Ulysses Attitude and Orbit Operations: 13+ Years of International Cooperation

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Abstract

[*]This paper describes some of the operations experience of the ESA flight dynamics and NASA/JPL navigation teams on the Ulysses mission. It provides an overview of the major mission milestones and key dates for Ulysses and brief introductions to the attitude and orbit control systems on-board the spacecraft and the on-ground flight dynamics and navigation systems. A section of the paper discusses some aspects of attitude manoeuvre operations while another discusses the orbit determination strategy employed on the mission. There is also a discussion of the solar heating induced spacecraft nutation and the techniques employed to control it. Finally some low cost operations practices are presented.

Mission Overview

The Ulysses mission is a collaborative effort of the European Space Agency (ESA) and the National Aeronautics and Space Administration (NASA) to make the first-ever measurements of the unexplored region of space above the Sun's poles. The mission is unique because it adds another dimension to our understanding of the Solar System - exploring the heliosphere within a few astronomical units of the Sun over a full range of heliographic latitudes.

The spacecraft has been in continuous operation since it was launched on 6th October 1990 using the space shuttle Discovery. This came after a 4 year hiatus due to the space shuttle Challenger accident in 1986. An extension of the current mission until March 2008 was recently approved. By then the spacecraft will have completed its third set of passes of the Sun's polar regions. Some mission milestones are presented in Table 1 and a graphical representation of the spacecraft orbit can be found in Figure 1.

Mission operations are carried out by a joint multinational ESA/NASA team out of NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, USA. The flight control team consists of ESA staff

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and contractors while JPL staff and contractors make up the ground operations, data management and navigation teams.

Date	Event	Date	Event
6 Oct 1990	Launch	31 Aug 2001	Start of 2nd north polar pass
8 Feb 1992	Jupiter closest approach (6.3 Rj)	13 Oct 2001	Maximum north solar latitude (+80.2°)
26 Jun 1994	Start of 1st south polar pass	10 Dec 2001	End of 2nd north polar pass
13 Sep 1994	Maximum south solar latitude (-80.2°)	4 Feb 2004	Jupiter Closest Approach (1684 Rj)
5 Nov 1994	End of 1st south polar pass	17 Nov 2006	Start of 3rd south polar pass
19 Jun 1995	Start of 1st north polar pass	7 Feb 2007	Maximum south solar latitude (-79.7°)
31 Jul 1995	Maximum north solar latitude (+80.2°)	3 Apr 2007	End of 3rd south polar pass
29 Sep 1995	End of 1st north polar pass	30 Nov 2007	Start of 3rd north polar pass
6 Sep 2000	Start of 2nd south polar pass	14 Jan 2008	Maximum north solar latitude (+79.8°)
27 Nov 2000	Maximum south solar latitude (-80.2°)	15 Mar 2008	End of 3rd north polar pass
16 Jan 2001	End of 2nd south polar pass	31 Mar 2008	End of mission operations

Table 1: Major Milestones of the Ulysses Mission

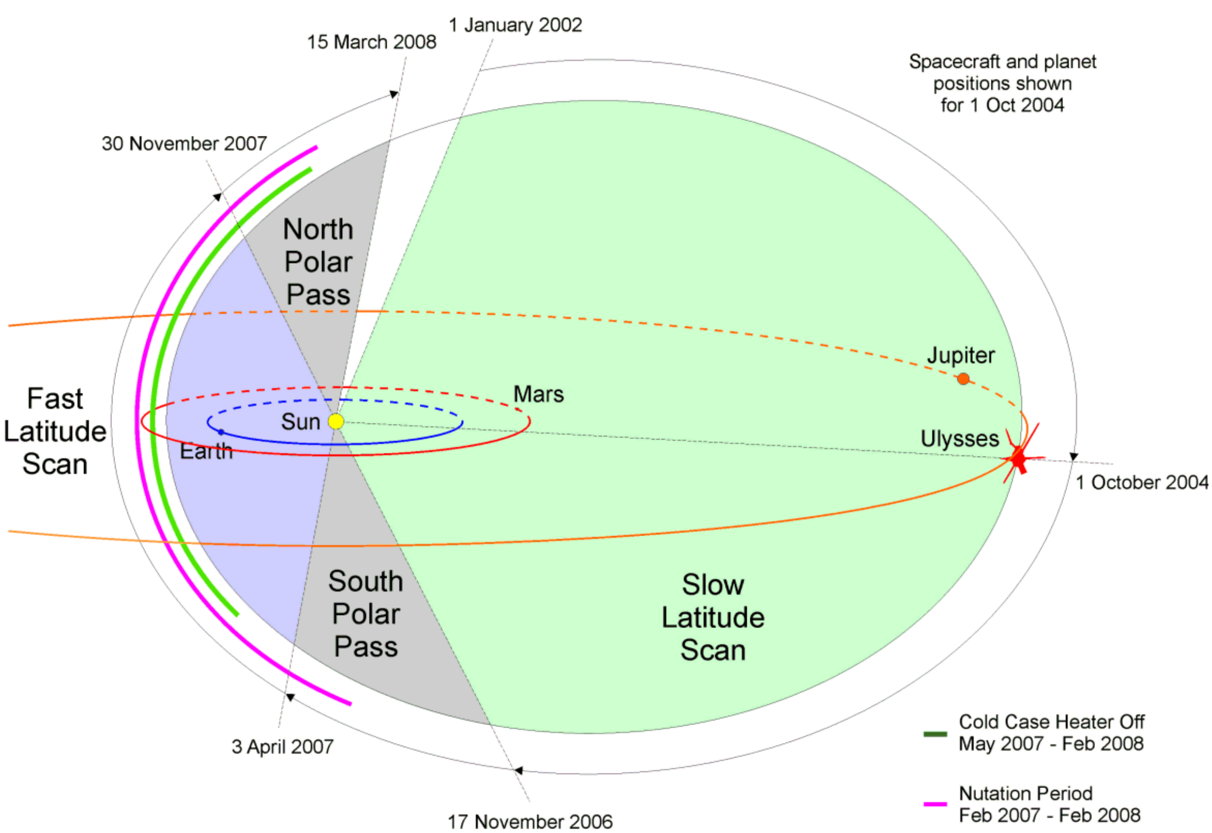

Figure 1: Ulysses Orbit 2002-2008

The ground stations used for routine support are provided by the NASA Deep Space Network (DSN) in Goldstone (USA), Canberra (Australia) and Madrid (Spain). Ground stations which have provided non-routine support in the past are ESA Kourou (French Guiana), ESA New Norcia (Australia), DLR Welheim (Germany) and University of Chile, Santiago (uplink only).

Attitude and Orbit Control Sub-System

The spacecraft is spin stabilised at a nominal rate of 5 rpm. The Z-axis of the spacecraft is defined to be along the spin axis. The attitude of the spacecraft is derived from measurements of the Sun and Earth directions. There four sets of sun sensors on-board the spacecraft. Two redundant cross-beam sun sensors with fields of view 90º apart and two meridian slit sun sensors with fields of view covering the +Z and –Z directions respectively. The Earth direction is determined by means of conical scanning (CONSCAN) of the S-band uplink signal from a ground station. This scanning is achieved by offsetting the S-band antenna feed on-board the spacecraft by 1.8º from the spin axis.

The reaction control subsystem (RCS) consists of a blow-down system using catalytic decomposition of monopropellant hydrazine fuel. There are 8 thrusters arranged in two blocks of four: lower and upper axial, spin up and down. The thrusters are rated to produce 2 N @ 22 bar thrust at start-of-life and 0.6 N @ 5 bar at end-of-life. The total fuel load was 33.5 kg at launch and at the beginning of March 2004 it was approximately 7.9 kg. By the end of the mission in March 2008, it is estimated that there will be 5 kg of fuel left. This figure provides more than sufficient margin for any inaccuracies in the fuel bookkeeping.

The fuel bookkeeping keeps track of the available fuel by estimating the fuel used during each manoeuvre based on the observed manoeuvre performance. This fuel consumption estimate is then subtracted from the running total of the available fuel to obtain a new value for available fuel. The initial fuel load is accurately known during tank filling prior to launch. By applying this technique rigorously for every manoeuvre since launch, this running total becomes a good reflection of the amount of fuel actually left in the tank at any one time. This technique has been and is being used with much success by the ESA Flight Dynamics Division on a wide variety of spacecraft which use hydrazine based reaction control systems.

A complete description of the AOCS can be found in ref. [1] and at the Ulysses mission operations web site (http://ulysses-ops.jpl.esa.int/ulsfct/spacecraft/AOCS.html).

Attitude Operations

The Flight Dynamics System

The Flight Dynamics System (FDS) supports all the routine and non-routine attitude operations and is integrated into the Ulysses Monitoring and Control System (UMCS) used by the flight control team. The UMCS in turn interfaces with JPL's Deep Space Mission Systems (DSMS) for telemetry reception and telecommand transmission.

An earlier generation of the FDS is described in detail in ref. [2]. The current generation of the FDS has been deployed since 1996 and uses X windows displays instead of text terminals. With the approval of the mission extension to 2008, a project is underway to migrate the UMCS platform, currently at its second generation, from OpenVMS/VAX to OpenVMS/Alpha to take advantage of higher performance hardware.

Routine Attitude Manoeuvres

Routine attitude manoeuvres consist of open-loop slews along the Earth path to maintain Earth pointing requirements. For these slews, an axial thruster is fired with a pulse width of 3.2º which corresponds to a duration of 107 ms at the nominal spin rate of 5 rpm. This thruster pulse width is the smallest available in the AOCS and was chosen to minimise the dynamic excitation on the spacecraft.

The LowerAxial1 thruster is used predominantly because it is well characterised. It has been used for 95% of routine attitude manoeuvres to date. A positive side-effect of using the same thruster continuously is that any deterioration in performance will be brought to light although there has been none to date. The negative side-effect of introducing a ΔV bias on the spacecraft orbit is taken into account during the orbit determination process. Such a bias has no significant effect on the orbit after the spacecraft achieved its current solar polar orbit.

The use of the UpperAxial2 thruster is to be avoided due to plume impingement on one of the instrument housing which leads to a significant spin down of the spacecraft.

The routine attitude manoeuvre schedule is driven primarily by the Earth drift rate (relative to the spacecraft) and the maximum allowable Earth off-pointing. The link margin determines the maximum allowable Earth off-pointing which varies from 0.3º to 1.2º depending on Earth range and downlink data rate. Spacecraft activities also drive the schedule because the on-board command buffer can only hold a maximum of 40 time-tag command blocks.

After each manoeuvre has been evaluated, a manoeuvre description file is produced which contains the predicted and observed values for the initial and final attitudes, the thruster firing parameters and the RCS data. This file is produced for non-routine manoeuvres as well. A copy is sent via e-mail to the navigation team automatically. Apart from historical reference, the manoeuvre description files enable audits to be made of the fuel bookkeeping process by re-simulating a sequence of manoeuvres and re-computing the amount of fuel used for these manoeuvres.

The observed attitude data for all manoeuvres are appended to an attitude history file which is then uploaded to the Ulysses mission operations web site (http://ulysses-ops.jpl.esa.int/). This attitude history file is primarily used by the navigation and the data management teams although members of the Ulysses science teams have been known to refer to it occasionally.

The spacecraft is powered by a radioisotope thermoelectric generator (RTG) in common with most deep space missions whose trajectories take them to Jupiter's orbit and beyond. Lately the need to share the ever decreasing power available from the RTG has become a constraint on the manoeuvre schedule, see ref. [3]. Prior to a manoeuvre, at least 6 W is required for catalyst bed pre-heating. The pre-heating time has been reduced to 85 minutes, at the time of writing, which is just long enough to reach a holding temperature of 150ºC. No uplink and no tape recorder operations are permitted during this period for the same reason.

Non-Routine Attitude Manoeuvres

Of the non-routine attitude manoeuvres, the CONJ manoeuvres are probably the most interesting apart from the Earth acquisition manoeuvres during the launch and early orbit phase (LEOP). The LEOP manoeuvres are beyond the scope of this paper.

The CONJ manoeuvres are open-loop slews executed by the on-board CONJ program based on a fixed set of thruster firing parameters, repetition count and execution interval which are uplinked from the ground. This manoeuvre strategy is employed around periods of solar conjunction when the radio path between the Earth and the spacecraft traverses the Sun's coronal region. Downlink is usually severely degraded because the radio frequency noise from the Sun is so overwhelming that telemetry arriving at the ground station is corrupted to the extent that the error correction coding is rendered useless. The telecommand has greater immunity due to its low bit rate, nominally 15.625 bps compared to the telemetry bit rates of 1024 to 8192 bps. Nevertheless, the effect on the uplink is not insignificant because the on-board CONSCAN measurements become noisier. This results in greater uncertainties in the attitude determination. Typically the CONJ parameters are set to produce a sequence of slews which take the spacecraft attitude around the Sun instead of directly following the Earth path past the Sun. A plot of the manoeuvres executed for Conjunction 6 from 28th August to 9th September 1998 is show in Figure 2. The viewpoint of this plot is from the spacecraft looking at the Earth and the Sun.

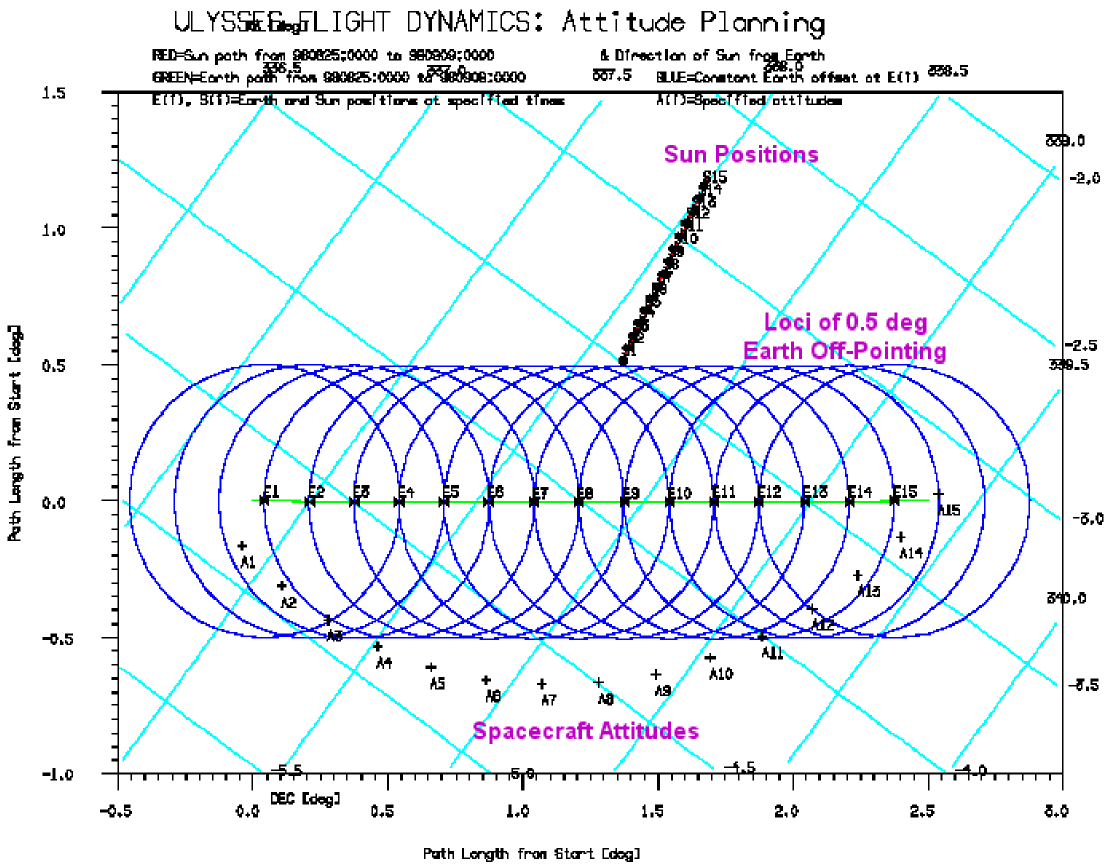

Figure 2: Ulysses Conjunction 6 Sun Avoidance Manoeuvres

Orbit Operations

Orbit Characteristics

The osculating elements and some other characteristics of the unique polar heliocentric orbit of Ulysses are given in Table 2 for an epoch of 1-Jan-2004. The reference frame for the data is the Earth-Mean-Equatorial system of 1950.

Semi-major axis:	506,540,923.365 km (3.39 AU)
Eccentricity:	0.596
Inclination:	100.976º
Argument of perihelion:	350.268º
Longitude of ascending node:	337.346º
True anomaly:	170.876º
Mean anomaly:	151.390º
Period:	6.23 years
Perihelion radius:	204,449,137.356 km (1.37 AU)
Aphelion radius:	808,632,709.373 km (5.41 AU)
Distance to Earth:	2414.982 light seconds (40.25 light minutes)

Table 2: Characteristics of Ulysses Orbit (heliocentric, EME.50, epoch 1-Jan-2004)

Launch and Trajectory Corrections

The spacecraft was transported by the space shuttle Discovery to low Earth orbit. From there, it was released from the shuttle and two solid rocket motor upper stages, the Inertial Upper Stage (IUS) and the Payload Assist Module (PAM-S), placed the spacecraft on its outbound trajectory to Jupiter.

On the way to Jupiter, a total of 3 trajectory correction manoeuvres (TCM) were carried out. These TCM's were implemented as vectored ΔV using the on-board thrusters. The thrusters were fired in the axial and radial directions separately such that the vector sum of axial and radial ΔV components equalled that of the ΔV required for the trajectory correction. Compared to the more traditional "turn and burn" ΔV, there is no loss of Earth pointing which allows for continuous high rate telemetry during a very critical manoeuvre. It helps to relieve the anxiety of the operations team because there is no waiting for the spacecraft to reacquire the Earth and re-establish communications in order to see the outcome of the manoeuvre. However these advantages are traded off against higher fuel consumption.

By aiming to arrive at a particular point in Jupiter's B-plane (plane through the centre of Jupiter and normal to the spacecraft velocity vector), the gravity of Jupiter was used to rotate the orbit of Ulysses from the in-ecliptic plane to one over the poles of the Sun. This crucial event took place on 8th February 1992 06:00:34 UTC at a Jovicentric distance of 408,894 km (6.3 Jupiter radii). The inclination of the spacecraft orbit relative to the ecliptic changed from 2.3º to 85.1º. The perihelion distance was increased from 1.0 to 1.37 AU, so Ulysses was never closer to the Sun than on launch day!

Tracking Data

Routine navigation operations involve receiving tracking data from the DSN using the 34 m and 70 m antennas. Uplink from the DSN to the spacecraft is on S-band while downlink is on X-band.

Tracking data for Ulysses consists primarily of two measurement types: Doppler and range. Typically one pass per day is scheduled for Doppler and 2 passes per week for range. The nominal spin rate of 5 rpm induces a Doppler bias in the tracking data which is subsequently corrected in the solution. In the future, the number of range passes per week is expected to be reduced to accommodate the more severe power constraints on-board the spacecraft.

Orbit Estimation Strategy

The orbit estimation strategy consists of modelling the orientation of the spacecraft, estimating several parameters based on *a priori* values, and stochastically estimating the range data measurement bias and miscellaneous non-gravitational accelerations.

Modelling of the spacecraft attitude is based on data from the attitude history file. This improves the accuracy of the navigation solutions by helping to model the acceleration effects of solar radiation pressure. The estimation strategy also estimates for the state, effects of attitude manoeuvres and the specular reflectivity coefficient. Estimation of the attitude manoeuvres only occurs in the radial direction (from spacecraft to Earth) and uses the *a priori* epoch and ΔV values given in the attitude history file.

Finally, the estimation strategy stochastically estimates the range measurement bias per pass produced by each DSN station and various non-gravitational accelerations. Future improvements in the estimation strategy could include estimating the attitude manoeuvres in the directions normal to the radial (even though the net effect should be small because all the manoeuvres are commanded to point in the radial direction).

Orbit Determination Strategy

The routine Ulysses orbit determination strategy uses a 90 day data arc with a 60 day overlap. Previous covariance analysis indicates that a 90 day data arc captures the small Ulysses orbit perturbations better than shorter data arcs. To ensure a more accurate orbit prediction, the post-fit orbit propagation assumes a continuous Earth pointing orientation and a continuous attitude change based on the Earth drift rate as seen from the spacecraft. The predicted solution spans one year and one month with a delivery every month. The predicted solution is used for mission planning, generating ground station view-periods, generating uplink predicts and analyzing science data. In addition to the monthly ephemeris delivery, the navigation analyst also produce a geocentric and topocentric one-way light-time file.

Navigation Software

Orbit estimation and navigation uses the Orbit Determination Program (ODP) and Double Precision Trajectory Program (DPTRAJ) software suite developed at JPL. A user interface layer called NavShell, which consists of PERL scripts, is implemented to provide a more convenient and standardised use of the ODP and DPTRAJ programs. Future plans for the improvement and streamlining of the navigation operations include adding a layer of scripts on top of NavShell to facilitate automation of the various navigation processes and tasks.

Solar Heating Induced Nutation

The Nutation Phenomenon

An undesirable nutation of the spacecraft was observed shortly after the deployment of an axial boom on 4th November 1990. This nutation reached a full cone amplitude of 2.3° within 6 hours. Over the course of the following 11 days it reached a maximum of 6°.

The axial boom consists of a collapsible copper-beryllium tube mast. It was rolled up when stowed during launch and when deployed extends along the –Z-axis of the spacecraft for 7.5m. Investigation of the anomaly concluded that at certain solar aspect angles and solar ranges, the axial boom would flex due to differential solar heating as the spacecraft spins. The effect of this boom flexing is made worse by free play at the boom root and the efficient transmission of the boom motion to the spacecraft body at the boom deployment motor. Furthermore the passive nutation dampers were not tuned for this kind of nutation behaviour, ref. [4] and [5].

If this nutation was left uncontrolled, it would have threatened both the quality of the science data and the health and safety of the spacecraft itself. The large antenna off-pointing from the Earth caused by the nutation would require the downlink data rate to be reduced which in turn would result in lower science data return. The flexing of the boom might result in it failing due to fatigue and this could cause some structural damage to the rest of the spacecraft body.

A nutation forcing factor (NFF) which is proportional to the fraction of the axial boom illuminated by the Sun and inversely proportional to the square of the heliocentric distance is used to predict the recurrence of the phenomenon in order to plan future operations. See Figure 3.

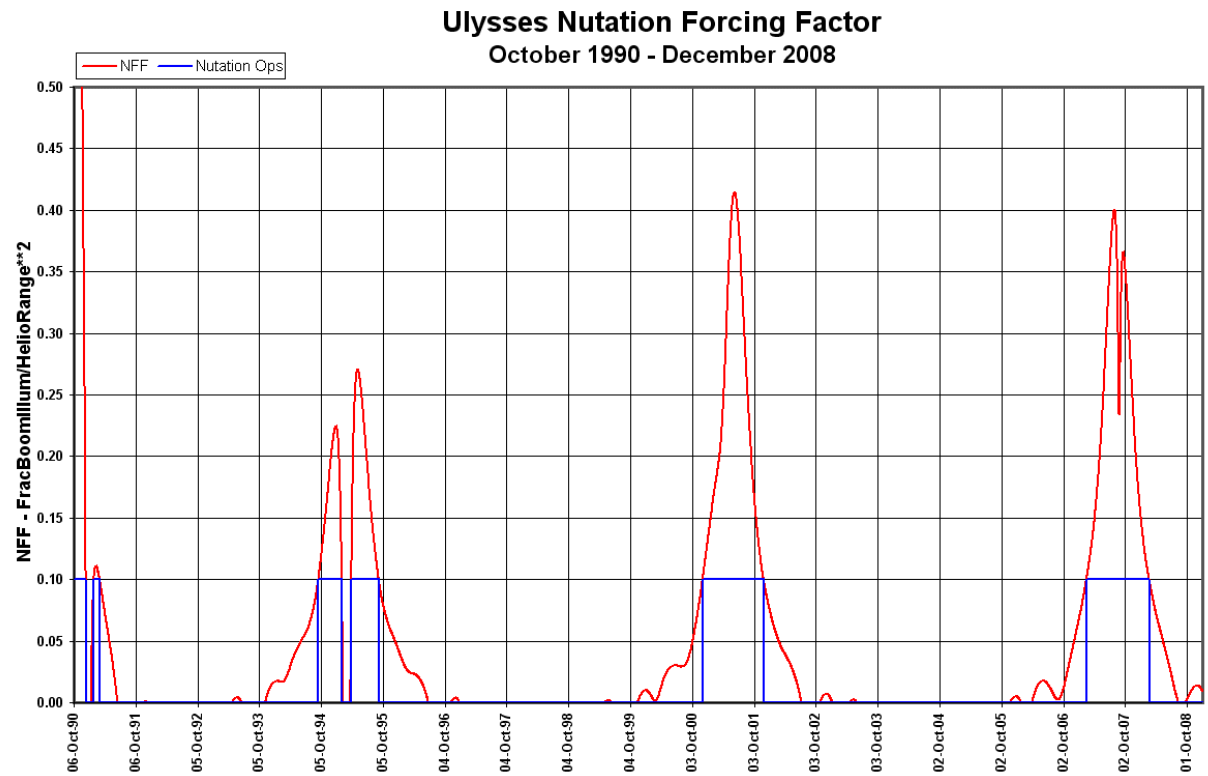

Figure 3: Ulysses Nutation Forcing Factor and the Nutation Seasons

Nutation Damping Operations

After some experimentation it was shown that the nutation could be damped to a low level using one of the AOCS autonomous control modes namely closed loop CONSCAN. This was employed during the first nutation season with much success and was shown to reduce the nutation amplitude to within the closed-loop CONSCAN deadband.

During the course of the second nutation season (August 1994 to August 1995), it was realised that if the spacecraft is slewed away from the Earth and then closed-loop CONSCAN activated, the number of closed-loop CONSCAN thruster firings would be increased compared to if it was activated at lower Earth off-pointing. The increase in these thruster firings would then result in a greater damping effect on the nutation. This proved to be true when it was implemented and this technique managed to damp the nutation to *below* the closed-loop CONSCAN dead-band.

During the third nutation season (November 2000 to December 2001), this technique was further refined whereby closed-loop CONSCAN was enabled *while* slewing away from the Earth to increase the Earth off-pointing. The effectiveness of this technique was discovered when closed-loop CONSCAN was accidentally enabled during a slew away from the Earth on one occasion and it was observed that the nutation dropped more rapidly and to a lower level than previously seen.

Nutation Monitoring

Prior to the start of the second nutation season, additional tools were developed to monitor the nutation and resulted in a suite of software called ARGOS, ref. [6]. Before ARGOS was implemented, the only nutation monitoring capability was provided by the on-board attitude measurements. These proved to be inadequate for real-time monitoring because of the low engineering data rate when the telemetry sub-system is configured for science mode. Science data gathering is particularly important during the nutation seasons because they occur during the periods of high heliographic latitudes and fast latitude scan, see Figure 1, which are of prime scientific interest.

Some modifications were made to the ground data network so that real-time Doppler and downlink signal strength data are sent from the ground stations to the Ulysses mission support area. During the second and third nutation seasons, these data were used by ARGOS to provide real-time, graphical representations of nutation, Earth aspect angle and Doppler residuals. The Ulysses ground operations controller monitored these displays around-the-clock to observe anomalies and trends and to determine if the active nutation damping was needed in consultation with the flight control team.

ARGOS was also capable of detecting individual thruster firings from their effects on the Doppler signature of the downlink signal. This proofed to be very useful because the AOCS does not keep count of thruster firings when operating in one of its autonomous control modes. The thruster firing information from ARGOS along with the temperature profiles of the catalyst bed were used to reduce the uncertainties in the calculations for fuel bookkeeping.

Low Cost Operations Practices

The Routine Phase Management System (RPMS) of the FDS provides a interface to the Ulysses FDS for routine attitude operations. Its implementation was a conscious effort to pursue low cost operations because it was intended to be used by non-flight dynamics specialists. The RPMS enables manual execution of the routine attitude operations procedures via a menu driven command shell interface to the FDS. These operations procedures include planning of the routine manoeuvres, telecommand generation, manoeuvre monitoring, attitude determination and manoeuvre performance evaluation. RPMS ensures compliance with specific procedural steps for the aforementioned operations without the need for written procedures. Input range checking and data type validation are implemented in all RPMS data entry forms to ensure that the FDS software operate on input data which are at least “sensible”. RPMS thus frees up the sole mission-dedicated flight dynamics engineer to perform “non-routine” tasks like maintenance and enhancement of the FDS, off-line analysis of AOCS performance, attitude sensor calibration etc.

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