science and interdisciplinary investigations*.

TABLE 3. *Ulysses mission characteristics*.

TABLE 4. *Ulysses mission timeline*.

TABLE 5. *Bit rates available in different Ulysses telemetry formats*.

TABLE 6. *Parameters in the Ulysses Common Data File*.

FIGURE 1. The Ulysses trajectory viewed from 15° above the ecliptic plane. Tick marks are shown at 100-day intervals.

FIGURE 2. The Ulysses spacecraft.

FIGURE 3. Layout of the scientific instruments on the Ulysses spacecraft, shown here in launch

configuration. The experiment acronyms are listed in Table 1.