IMPLEMENTATION AND VALIDATION OF A PC BASED ESATAN MODEL FOR THE ULYSSES SPACECRAFT

S. Bishop[1], F. Castro[2], C. Goulding[3], D. Presti[3], A. Woodcock[2]
Jet Propulsion Laboratory, 4800 Oak Grove Drive, MS 264-114, Pasadena, CA 91109, USA;
e-mail: colin.goulding@jpl.nasa.gov

ABSTRACT

*The current trend of extending scientific missions well beyond their prime mission poses many challenges in the design and operation of the thermal subsystem. As thermal limits are approached and anomalies cause the spacecraft to operate in modes not considered prior to launch, these extended missions become more reliant on analysis tools. Launched in 1990, the Ulysses spacecraft completed its prime mission of exploring the heliosphere at high latitudes in 1995. Due to the unique science returned by Ulysses, the spacecraft's life has been extended and operations are currently due to end in March 2008.

The main challenge in the extended phase of the Ulysses mission is the maintenance of the monopropellant hydrazine fuel lines above freezing. This has been performed through careful spacecraft configuration selection based on the monitoring of onboard thermistors for a number of sections of the pipework. In addition the Ulysses thermal model has been used extensively to predict the thermal response of the spacecraft to conditions outside its nominal design limits.

Written and implemented in the 1980s, the Ulysses Thermal Model is a 400-node SINDA model run on a VAX platform allowing one steady state solution to be run at any one time. This current work involved a migration of the model to PC ESATAN, the European Space Agency's thermal analysis code, and the development of an Excel-based user interface to enable ease of use among all members of the spacecraft team. Both input and output functions were implemented in Excel to enable quick turnaround times for thermal analysis and model verification.

This paper will outline the implementation and validation of a PC-based ESATAN thermal model of the Ulysses spacecraft. The shortcomings of the original nominal model and the alterations required for useful modeling during the extended mission will be discussed. Recommendations for the development of thermal models that cover the complete life cycle of a spacecraft will also be 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 as 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. Mission operations are

* The work described here was performed by LSE SPACE AG (1),VEGA Group PLC (2) and SciSys Ltd (3) under contracts to the European Space Agency.

being carried out by a joint multinational ESA/NASA team out of NASA's Jet Propulsion Laboratory (JPL) in Pasadena, California, USA. ESA provides the flight control team while the ground operations, data management and navigation teams are provided by NASA.

The spacecraft has been in continuous operation since it was launched on 6th October 1990 using the space shuttle Discovery. Following launch, an Inertial Upper Stage (IUS) and Payload Assist Module (PAM) propelled Ulysses towards Jupiter. Passing over the north pole of Jupiter (at a closest distance of 6.3 Jupiter Radii) the spacecraft was slung out of the ecliptic plane and entered its operational orbit in February 1992.

Ulysses' prime mission ended in 1995 following the observation of the Sun's poles at solar minimum. The mission was extended to cover a second set of polar passes in 2000 and 2001 to observe the poles during solar maximum. A further extension until March 2008 was approved which will enable the observation of the solar poles, once again at solar minimum, but with the Sun's magnetic field reversed. A graphical representation of the spacecraft's third solar orbit is presented in Figure 1. [Ref 1, Ref 2]

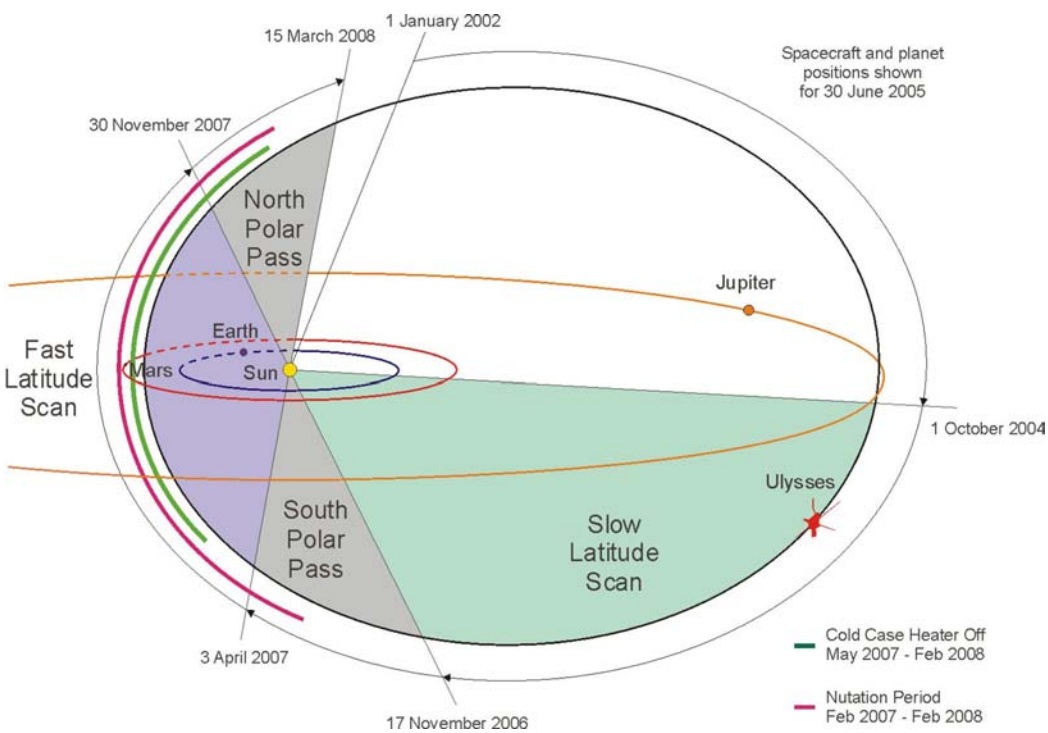


Figure 1: Ulysses Third Solar Orbit 2002-2008

ULYSSES THERMAL ENVIRONMENT OVERVIEW

The Ulysses thermal environment is primarily a product of the two parameters detailed in Figure 2, namely the solar incident radiation and electrical power available. Ulysses' unique orbit, while essentially stable, varies from 1.0 A.U. at launch to 5.4 A.U. at aphelion producing a solar flux

varying from 1400 to 45 W/m^2. This thermal cycle has a periodicity of 6 years as the spacecraft repeats its orbit. Coupled with this thermal cycle is the ever-decreasing power available to operate the spacecraft subsystems, instruments and heaters. This is due to the decay of the onboard radioisotope thermoelectric generator (RTG) power output, which has decreased from 285W of electrical power available at launch to 202W as of the end of June 2005. [Ref 3]

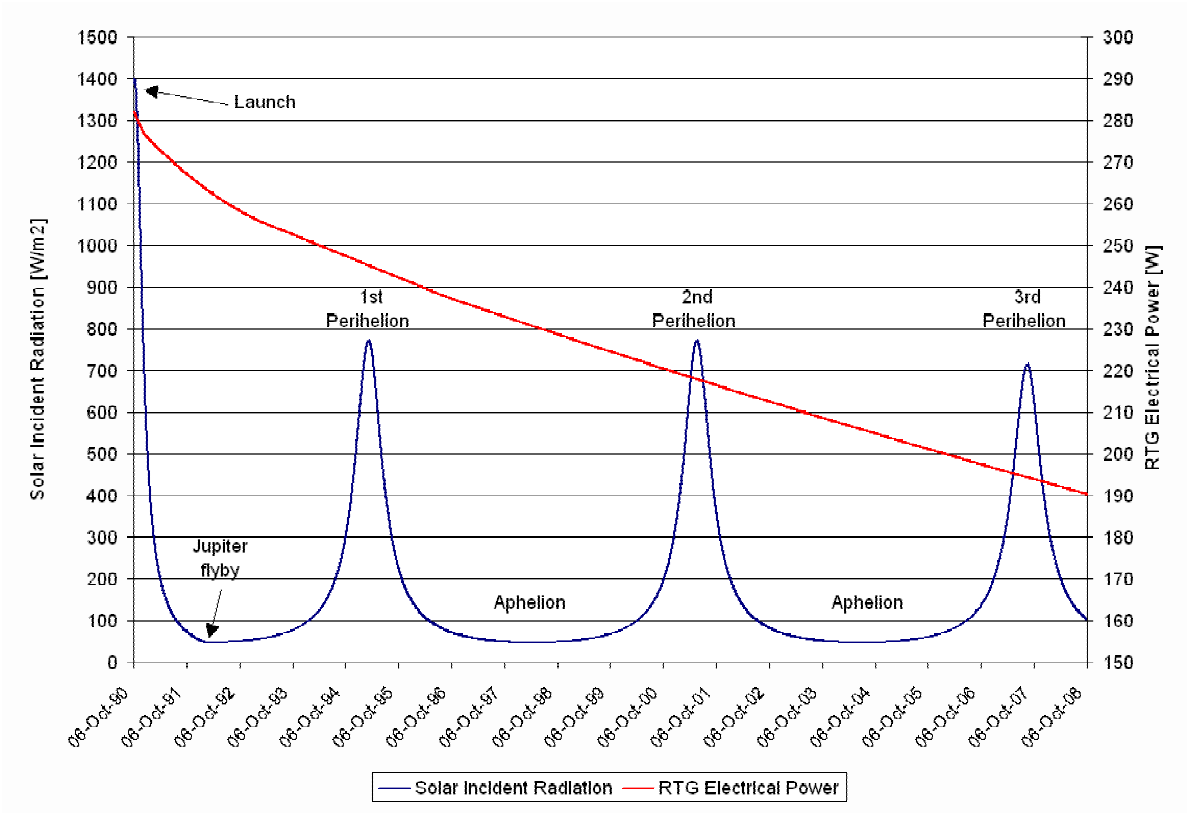


Figure 2: Ulysses Thermal Drivers

As the RTG electrical power output dropped below the prime mission requirement (237 W), a payload power-sharing plan was implemented to ensure that there is sufficient power to maintain the reaction control equipment (RCE) within its operating temperature range. The payload has been categorized into core (permanently on) and discretionary (cycled on and off) sections, with the definition of each being based on both scientific importance and spacecraft health. The payload power-sharing plan ensures that the overall power demands can be met, and that sufficient internal thermal dissipation occurs, albeit resulting in temperatures well below those experienced during the prime mission. The thermal trends as experienced inside the main body of the spacecraft are shown in Figure 3.

The thermal environments associated with each spacecraft configuration are fundamental in ensuring the well being of critical spacecraft components. The location of the instruments and their local dissipation therefore play a fundamental role in the definition of the payload power-sharing plan. All configurations used presently were identified through the use of thermal modeling using a lumped capacitance 400-node model developed prior to launch. The cumulative

downward thermal trend made the third orbit's aphelion (June 2004) significantly colder for the spacecraft than previous occurrences. As the cooling continues, and thermal limits are approached so the need for reliable analysis tools becomes more critical. In addition Ulysses is operating significantly beyond its design life and the occurrence of spacecraft anomalies further complicates any power and thermal analysis.

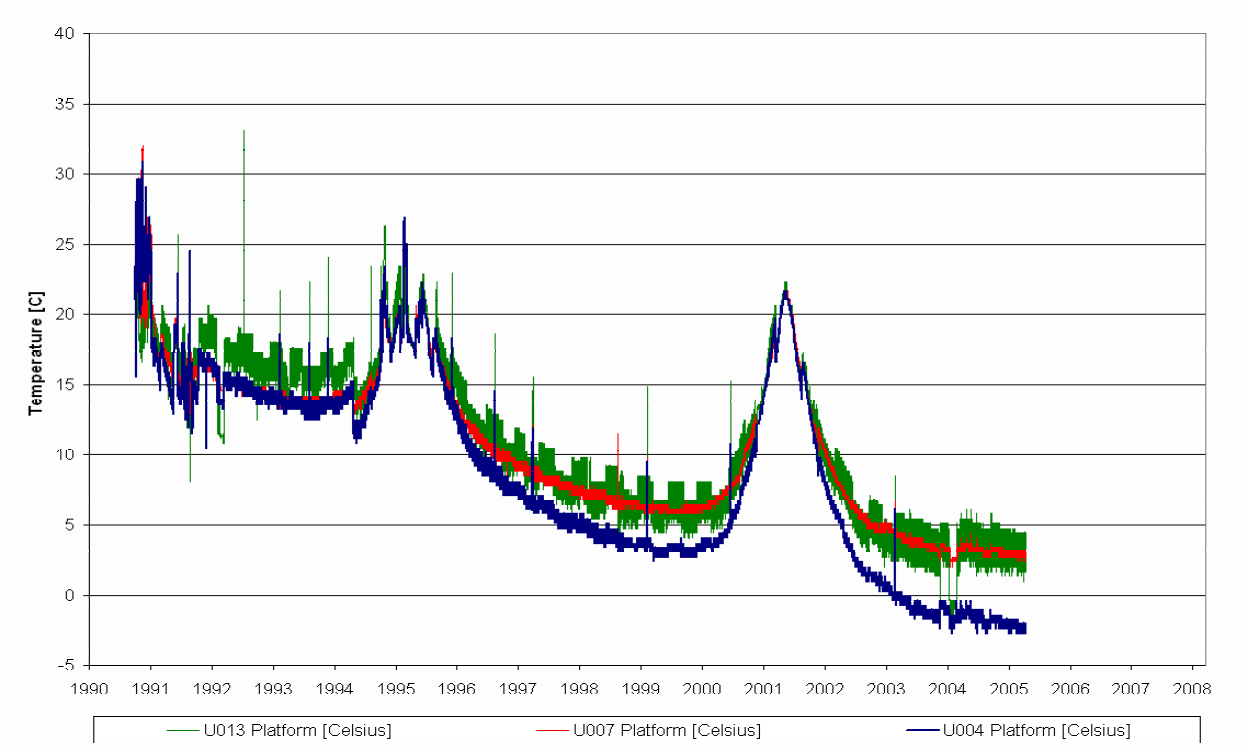


Figure 3: Ulysses Internal Temperature Trends

ULYSSES THERMAL SUBSYSTEM OVERVIEW

Thermal control of the Ulysses spacecraft, its subsystems and most of the experiments is achieved by passive means in conjunction with a set of dedicated heaters. Electrical power generated by the RTG is used to power the spacecraft subsystems and payload with the remainder used to power four spacecraft heating circuits. Three of these circuits, namely the hot case, cold case and X-Wing heaters, are used to maintain the RCE within its operating temperature range over the full spread of heliocentric distances experienced by the spacecraft. The fourth circuit, which draws any power not used by the subsystems, payload and first three heating circuits, consists of a set of power dumpers (both internal and external) to control the spacecraft internal temperature. [Ref 4]

The power available to the Internal Power Dumpers (IPDs) along with a typical temperature plot of the pipework over the course of the mission are shown in Figure 4. External Power Dumpers (EPDs), no longer used, were employed earlier in the mission to dissipate any excess power outside the spacecraft. This external dissipation was necessary during the periods following

launch, due to the combination of the close distance to the Sun and higher RTG power output, and during subsequent perihelion passes in order to avoid over-heating of the spacecraft's propellant.

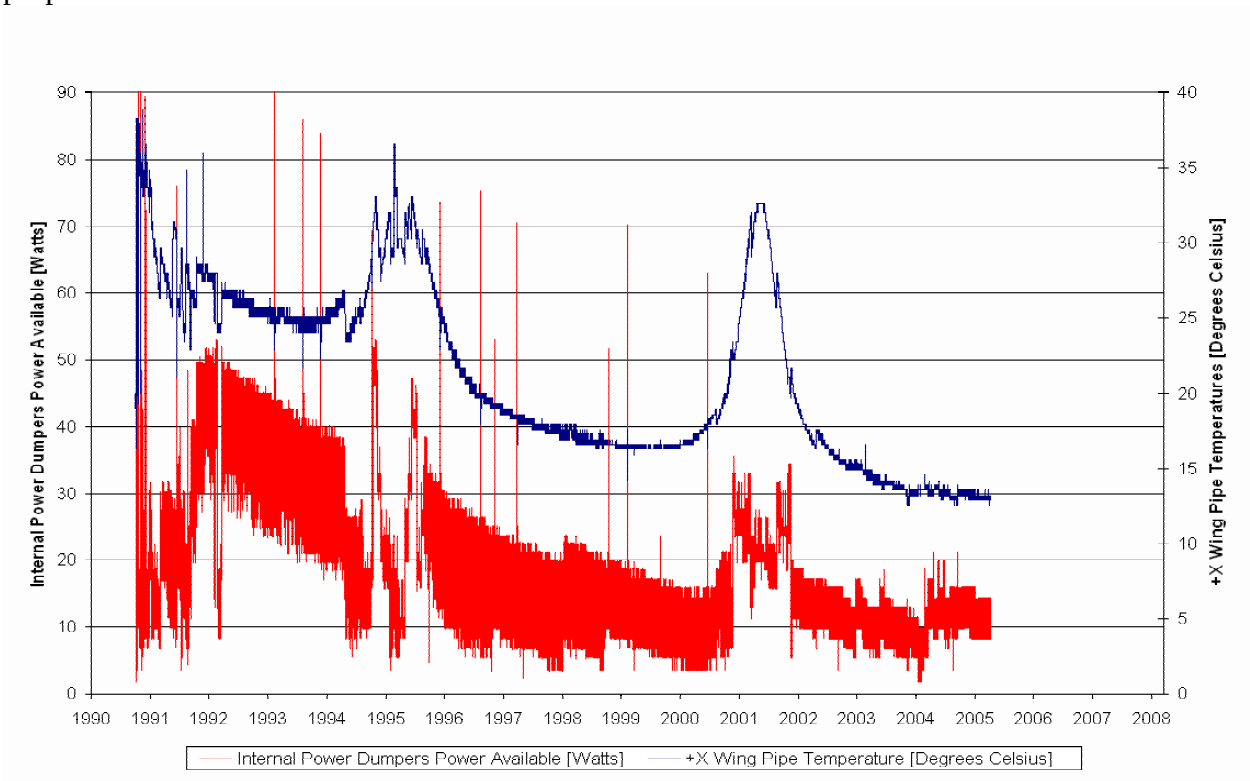


Figure 4: Ulysses Internal Heating Power and Pipe Temperature Trends

As the RTG output has decreased considerably throughout the successive mission extensions, the spacecraft's general thermal environment has cooled significantly. The spacecraft's thermal configuration has been optimized, i.e. the units and experiments configurations chosen deviate from the prime mission objectives, as the main goal is to achieve thermal well being of the critical spacecraft components. But even after thermal optimizations, some of the spacecraft's platform temperatures are the lowest ever observed. The spacecraft's RCE, and especially the propellant – hydrazine – have been always considered critical components. Now, more than ever, the RCE is considered the thermal driver of the mission.

During the latest coldest phase of the mission, portions of the propellant pipework have reached temperatures close to 3ºC. As hydrazine, depending on its degree of purity starts to freeze between 2ºC and 1.5ºC, particular care has to be taken in order to minimize the risk of freezing the fuel. Temperature monitoring is done via thermistors located on components or on the platform. The RCE temperatures can be directly monitored at specific locations. However, the temperatures of some critical parts of the pipe work are not measured directly and their actual temperatures can only be inferred or estimated, based on other neighboring temperature readings and using thermal modeling tools. The results of thermal-vacuum pre-launch tests have also been used to estimate temperatures of certain parts of the spacecraft that are not directly measured.

Ulysses is currently in the coldest thermal environment it has ever experienced, due to its large distance from the Sun and the low power output of the RTG. Although the spacecraft is gradually approaching the Sun, its internal thermal environment will not change significantly until mid 2006, as the benefits of the slow increase in solar incidence radiation are offset by the slow decay of the RTG power.

As the spacecraft approaches perihelion in 2007, the rate of increase in solar radiation will largely overcome the decay in RTG power and the spacecraft will experience an overall abrupt temperature increase. This will allow some of the RCE dedicated heaters, namely the X-wing and cold case heaters, to be switched off and to divert this available power towards providing a fully switched on payload.

The main drivers for this extended mission phase are:

- The health of the payload and the scientific data return. Many instruments have been forced to operate below their optimum temperature limits and often at lower temperatures than were ever envisioned.

- The health of the RCE. The hydrazine in the pipe work has to be prevented from freezing. Although freezing of one of the two redundant branches would still allow the routine Earth-pointing maneuvers to be performed with the other branch, the thawing of the frozen branch as the spacecraft approaches perihelion could be catastrophic if not controlled extremely carefully, since hydrazine contracts when it freezes and expands when it thaws.

ESATAN THERMAL MODEL DEVELOPMENT

Prior to Ulysses approach to the coldest phase of its mission in 2005, a large number of spacecraft configurations were analyzed using the VAX-based SINDA model. Due to the definition of a core payload (always on) and a discretionary payload (cycled on and off) for power saving purposes, the number of possible configurations for the spacecraft was significant. With a small spacecraft team (3 systems engineers) this process was extremely time consuming due to the limitations of the VAX system. The VAX system consisted of a hard-coded user interface accepting one configuration for one day of the mission and producing output data for each node in an unwieldy document to be transferred and analyzed on a PC. This would then be repeated for the first day of each month until the end of the mission for each proposed configurations. Configurations, which jeopardized the health and safety of the spacecraft, would then be discarded and those favorable configurations analyzed in more detail.

For these reasons it was decided to migrate the thermal model to the European Space Agency’s PC-based thermal code, ESATAN. In addition to increasing the modeling capabilities of the operations team this project also resulted in a much greater understanding of the thermal model at a time when all spacecraft operations were being driven by its outputs. Thermal parameters such as node definitions and conductor definitions were extracted directly from the SINDA text files and placed in Excel spreadsheets allowing quick conversion to ESATAN input formats.

Comments were added and a power model was implemented in Excel, based on the SINDA model to allow for training and validation. An up-to-date RTG power output model was implemented and arranged in an ESATAN input format along with relevant ephemeris data. An overview of the model is shown in Figure 5, highlighting the fact that the operations team can now perform thermal analysis through a PC-based Excel interface, a screenshot of which is shown in Figure 6.

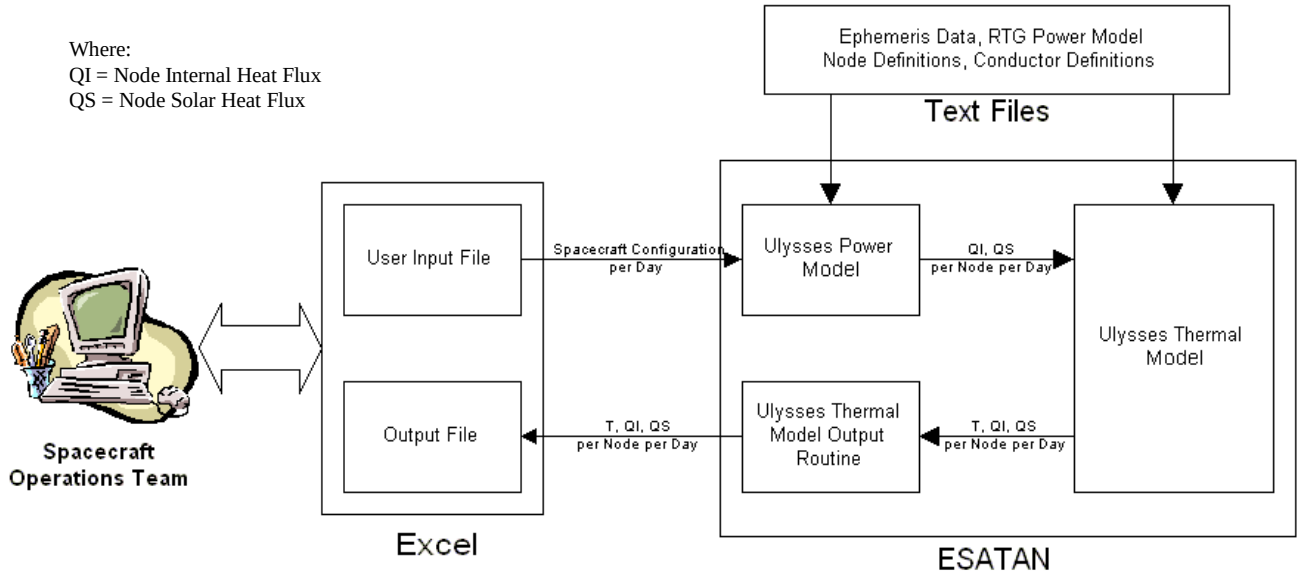
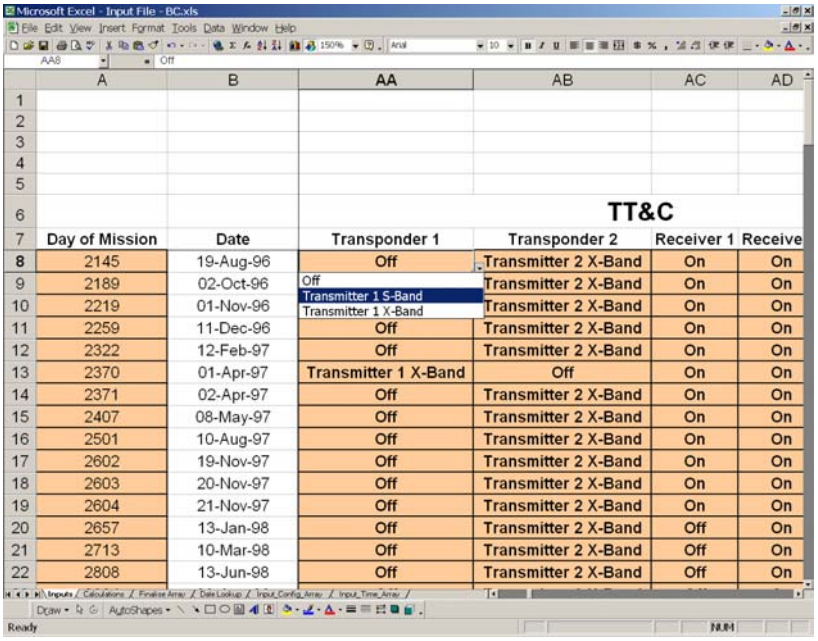


Figure 5: Ulysses ESATAN Thermal Model Overview

The power model implemented in ESATAN is a text-based MORTRAN model, which receives the user inputs as an array of spacecraft configurations on given days of the mission. The power model outputs an array containing the spacecraft configuration for each day between the start and end date of the simulation run in addition to the spacecraft ephemeris and RTG data on each day. This approach provides a quick and easy method to model the nominal mission configuration based on the current payload power-sharing plan. Proposed changes to the plan or investigations of other configurations may also be run easily by all members of the operations team based on the nominal input configuration file. This drastically improves the response of the spacecraft team to modeling any requested changes to the payload power-sharing plan as well as predicting the effects of a power anomaly on all future planning.

The power model then solves for QI and QS for each node and passes the data to the thermal model for solution. This process is repeated for each day in the simulation run and the data exported to a comma-separated variable (CSV) file for analysis by the spacecraft team. Simulation runs for the remainder of the mission may now be performed in the space of a morning while a similar task using the previous model would take weeks. Visual Basic macros may be used for data processing and organization and Excel input files saved together with CSV output files for future reference. Processing of output files to covert power and temperature predictions to telemetry values have also been added for comparison purposes.



	A	B	AA	AB	AC	AD
1						
2						
3						
4						
5						
6				TT&C		
7	Day of Mission	Date	Transponder 1	Transponder 2	Receiver 1	Receive
8	2145	19-Aug-96	Off	Transmitter 2 X-Band	On	On
9	2189	02-Oct-96	Off	Transmitter 2 X-Band	On	On
10	2219	01-Nov-96	Transmitter 1 S-Band	Transmitter 2 X-Band	On	On
11	2259	11-Dec-96	Transmitter 1 X-Band	Transmitter 2 X-Band	On	On
12	2322	12-Feb-97	Off	Transmitter 2 X-Band	On	On
13	2370	01-Apr-97	Transmitter 1 X-Band	Off	On	On
14	2371	02-Apr-97	Off	Transmitter 2 X-Band	On	On
15	2407	08-May-97	Off	Transmitter 2 X-Band	On	On
16	2501	10-Aug-97	Off	Transmitter 2 X-Band	On	On
17	2602	19-Nov-97	Off	Transmitter 2 X-Band	On	On
18	2603	20-Nov-97	Off	Transmitter 2 X-Band	On	On
19	2604	21-Nov-97	Off	Transmitter 2 X-Band	On	On
20	2657	13-Jan-98	Off	Transmitter 2 X-Band	Off	On
21	2713	10-Mar-98	Off	Transmitter 2 X-Band	Off	On
22	2808	13-Jun-98	Off	Transmitter 2 X-Band	Off	On

Figure 6: Ulysses ESATAN Thermal Model Interface

In the process of migrating the model from the VAX to ESATAN a number of changes representing the spacecraft status as of 2005 were implemented. These include:

Implementation of the Electronic Power Converter (EPC) / Traveling Wave Tube Amplifier (TWTA) Anomaly.
The thermal model as developed prior to launch does not distinguish between the prime and redundant EPC/TWTA combination. From operational experience it was noted that the redundant units draw ~3W less power than the prime and were therefore used for the vast majority of the mission to date. As of March 2003 a TWTA failure left the spacecraft in a configuration not previously thought possible with the prime unit powered in addition to both EPCs. This has been implemented in the ESATAN model.

Thermostatic Heater Implementation
The spacecraft heating circuit consists of a number of thermostatic heaters, which have been implemented using two methods. The first from a power point of view is the worst-case power scenario with the heater drawing its maximum power rating for a short period of time. This is used as a worst-case power model. The second is used for long term steady state thermal modeling in which the heater draws power based on the spacecrafts heliocentric distance.

Input File Flexibility
Spacecraft operations during the extended mission no longer reflect those envisioned prior to launch. For this reason the input files have been expanded to allow the user to control all aspects of the spacecraft configuration. In addition for all future phases of the mission worst and best case scenarios have been defined providing upper and lower bounds on the thermal model outputs for validation purposes.

The ESATAN power and thermal model has undergone a significant number of validation runs before entering operational use. Comparisons with previous runs from the VAX-based thermal model were done prior to the implementation of any changes. Following the migration the thermal model was then recalibrated against telemetry as detailed in Figure 7. Actual telemetry is plotted against a worst-case thermal scenario, a best-case scenario and a number of routine spacecraft configurations.

As can be seen in Figure 7 the telemetry values are bounded by the thermal model outputs in various configurations. As each of the configurations is solved for steady state, which is not necessarily the case in reality, the predictions do not accurately represent the telemetry at any given time but rather bound the telemetry values over the course of the mission. While the steady state condition may not be reached often in reality, it may be approached from time to time if the spacecraft remains in a certain configuration due to a commanding error or ground station failure. From an operational point of view this therefore provides upper and lower bounds at any point in time, which drive operations in the current phase of the mission.

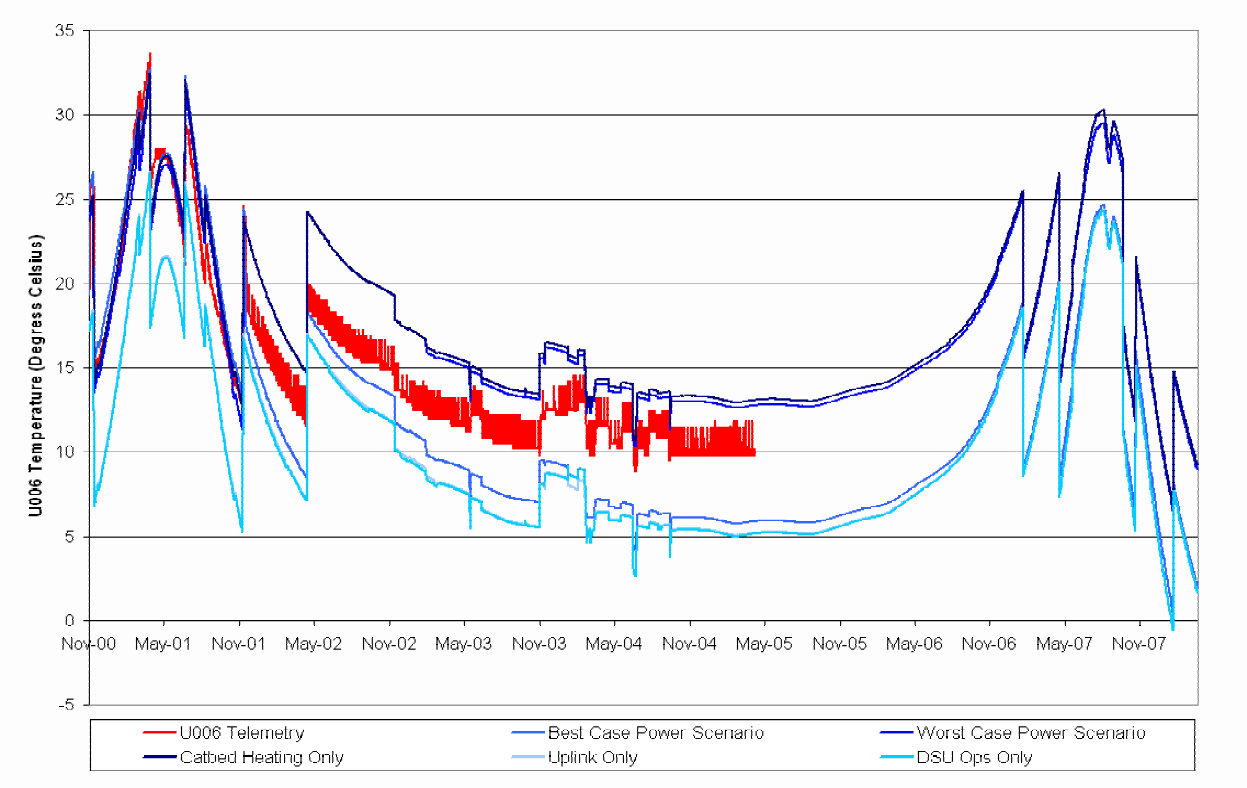


Figure 7: Calibration of Thermal Model Outputs against Telemetry

CONCLUSIONS

The current trend of extending scientific missions well beyond their design lifetime poses many engineering and management challenges in the design, building and operation of the spacecraft. Extending missions beyond their design life greatly increases scientific return for a very modest

increase in cost and in many cases enables unique scientific observations through the use of multiple spacecraft. As of July 2005 almost 50% of JPL's operational missions (REF JPL Website) were in their extended operations phase with many operating in configurations or under operational scenarios not envisaged during design and testing.

Extending a mission beyond its design lifetime also poses many challenges for the thermal subsystem. Decreased solar cell efficiency and battery degradation along with RTG power decay all result in less power for heating circuits. Unit or component failures and changes in material thermo-optical properties result in a varying thermal environment. All these factors lead to reduced thermal margins and pose a challenge to both the designers and operators of the system.

External changes such as alterations to the operation of the spacecraft and a loss in expertise through a reduction in staffing levels impose additional constraints, which should not be overlooked. Typically the number of anomalies a spacecraft experiences over the course of its lifetime follow the classic bathtub curve shape with an increase in the number of anomalies as the mission nears its end. This generally occurs as funding and staffing levels are being reduced, requiring analysis tools to be efficient, cost effective and accurate.

Many of the operational issues required to extend the spacecraft life coupled with component or unit failures render complex pre-launch modeling tools ineffective at a time when they are critical to the health and safety of the spacecraft. Models developed up to a decade before the start of the extended mission can be based on platforms or packages no longer feasible for a small cost-effective mission operations team, leaving the team to interpolate modeling runs from a nominal mission scenario. Based on the experience of the Ulysses mission operations team in updating its thermal model to ESATAN some recommendations for the development of thermal modeling tools are:

User Interface

The user interface should provide the operations team with the flexibility to run scenarios unforeseen during the design process. No assumptions with regards to the operation of mutually exclusive components should be made. Components often fail in surprising ways leaving the spacecraft in thermal conditions that have not been analyzed prior to launch. Allowing flexibility in the user interface reduces the need for editing the thermal model code by unskilled users. In the case of the ESATAN Ulysses model the user interface is implemented in Excel, from which a text file is imported at execution time. This text file may be edited prior to the solution routine allowing users to easily implement anomalous component behaviors without editing the thermal model code. Output files should also be provided in a platform-independent format such as a text file. Output processing should allow for quick identification of nodes, which correspond directly to telemetry channels in addition to the ability to convert thermal model outputs to discrete telemetry levels.

Good Documentation

In addition to commenting code and the development of user manuals a number of other documents have proven very useful in the Ulysses extended mission for analysis of non-telemetered components. While thermistors may be placed in thermally sensitive locations prior

to launch there will exist locations during the mission extension, which become critical but are not telemetered. For this reason the use of thermal testing documentation coupled with detailed node information allows for the development of a number of temperature offsets from known telemetered locations to nodes of interest.

Decoupling of Power Sources

In addition to flexibility in the user interface, the ability to model down to a component as opposed to a unit level mitigates a lot of the issues with respect to modeling spacecraft anomalies. Failure of individual heaters on heater circuits in addition to unforeseen power configurations due to operational needs often reduce the usefulness of complex pre-launch thermal models.

Development of Best and Worst Case operational scenario

From an operational point of view the development of easy to run best and worst case scenarios for each day of the mission provides the team with upper and lower bounds for their daily operations. In general, due to power redistributions onboard as daily operations are performed, these steady state worst and best cases will not be reached. Nevertheless, they are useful reference points in the event of a loss of ground station or other onboard problems that force the spacecraft to remain in the same configuration for many hours.

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CONTACT

Questions or requests for additional information may be directed to:

Colin Goulding,
Jet Propulsion Laboratory, 4800 Oak Grove Drive, MS 264-114, Pasadena, CA 91109, USA
e-mail: colin.goulding@jpl.nasa.gov