Beagle 2 Mission Operations: Architecture and Approach

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Abstract

The Beagle 2 project [1] is the UK-led effort that placed a small lander on the surface of Mars in December 2003, as a component of the European Space Agency's Mars Express mission. Unfortunately, communications were never established with the Beagle 2 and so we cannot report results, or even the state of the lander. However, this setback does not prevent us from describing the operations architecture, the approach to cruise and landed phase operations, and the early part of the surface mission. The primary purpose of the project is to examine the surface of Mars, performing astrobiology and geology experiments. A unique project in numerous aspects, the Beagle 2 lander has presented specific spacecraft operations challenges.

This paper describes the ground segment architecture of the Beagle 2 mission from an operations perspective. A summary of the mission is given, followed by a description of each component of the lander operations network and their interactions. This highlights some specific areas of interest within the spacecraft operations community: multi-site planning and control; international cooperation in data relay services; the mixing of strong industrial and academic teams; the use of 'off-the-shelf' solutions; the role of virtual reality; approaches to operations planning; the user interface and internet technology.

Finally, a planning and operations cycle is demonstrated, including both platform management and science-related functions. The scenario provided is taken from real Beagle 2 mission operations planning, as uplinked to Beagle-2 just prior to ejection from Mars Express.

Mission and Lander Overview

The Beagle-2 lander was a late addition to the Mars Express mission. With a tight mass budget constraint and little time for development, the lander has almost no redundancy in any system, and has a simple execution model based in a single processor. It is nevertheless a complex machine, with some key characteristics given in list form below.

- High payload fraction designed for in-situ analysis of sample composition
- Robotic ARM supports PAW (position adjustable workbench)
- PAW supports most payload items
- Imaging payload (stereo cameras, microscope)
- Lander base contains mass spectrometer and gas analysis package (GAP)
- 'Static' lander (no mobility)
- Piggyback payload of Mars Express
- Rapid development and build programme
- Minimal mass budget (60kg)

- Environmental sensor suite
- 6 months nominal operating life

Ground Segment Architecture

The Beagle-2 ground segment includes several facilities that span across functions and organisations. Here we present each facility, and summarise the operational contribution or capability that each provides.

Lander Operations Control Centre (LOCC)

The LOCC is located at the National Space Centre in Leicester in the U.K. It is the centre for lander operations during both the cruise phase and landed phase of the mission. Its capabilities include: platform operations and payload operation, simulation and planning, command generation and validation, lander control and monitoring. The LOCC is a custom-built facility for Beagle-2, but was specifically sited so that it formed a part of the visitor exhibition space of the Centre. One wall of the LOCC is a window open to members of the public, enabling them to see the team and equipment at work. This aspect significantly raised interest in and support for the mission, but also imposed some operational constraints. For example, the layout of the room was chiefly designed for public benefit, rather than operational reasons.

The LOCC is responsible for generation of command stacks, processing platform telemetry, engineering and platform support, and validation of Beagle 2 activities using the Ground Test Model (GTM) –described in 'Operations Resources' below . To support operations, the degree of automation provided by the system manages the Beagle-2 workload such that the very small team can achieve timely operations of the following typical activities;

- Scheduling of experiments and engineering operations planned around contacts
- Preparation of lander telecommanding
- Checkout validation of lander telecommanding sequences with the GTM
- Timeline validation against thermal, power and mission constraints
- ARM-PAW manipulation control command sequence validation
- Telemetry parameter monitoring including graphing, limits checking, exporting, distribution
- Interoperability with MEX and Odyssey missions
- Synchronisation of data between the facilities (LOCC, LOPC and LCC)

Lander Operations Planning Centre (LOPC)

The LOPC is located at the Open University in Milton Keynes in the U.K. It is the primary centre for planning and monitoring the payload. Its capabilities include payload operation, data monitoring and management of the mission Data Product Archive (DPA). It also constitutes a complete 'live backup' facility for the LOCC and vice versa – operations can be switched to the alternative facility within a very short timeframe (roughly a 1 hour drive in moderate traffic). This is achieved through the simultaneous delivery of telemetry to both centres, and by command history and other vital information being synchronised at regular intervals. The LOPC is supported by similar systems to the LOCC, as shown in Table 1.

Local Control Console (LCC)

The LCC is a novel asset to the Beagle 2 ground segment, and comprises a pair of identical laptop PC systems. Primarily intended for use during cruise phase only, it is operated within the PI support area (PISA) at ESOC. Its capabilities include probe control and monitoring, and fallback operations planning. It can be regarded as a ‘portable LOCC’. The laptops are configured to host SCOS2000 and primary and backup servers, and at ESOC become a part of the network allowing despatch of telecommands and receipt and analysis of telemetry.

	LOCC	LOPC	LCC
A TM/TC database system providing facilities for preparing the operational database of telecommands and telemetry, telemetry displays and other mission parameters	X	X	X
A mission control system providing facilities for database management; preparing and forwarding telecommands; and receiving, decoding, and archiving of telemetry	X	X	X
A mission planning system providing facilities for mission events timeline (MET) scheduling, platform and payload operations planning, timeline validation, and constraint/conflict checking	X	X	X
A ground test model console for preparing, encoding and forwarding telecommands to the Ground Test Model (GTM) and EGSE; receiving, decoding, archiving and browsing of telemetry from the GTM. This console is substantially the same as that used to control the real lander.	X		
A data product archive (B2DPA), providing facilities for storage, configuration control, authorised access, backup and cataloguing of mission specific data products derived from other on-site systems.		X	
Payload support consoles (one per payload)	*	X	

** only for the Stereo Camera System*

Table 1 - Core elements of the Beagle-2 Ground Segment

European Space Operations Centre (ESOC)

ESOC is the hub of all European space operations activity, and as such has a vital role within the Beagle 2 mission. Commands for Beagle-2 that are sent during cruise phase are sent to ESOC for transmission to Mars Express. This is achieved using a customised FTP client that continually runs polling for data on numerous interfaces, including event files, command loads, telemetry dumps, stacks and command histories. Telemetry is returned via the same mechanism, and distributed within the LOCC to SCOS2000 systems, using standard FTP between Linux-based desktop PCs.

NASA Jet Propulsion Laboratory (JPL)

In addition to their own Mars programmes, JPL have an important role in the Beagle 2 mission, both in providing access to the Mars Odyssey orbiter, and in coordinating all UHF communications around Mars. Prior to any operations, JPL provide the Beagle 2 team with an Odyssey to Beagle 2 contact schedule (in the form of geometric visibilities of the landing site from Odyssey). Subsequently, the Beagle 2 team provide both requests for contact passes with Odyssey and information regarding expected Mars Express contacts. All inputs are combined with similar data for the MERs and run through planning software at JPL. A weekly meeting is used to resolve any conflicts/issues arising from the requests. All information is exchanged in ASCII text files using Secure Shell file transfer over the internet, using public key encryption.

During operations, the LOCC provide JPL with a binary encoded telecommand file destined for Beagle 2. A trigger file triggers automated processors which forward and uplink the file to Mars Odyssey ready to be radiated to Beagle 2. Information is exchanged between the LOCC and JPL using the same Secure Shell method as for planning.

Operations Resources - Ground Test Model

A major resource available to the operations team at the LOCC is the Ground Test Model (GTM). This is an almost complete working replica of the Flight Model, and can be used to test all operations before they are sent to the lander. There are a number of components that comprise the GTM. Mounted outside the base of the lander are the Development Model (DM) common electronics (including battery and solar panel power supply simulation) and an Engineering Model (EM) Transceiver.

The common electronics runs the relevant version of the software, either Lander Software (LSW) or Probe Software (PSW). The lander shell itself is DM quality, and contained within in are representative dummy solar panels, as well as the DM instrument ARM. The final part of the GTM hardware is the instrument PAW, of which two versions are available for testing. The first is a 38% mass PAW (to simulate its weight under Martian gravity) which is primarily used for the testing of ARM manoeuvres in Earth gravity. The second is the Qualification Model (QM) PAW, consisting of the majority of the PAW instruments, and is electrically connected to the common electronics (and may be operated either mechanically interfaced to the ARM, or “stand-alone”).

The GTM includes support PCs and EGSE equipment. One platform runs the ESA SCOS system for commanding the GTM and processing telemetry. A MS-Windows-based PC provides various simulated inputs, and an emulation of the communications link providing the interface between the EGSE and the GTM lander.

Operations Resources - Virtual Reality Model

Due to the nature of the Beagle-2 lander, where the use of the majority of instruments involves a least some operation of the ARM, correct positioning of the ARM is very important. To assist ARM operations planning, a virtual reality model was developed by the University of Wales (Aberystwyth). Not only does this allow for position determination (*i.e.* joint angles required to reach a certain configuration) but also allows a sequence of manoeuvres to be developed and tested to find the safest route the ARM can take (*e.g.* avoiding collisions), or to optimise time taken or power consumption. Additional benefits of the ARM VR system are the ability to calculate motor current values and durations of the operations for planning of more complex manoeuvres and timelining sequences in the Beagle-2 common electronics computer. Figure 2 illustrates the VR system.

Operations Resources – LTST Clock

Although all operations and planning are carried out using UTC, it is often necessary to check the solar time at which operations will be carried out. Knowledge of the Local True Solar Time (LTST) gives an indication of the expected power and thermal conditions which will be experienced by the lander. For example, given a choice between two contacts with an orbiter on a particular Earth day, if one occurred during the local daytime and the other during the local night, the daytime contact would be much more favourable from the point of view of available power.

A program was written using an LTST algorithm [2] which calculates the solar time at a specified latitude and longitude on Mars. This was then used to calculate LTST at the Beagle2 landing site, as well as a Day/Night terminator map and times to/from sunrise/sunset at the landing site. The output map is illustrated in Figure 3.

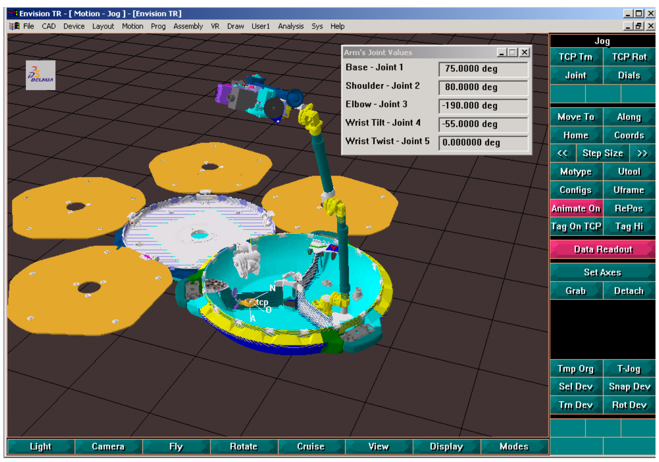

Figure 2 – Virtual Reality System

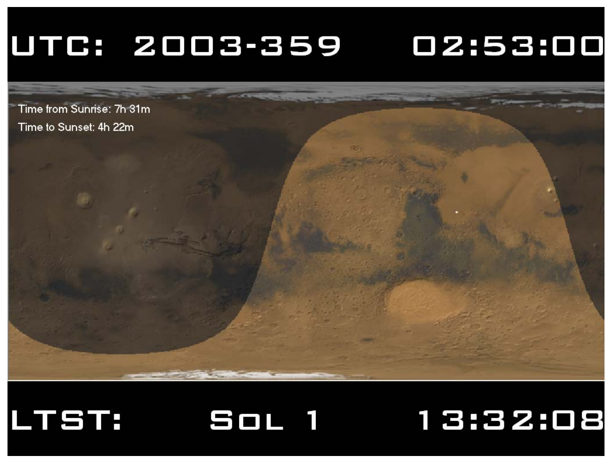

Figure 3 – LTST Clock with Sunrise/Sunset

Operations Resources - Science Payload Operations Database

The separation of science teams and science planning from the operations and engineering team has several advantages, but does introduce another interface that requires careful management. A method for managing the vital communications between the teams was developed that enables the scientists to describe their experiment in an agreed 'language' that was designed to support several roles. All such 'SPOD files' are readable both by humans and computer software. Any payload activity is described in a single file using a scheme that offers the following features -

Version control and status checking

Any given SPOD file may have various levels of validity, for example is only a draft of an idea for a payload activity, is a 'science team approved' file, or it may be a fully validated sequence that has run on at least the GTM and so is ready for upload to the real lander on Mars. A history of changes is also maintained within each file.

Constraint and sequence validity checking

The next section of the SPOD file contains information used by OPS. OPS is a tool developed for Beagle-2 that facilitates checks against power and thermal constraints, timing constraints, conflicts in schedule with other payloads and/or lander resources, and so on. The OPS achieves this by modelling status and every testable condition against a mission schedule file exported from the main control system scheduler.

Command Sequence Specification

The final section of a SPOD file actually details the operations to be performed by the lander in a form meaningful to both science teams and the flight operations team. Science teams select entries from the available timeline commands and provide them in the SPOD file, with any associated parameters. The OPS interprets the sequence in order to perform constraint validation, and the flight operations team interprets the sequence in order to validate the sequence and 'encapsulate' the sequence with required platform management tasks such as power switching, telemetry and log management, etc.

```
<ON_EXECUTION>
set (' $DATAVOLUME += $SEQUENCE_DATA');
check (' $PAW_WAM_STATUS == "RETRACTED" ');

<ON_DURATION>

<ON_COMPLETION>

<SEQUENCE>
SCS_Camera_Heads_On, 1
# RED near (670 nm)...
SCS_Select_Left_FW_Position, 07
SCS_Acquire_Right_Image, 0, 0, 0
# GREEN near (530 nm)...
SCS_Select_Left_FW_Position, 03
SCS_Acquire_Left_Image, 0, 0, 0
```

Figure 4 - Extract from a SPOD file

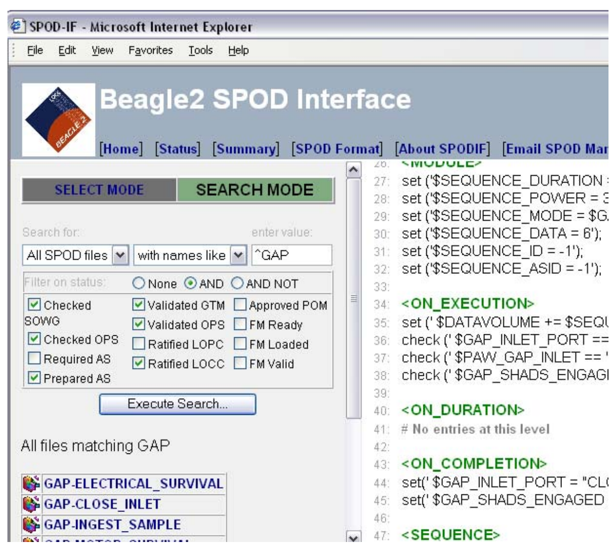

Figure 5 - Snapshot of the SPOD Web Interface

A database is used to manage the set of SPOD files for describing all payload operations of Beagle 2, and to enable all team members to have visibility of the current state of planning, a web-based tool is available for viewing the latest version of the SPOD. SPOD is a very simple and successful system for managing the interface between the various science teams responsible for payload and the small team that must interpret, implement and validate their intentions against the constraints of the spacecraft.

Planning and Operations

The Lander Software and the Mission Events Timeline

Control of Beagle 2 surface operations is managed by the Lander Software (LSW). LSW autonomously handles the core lander functions and programmable operations are implemented via a Mission Events Timeline (MET) and an onboard catalogue of Activity Sequences (AS). The MET is a linear queue of lander subsystem or payload instructions, with individual instructions scheduled for execution at an absolute Lander On-Board Time (LOBT). Activity Sequences are repeatable blocks of lander and payload instructions tied into a stand alone entity and tagged with a unique identifier. These entities may be called for execution at a specific LOBT. The use of Activity Sequences simplifies the construction of such payload operations which are complex and intended to be repeatable.

The MET is the primary operator interface with Beagle 2 during the landed phase. All science operations and the highest level of lander management operations are executed by adding entries to the MET via telecommand during the Mars Express and Mars Odyssey overflight opportunities. With careful planning the MET allows landed operations to be executed autonomously and safely, during extended periods without operator intervention. Contact downtimes are on average 1 sol with Mars Odyssey and may be up to 4 sols with Mars Express.

The landed phase of operations begins at handover of control to the Lander Software from the Probe Software (PSW). The Probe Software executes for the periods when Beagle 2 is powered on its journey to Mars; for tests and upload of software during cruise phase and performing the critical activities of the entry, descent and landing phase. The PSW final action, once Beagle 2 has come to rest on the surface, is to release the clamp-band holding the two 'clamshell' halves of Beagle 2 together. PSW then hands over to LSW and the Mission Events Timeline begins to execute, populated with preloaded entries for the first 3 sols on the surface.

Mission Event Timeline for Sols 1 to 3

LSW inherits Beagle2 from PSW with the processor and electronics drawing power from the battery. The transceiver is off, the solar panels folded into the lid covering the UHF antenna and the lid closed. At a minimum the MET on handover to LSW must include entries; to drive the lid main hinge to open Beagle and the individual panel hinges to deploy the arrays and, at a time coordinated to the overflight of Mars Odyssey 2 hours and 40 minutes after predicted landing time, switch on and configure the transceiver to respond to a hail from the orbiter. To execute these operations in the time immediately following handover, a set of 'default' MET entries and Activity Sequences are stored in EEPROM. These entries, loaded via the Mars Express umbilical link and PSW during the cruise phase, are transferred from EEPROM to the MET executing in RAM as part of the PSW / LSW handover.

The EEPROM allocation for MET consisted of 15 entries designated specifically for transceiver operation plus an additional 206 bytes for the first sols lander and science operations. 8 Activity Sequences dedicated to operations on the first few days were also loaded during cruise. The 15 communications session management entries were chosen to cover overflight opportunities up to the 17th of January. Utilising the flexibility of Activity Sequences to perform combined operations and by careful selection of MET entries the timeline for lander and science operations was extended from 1 sol to cover the first 3 sols on the surface. This provided scope for science and lander management activities to continue to be carried out without delay should successful communications not be established on the first or second opportunity. Figure 7 details the preloaded MET entries covering early activities for sol 1.

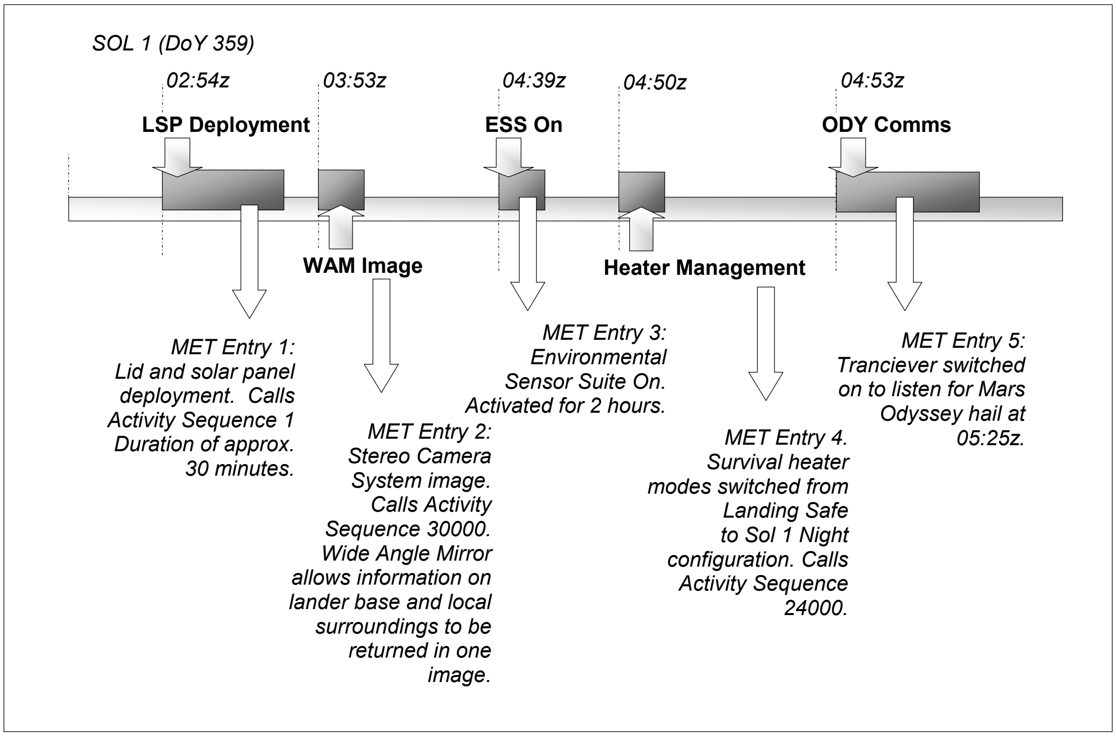

Figure 7 - Beagle 2 Operations Sol 1, Default Mission Events Timeline

Development, Testing and Implementation of Initial Surface Operations

MET entries to switch on the transceiver for communication sessions were selected based on predicted lander visibility times provided by the Mars Odyssey Navigation team at JPL and the Mars Express Flight Dynamics teams at ESOC. Entries to coordinate transceiver sessions with 8 Mars Odyssey overflights during the first 7 sols on the surface were programmed. Two Mars Odyssey overflight periods per sol, one before sunrise and one in late afternoon, were typically available and selection was further influenced by Beagle 2 power subsystem constraints and perceived quality of link based on orbiter lander geometry. Contact durations were of the order of 20 minutes and the programmed times for the initial communications session entries were configured in order that the receiver remained on for a significant period before and after the predicted overflight times to account for any deviations from the predictions.

Mars Express communications timings were based on a forward predict from the planned insertion burns required at Mars to achieve a mapping orbit. Communications sessions timed to listen for a Mars Express hail were programmed on to the MET to execute from sol 13.

The first (and absolutely critical) lander operation is the deployment of the lid and solar panels. This was developed and tested on the Ground Test Model while at EADS-Astrium (Stevenage, UK) in January 2003. The Activity Sequence consists of driving the lid hinge motor from closed (0°) to an angle of 180°, releasing the solar panels held in place by frangibolts and driving the panels one at a time in order from fully stowed (0°) to 160°.

20 minutes after deployment is complete the first imaging Activity Sequence is executed. The right camera of the Stereo Camera System is used with the Wide Angled Mirror to achieve a single black and white image of a 360° field then compressed by a factor of 10 to ensure return within data volume budget of the first Mars Odyssey pass. The Activity Sequences used to execute each of the four Wide Angle Mirror images on the MET across sols 1 to 3 have essentially the same structure, comprising the suspension of background lander operations to free resources for the camera, selecting an appropriate filter, taking and compressing the image. The MET for the first night on the surface includes an attempt to image the transit of Phobos across the field of view of the left camera – an operation which would provide valuable data for determining landing site location.

During early afternoon on the second sol, when predicted margins on available solar array power and battery state of charge are healthy, payload management activities have been programmed. The Gas Analysis Package is powered and engineering telemetry parameters sampled to ascertain instrument health. The ARM and PAW are released by activating hold down frangibolts. This is carried out at the earliest opportunity in order to eliminate a thermal path and reduce losses from the area of the battery and electronics rather than as a precursor to ARM manoeuvres. The default MET contains no further entries relating to ARM operation – unstowing and moving the ARM out of the protective envelope of the base can not be planned safely before the operations team has the opportunity to asses the landing locality using the returned WAM images. The Pluto launch lock pin is released shortly after as early as possible into the mission to reduce the possibility that dust build up could clog the mechanism.

At launch Beagle 2 EEPROM contained a provisional set of MET entries, Activity Sequences and communications sessions however detailed definition of the early landed phase operations did not begin in earnest until well into cruise phase. The 15 communication session, MET and Activity Sequences for sols 1 to 3 were uploaded to Beagle 2 EEPROM during two of the Beagle 2 checkouts on the 22nd of November and the 17th of December. A focussed campaign of testing preceded these dates. The Ground Test Model facilitated verification of the MET and AS on flight representative instrument hardware controlled by flight representative avionics running the final version of the LSW. This version of the software was also uploaded during cruise phase. The functionality of each of the 11 Activity Sequences for upload was validated, each tested as individual entities on the GTM. System level validation end to end test involved upload the default MET, AS and comms sessions in PSW, PSW handover to LSW following EDLS, full LSP deployment, execution of camera image Activity Sequence, establishment of successful comms and return of the compressed image.

With the functionality verified, the viability of the MET for sols 1 to 3 from a power subsystem view was established using the SEA Beagle-2 Power Model. Flexibility within the model allowed the MET to be tested against a background of differing environmental and system variables; predicted temperature of battery, orientation of the lander and solar arrays, sunrise and set times and optical depth of the atmosphere for example. One critical output of the power model is visibility of the variation of the battery state of charge in response to the loads seen as MET entries switch power to payload and lander units. It is essential to ensure battery state of charge is maintained above a level where night time operations (essentially heater cycling to keep battery and electronics within operational temperatures limits) remain practicable.

Summary

Beagle 2 was ejected successfully from Mars Express at 10:30z on 19th December 2003. A telemetry link is not maintained during the 5 days of coast phase, nor during the probes descent through the Martian atmosphere. The first contact after this, following a successful landing was expected at 04:54z on Christmas Day. Contact with the spacecraft was not established on this pass and no contact has been made to date.

From Christmas day the Beagle 2 operations team at the LOCC, support by the orbiter teams at ESOC and JPL, embarked upon a concerted period of active attempts to contact Beagle 2 on the surface. All recoverable failure modes were identified and contingency commanding implemented. The operational search period fully exercised the operations system described in this paper. Command loads were sent from Mars Odyssey and Mars Express to Beagle 2 on 26 occasions over the period December 25th 2003 to February 3rd 2004. Early commanding attempts were planned with reference to the existing Sol 1 to 3 onboard Mission Events Timeline and the timing of all operations was managed using the Mars Clock utility. Commands stacks were constructed using the SCOS 2000 MCS, verified on the Ground Test Model and delivered to the JPL and ESOC control systems via the described ground segment architecture. The entire Beagle-2 operations concept was demonstrated end-to-end during cruise, and at least as far as Mars Odyssey during landed phase.

Active operational attempts to contact for Beagle 2 were scaled down in early February. The Mars Odyssey Spacecraft continued to hail and listen for Beagle 2 on each of three passes per sol until early March. The search for the spacecraft on the surface of Mars continues to date with images of the landing site being returned from instruments on board Mars Global Surveyor and Mars Express. The legacy of the Beagle 2 experience, including the successes and lessons learnt concerning the operations architecture and approach during the cruise and search phases, has direct relevance to the planning of European missions to Mars as part of the Aurora programme.

References

[1] Internet resource: www.beagle2.com

[2] Allison, M. and McEwen, M., "*A post-Pathfinder evaluation of areocentric solar coordinates with improved timing recipes for Mars seasonal/diurnal climate studies*". Planet. Space. Sci. 48, pp.215-235, 2000.