Presentation

"BEAGLE-2 AFTERMATH" : LESSONS LEARNED AND THE POST-LANDING PHASE

M. R. Sims(1), **E. I. Chester**(2)

(1) *Space Research Centre, University of Leicester, University Road, Leicester LE1 7RU, UK.*
Email: mrs@star.le.ac.uk
(2) *ESOC, Robert-Bosch Straße 5, 64293 Darmstadt, Germany. Email: ed.chester@esa.int*

1. ABSTRACT

Beagle-2 was an ambitious, risky mission, driven by the possibility of outstanding scientific return value and a dedicated consortium team. Last seen leaving Earth on 2nd June 2003, and then leaving Mars Express on 19th December, the fate of Beagle-2 remains unknown. The objectives to investigate bio-signatures, environment, climate and geology, combined with the unconventional public profile, captured media and public attention to an unprecedented level. Much of the detail of operations, delivery to Mars, and the follow-up activities after mission failure, were thus hidden in the noise firstly of widespread enthusiasm, and then of disappointment.

Recent debate about the future of Europe's Aurora programme for Mars exploration concluded with a recommendation for continuation of robotic exploration, with three candidate missions being proposed for the 2011 opportunity. While only one of those inherits concepts and development directly from Beagle-2, we propose that any future European robotic mission can build on the lessons learned from our first step towards Mars.

This paper undertakes to address the points of both preceding paragraphs: it presents a concise summary of events around Beagle-2 landing, but more importantly the lessons learned – and how they were identified, the operational methods, the post-landing analysis work, the search for the missing lander, and strategies to be followed or avoided for future lander missions. The following sections bring together items from various sources, and it is hoped that the result is a short, yet sufficiently technical, summary of the "Beagle-2 Aftermath".

2. INTRODUCTION

At the outset, ESA's Mars Express (MEX) mission represented a unique opportunity to explore Mars (with platform and payload being largely reused from other missions, and a conveniently timed 'cheap' launch window in 2003). The Beagle-2 probe was conceived to search for evidence of past or present life on and below the Martian surface, and complemented MEX well, answering the call for proposals for lander elements to be added to the baseline mission.

Launch, commissioning and cruise phases were completed very successfully, leading to ejection from MEX at 08h31Z on 19th Dec 2003 for a 6-day coast phase to Mars atmospheric entry. From the time of ejection, no telemetry was received and the mission was subsequently declared lost. There is no evidence (yet) to suggest when or how the system failed. It is possible that future high-resolution imaging may help identify the failure mode.

2.1 Summary of Events

Table 1 and the elaboration below summarise key events in the mission, to set the scene for the analysis and follow-up work.

Table 1: Summary of Events

Date	*Time*	*Event*
02/06/2003	17:45	Mars Express launch
04/07/2003	20:04	Checkout A – Post-launch checkout
05/07/2003	19:03	Checkouts B,C - Heater/Timer tests
12/07/2003	16:46	
01/09/2003	12:40	Checkout D - Memory scrub
07/10/2003	11:03	Checkouts E,F – Software upload tests
09/10/2003	11:48	
21/11/2003	08:00	Checkouts G,H – Software uploads
22/11/2003	10:15	
17/12/2003	06:34	Checkout I - Ejection timer load
18/12/2003	06:33	Checkout J - Pre-ejection timer check and final system checkout
19/12/2003	08:31	Ejection from Mars Express
25/12/2003	02:51	Predicted atmospheric entry

Beagle 2 was switched on, checked out and switched off a total of 10 times during the Cruise phase. Thermal telemetry followed the predicted behaviour from thermal modelling very closely, with no anomalies. While several anomalies were discovered in flight related to software and electronic systems, these were all understood, repeatable on ground, and were subsequently corrected or avoided procedurally. All were attributed to 'learning to fly'. On two occasions (for different reasons) telemetry was lost from the probe while attached to Mars Express, with successful analysis and recovery in both cases.

Battery and energy management worked nominally throughout the mission. The lander software (LSW) was replaced successfully on 21st Nov, following ground validation. This was necessary after a new failure mode was identified in the lid and solar panel deployment sequence. A configuration issue with the heater circuit for the XRS (X-ray Spectrometer) backend electronics was identified and corrected.

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A ‘ground test model’ (GTM) of Beagle-2 was established in the Lander Operations Control Centre (LOCC) during the early part of the cruise. The GTM was used to validate procedures, sequences, databases, science operations, interfaces, software patches and so on. This was used nearly continuously in both ‘Probe’ (cruise to Mars) and ‘Lander’ (surface operation) modes with great success.

Each checkout was planned to achieve the following objectives:

- ensure continued correct operation and configuration
- address anomalies and actions from previous checkouts
- prepare the probe for ejection

The additional checkouts to update the landed-phase software also included operational validation and ejection preparation activities. The pre-ejection checkout was passed successfully, and a GO given by all teams for release.

3. EJECTION

Before discussing operations and the ‘landed’ phase, the release from MEX and coast phase are also summarised as they are an obvious starting point for a possible failure tree. Entry, Descent and Landing (EDL) was completely managed by the probe software (PSW), and was completely pre-programmed and autonomous. Parameters of the sequence were updated during checkouts as models and timings became more precise. Ejection from the mothership was confirmed in multiple, independent ways:

- Responsive ‘glitch’ in S-band Doppler at pyro firing (07h39)
- Spacecraft telemetry showing Beagle 2 disconnected (10h32)
- Spacecraft AOCS data (11h12)
- Monitoring camera images showing separation

The status of Beagle-2 was well known at ejection:

- Separation δV was 0.31ms^{-1}, as required.
- Battery charge level was verified >98%
- Confirmed software status and critical data area integrity.
- Descent timer, clock and latches in required state.
- EDL system parameters as expected.

All parameters for entry, descent and landing were within required limits, and a small landing ellipse was predicted. The MEX visual monitoring camera (VMC) took a sequence of images of ejection, showing Beagle-2 depart as expected (see Figure 1). These were post-processed to independently confirm ejection δV, angle, but it was not possible to confirm probe spin-rate.

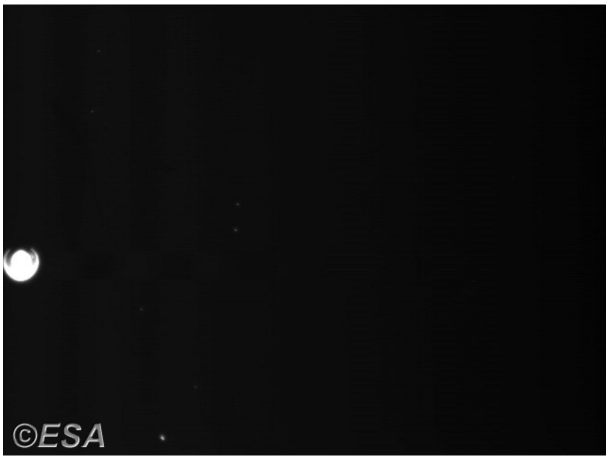

Figure 1: VMC Image of Separation

At the end of the coast phase, a redundant timer activated the power system and Beagle-2 would have booted up 2.5 hours before the predicted top of atmosphere. The probe software in EDL mode monitored accelerometers, timers, and a radar altimeter to control landing events during the descent (see Figure 3). However, without a descent transmitter to provide even simple telemetry (*c.f.* MER) it remains unknown how far through the sequence the probe got.

3.1 Landing Site and Targeting

The landing site was selected 2 years before launch, and was highly constrained by the orbit insertion requirements of MEX. Subsequent analysis [1] shows highly precise targeting, and some final tolerance at system level to late re-targeting. The initial landing ellipse was 495km × 93km (see Figure 2); a vast area reflecting the unknowns in trajectory, manoeuvre precision, system performance, atmospheric model uncertainty, and coarse modelling of the Beagle-2 EDL systems. However, the final ellipse was only 57km × 7.6km, an area two orders of magnitude smaller. This was achieved by the DDOR method using spacecraft already in orbit around Mars and background quasars.

Imagery of the landing site was available only at low resolution, and aside from being a region that was close to ‘flat’ overall and within the latitude ranges achievable, it is believed to be an ancient sea bed, and therefore an excellent location for the Beagle-2 payload suite to do its work. There were however significant unknown hazards in cratering, rock distribution, dust storms, *etc.* which could not be assessed at the time of site selection.

Lessons Learnt

Obtain a full landing site survey
DDOR navigation is necessary
Consider landing site changes during cruise
Eject as close as possible to target

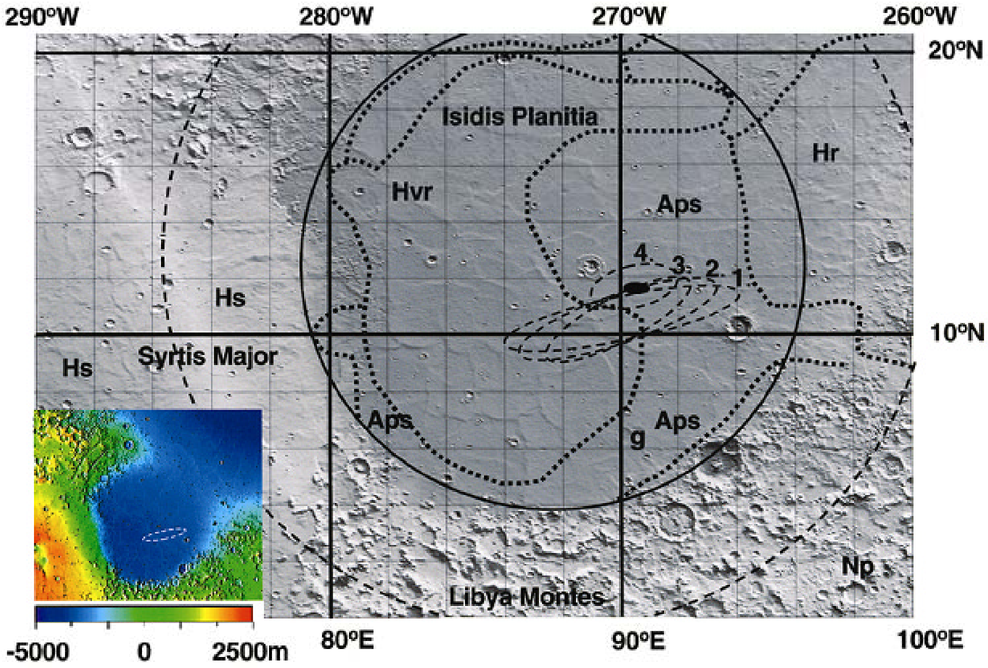

Figure 2: Landing Ellipse Evolution in Isidis Planitia

4. COMMUNICATIONS

Before proceeding to discuss the events around landing and follow-up activities, it is helpful to review aspects of the communications design and modes of Beagle-2, as the strategy for mission recovery was entirely governed by these aspects. The communications approach was based upon the CCSDS 'Proximity-1' protocol, where an orbiter acts as a relay in the link, following a hail and acknowledge handshake to establish the communications session. The differences between the Odyssey and MEX orbits led to a wide range of possible communication opportunities, having different characteristics.

All communications sessions were subject to sufficient power being available. The battery state of charge (BSOC) level is monitored and the software can veto a session if enabling the transmitter would sink enough power to endanger the overall lander. The threshold BSOC levels are mode-dependant. The design of the 'Communications Search Modes' (CSM) was therefore critical: three levels of autonomy were implemented to handle situations when scheduled communication opportunities were missed, as follows.

4.1 CSM-1

Odyssey overflights conveniently occurred at the same local true solar time (LTST) each day. In so-called CSM-1, Beagle could therefore autonomously add a morning (03:35) and an afternoon (15:35) Odyssey pass onto the mission timeline, giving each an 80 minute window. Future scheduled passes are retained. If the lander receives a hail while in any CSM mode, it instantly transfers into normal operations mode again.

4.2 CSM 2

CSM-2 adds a layer of intelligence to CSM-1, and has two sub-modes: Day and Night. In the event of a clock error, the LSW can determine the approximate time (in LTST) based upon apparent sunrise and sunset, which in turn are detected by current monitors in the solar panels. We defined 'Day' as 10:00 to 18:00, and the remainder of each sol as 'Night' for operations purposes. During daytime, the transceiver is on for 59 minutes of every hour, during which the following events occur:

- Receiver is on, awaiting a session hail
- 10 seconds of 'expedited mode' telemetry is transmitted
- A 10-minute cycle: 9 mins transmitter off, 1 min unmodulated carrier transmission.

If the lander believes it to be night-time however, the cycle time reduces to 1 minute in every 5, and consequently the carrier transmission never occurs (to conserve power during the night).

4.3 Auto-Transmit Mode

In this final mode, operation is similar to CSM-2 except that the 'expedited' telemetry period is extended. Beagle-2 would have attempted to transmit telemetry regardless of the hail protocol. This covers a scenario wherein an orbiter is listening, but for some reason the forward link (hailing) is unsuccessful. Table 2 summarises all contact opportunities used.

Following detailed discussion about the implementation of the Proximity-1 protocol on each orbiter, it became clear (on 30th Dec 2003) that the model for the current lander mode could no longer be applied, as it was unknown whether commands had been received or not.

Table 2: Overflights and Communications

Date	Time	Route	Mode
25/12/2003	05:25	Odyssey	H
25/12/2003	22:20	Jodrell	L
26/12/2003	18:06	Odyssey	H
26/12/2003	20:09	Odyssey	H
26/12/2003	23:00	Jodrell	L
27/12/2003	06:49	Odyssey	H
27/12/2003	22:56	Jodrell / Stanford	L
29/12/2003	08:13	Odyssey	H
30/12/2003	07:57	Odyssey	H
30/12/2003	20:54	Odyssey	H
31/12/2003	09:38	Odyssey	B
01/01/2004	22:19	Odyssey	H
02/01/2004	11:02	Odyssey	H
07/01/2004	12:12	MEX	H
07/01/2004	13:33	Odyssey	H
08/01/2004	02:31	Odyssey	H
09/01/2004	13:27	MEX	H
10/01/2004	14:04	MEX	H
12/01/2004	02:02	MEX	H
22/01/2004	22:10	MEX	C
24/01/2004	23:19	MEX	H
25/01/2004	22:53	Odyssey	H
28/01/2004	19:30	Odyssey	H
30/01/2004	04:58	Odyssey	B
31/01/2004	04:41	Odyssey	B
03/02/2004	04:35	MEX	I
followed by Odyssey listening until…			
10/03/2004	18:16	Odyssey	L

H – hail and command; L –listen-only;
C – listen canister mode; B – blind command;
I – invalid hail and command

Assuming nothing about the mode, critical path analysis was performed to determine definite time windows when the lander should have entered specific search modes. The new goal was to force the lander into CSM-2 by avoiding communication for several consecutive days – with the result that if the lander was functioning, we would then have known when the transceiver was powered.

Lessons Learnt

Search modes should be default until contact is established. The B2 approach was success oriented.

5. LANDING

Timed operations after landing were controlled by the Mission Events Timeline (MET) and a suite of Activity Sequences (AS) running together in LSW. The MET is populated initially from stored events in EEPROM, then by time-tagged commanding, and by autonomous scheduling as above.

The Operations Phase includes 3 categories of operations, discussed in the following subsections 5.1-5.3.

5.1 Entry, Descent and Landing (EDL)

The EDL sequence is illustrated in Figure 3. Atmospheric entry occurred at 5.5 kms^{-1} and an angle of 16.5°±1° below the horizontal. Two accelerometers measure the deceleration profile of Figure 3, and are monitored by the probe software's (PSW) EDL algorithm. When either accelerometer reaches a critical trigger value, the pyrotechnics are activated, deploying the pilot chute and subsequently the main chute. A radar altimeter initiates airbag inflation at a height of around 200m above the surface.

The knowledge of the atmosphere at the time of entry was very limited, but data from MER-A and the SPICAM payload on MEX suggest high dust loads and low-altitude turbulence, with unknown surface winds. None of these factors can help the chances of success! Extensive atmospheric modelling was done as a part of the failure tree analysis; consult [2] for details.

Lessons Learnt

Know atmospheric variations
Minimise velocities at all stages if possible
Consider adaptive entry systems
Robust Entry and Landing System
Try to land at preferred time of day, in a favourable season!

There were a number of 'high shock' events during landing: aeroshell release, mortar firing of parachute, gasbag inflation and impact, every (unknown) bounce across an unknown surface, and finally release from the protective gasbags for an unprotected freefall from ~1.5m. Each of these constitute an uncontrolled environment, which while simulated or tested, can never be fully validated ahead of time.

Lessons Learnt

Minimise and test for all shock environments
Minimise 'uncontrolled' events

5.2 Autonomous Surface Operations

All planned operations for Sols 1 to 3 were pre-programmed and would have executed automatically following a successful EDL. A set of MET entries and sequences were prepared and loaded into EEPROM. These are summarised as planned, as if they had executed.

LSW inherits Beagle-2 from PSW (still running on batteries). At this time the transceiver is off, the solar panels are folded into the lid (covering the UHF antenna) and the lid is closed.

The first landed phase operation is Lid and Solar Panel (LSP) deployment. The lid main hinge is driven to 180° to open Beagle. The solar panels are released and the individual panels are driven to 160° to deploy the arrays (as in Figure 4, but note that the arm remains stowed, unlike the illustration).

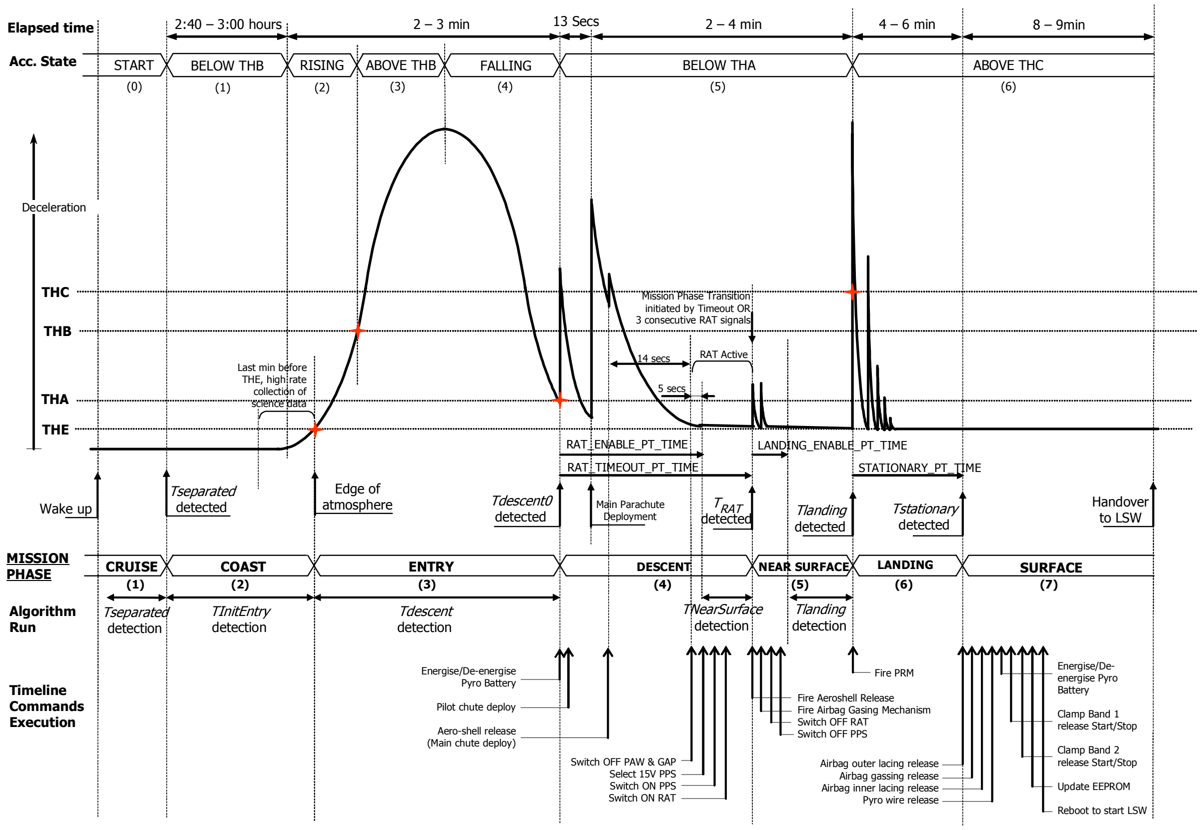

Figure 3: EDL sequence details

Only after this point was the antenna uncovered, but no orbiter was yet in position to receive a signal. Without further mechanism actuations, 20 minutes after deployment is complete the first imaging AS is executed. The right camera of the Stereo Camera System is used with the hemispherical Wide Angle Mirror (WAM) to obtain a single monochrome image of the immediate landing site. This image was then compressed by a factor of 10 to ensure return within the first Odyssey pass.

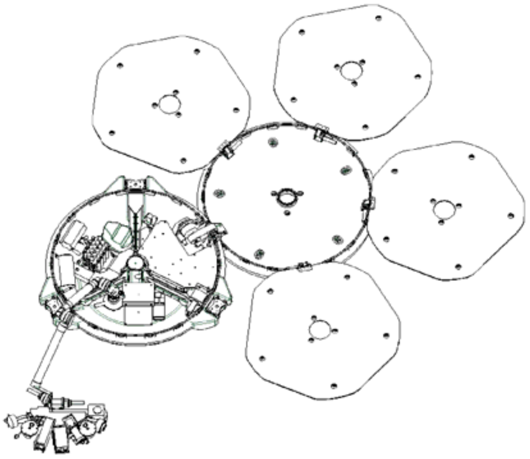

Figure 4: Beagle-2, Deployed

(antenna in lid not shown)

The value of this image is more than a media-friendly confirmation of landing; it would have provided information about the final location of airbags, the local gradient (via horizon angle) and a first impression of the likely payload operations (depending upon terrain/rocks in field of view) enabling detailed preparations.

NASA Odyssey rose over the horizon for the first overflight of the landing ellipse at about 05:25:20 LTST, and set 17m 35s minutes later. No UHF signal of any kind was received. The timeline continued regardless.

Operations for the first night on the surface included an attempt to image the transit of Phobos across the field of view of the left camera – an operation that would have provided valuable location data. During early afternoon on the second sol, when power system margins were predicted to be favourable, payload management was started. The Gas Analysis Package (GAP) is powered to obtain engineering housekeeping data (HK). The ARM and PAW frangibolts are released, to eliminate a thermal path from the battery and electronics. The Planetary Underground Tool (PLUTO, the “mole”) launch lock pin is released shortly after, to minimise the risk of dust ingress forever preventing mole deployment.

Fifteen pre-programmed transceiver operations were chosen to support overflight opportunities up to Jan 17th.

At this stage, each contact duration was approximately 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 predictions. Three communications sessions were selected to coincide with times when the Beagle landing site was visible from Jodrell Bank radio telescope. This allowed an earth-based search to be carried out in support of the search from Mars orbit. These sessions all formed part of the default timeline.

The fundamental design of the lander, while compact and mass-efficient, introduced a single large risk to communications: the full mechanical deployment sequence must be successful in order to allow the antenna to transmit; and at least partial deployment is required for any power generation.

Lessons Learnt

EDL comms are essential, assets, landing time *etc.* to be arranged

Minimise deployment sequence complexity and dependencies

Utilise robust power systems

Minimise shock and distortion risks

5.3 Commanded Operations

During the period of active commanding (25/12/2003 – 3/2/2004) the Beagle 2 operations team identified and investigated possible recoverable failure cases. Hypotheses were proposed, recovery strategies developed and rehearsed on the Ground Test model and contingency recovery commands sent via MEX and Mars Odyssey. Commands were despatched to Beagle-2 on 23 occasions. In this manner the identified recoverable failure modes were eliminated as described in the following subsections.

With no response from the surface it is not possible to draw any concrete conclusions about the impact of any of these strategies. The fact that the contingency commanding was not successful in establishing contact does eliminate several failure cases - naturally for any contingency commanding to have been successful, a forward communications path (at least) must first have been established. We present the primary recoverable scenarios.

5.3.1 Clock reset / Out of synch

A reset or jump in the Lander's On Board Time (LOBT) would have shifted the timings for operations on the MET, leaving communications sessions out of synch with orbiter overflights, or Jodrell Bank observations. For each commanding overflight, a new value of LOBT (an offset from the time of maximum elevation of the pass) was calculated, and instructions sent to reset LOBT to this predicted value. This was performed in every session from sol 3 onwards.

5.3.2 Entry into comms 'Search Modes'

The possible routes through the communications 'search mode' (CSM) tree involve complex permutations. A significant part of the operations team search strategy involved categorising these permutations and planning contingency operations accordingly.

Beagle 2 was hailed on overflights coinciding with the widest range of possible comms search mode opportunities. No attempt to hail was made between 12th and 22nd January. With the preset parameters for comms session management, this allowed adequate time for Beagle-2 to enter CSM-2 via *any* of the possible routes.

Software parameters controlled the intervening duration, or the number of missed communications opportunities, that must pass before entry to each search mode. Commanding to set these parameters to their minimum possible values was conducted from sol 14 onwards.

5.3.3 'Comms-free' Mission Event Timeline

The team tried to consider failure mechanisms that might result in the MET being empty of future communications events. Instructions to add additional transceiver operations to the MET were therefore included with every commanding opportunity.

5.3.4 Solar power marginal

If power margins were small (*e.g.* if deployment of the solar arrays had been incomplete), then the transceiver may have been prevented from switching on / responding to a hail correctly. Opportunities for successful communications would then be limited to times of peak available power.

Hail attempts were made at a wide range of times of day and hence a range of power regimes. Commanding to adjust the angle of one solar panel was included in all hail attempts. Array #1 was commanded from 20° above the plane of the lander base (nominal deployment), to lie flat in the plane – a configuration more robust to different orientations of the lander on the surface. This was established through extensive modelling of the power supply systems and expected loads. Commanding to drive all four solar panels flat was included in commanding sessions from sol 14 onwards.

All mechanism actuations included current monitoring as one proxy for obstruction monitoring (the payload workbench PAW provided additional, independent feedback). In case the obstruction monitoring algorithm current limits were somehow exceeded, we preceded the panel reconfiguration commands with instructions to double the current threshold for obstruction monitoring, thereby increasing the chances of recovery from a marginal power scenario.

5.3.5 Battery state of charge limits

An anomaly was identified in the execution of the Battery State of Charge (BSOC) monitoring algorithm that could have prevented the transceiver switching

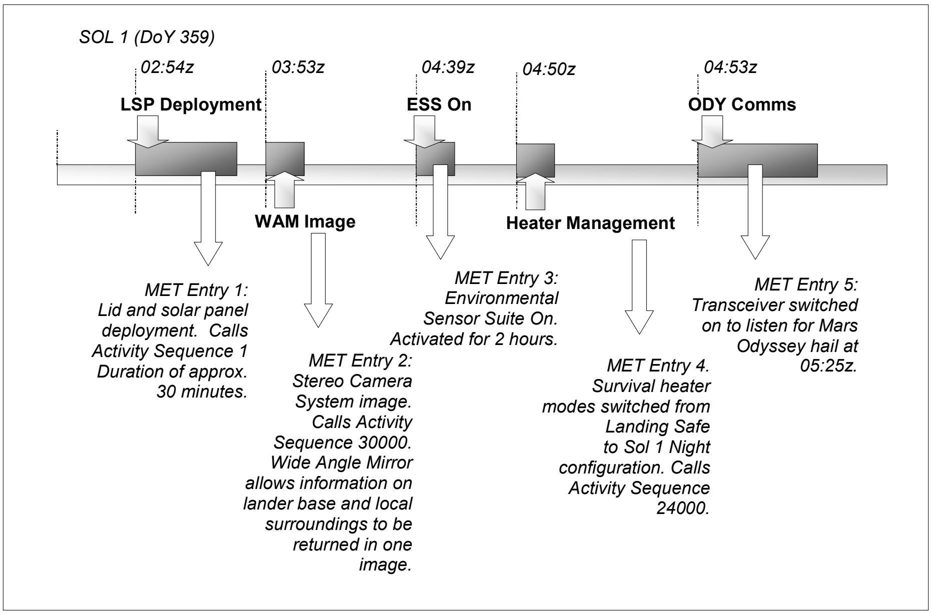

Figure 5: Sol-1 Default Timeline

correctly while in certain modes, even with a healthy, charged battery. Consequently, the software flag that enables the BSOC algorithm was reset via commands sent in each command load from sol 8 onwards. The battery charge level was thereby prevented from impacting communications. In the nominal mission scenario, the BSOC algorithm would have been an important safety feature during periods of extended autonomous payload operation without ground contact.

5.3.6 Power subsystem monitoring

Independently of the issues addressed in the previous 2 sections, the power subsystem itself included protection and management features. It is conceivable that with low power margins, the protection logic could prevent correct transceiver switching. Commands to deactivate such protection were included from sol 14 onwards (this included battery and bus current and voltage checks).

5.3.7 Sequential commanding failure

A fault in transceiver operation could have prevented the handshaking required for sequential commanding between orbiter and lander. According to the implementation of the PROX-1 protocol on MEX, lander commands are only released on confirmation of a successful hail. Conversely, the first frame of forward commands from Mars Odyssey are released immediately following the hail - before the session is confirmed as active by return hail acknowledgment from the lander.

Odyssey also provided an additional facility for blind commanding whereby commands can be resent continually for the duration of the overflight. This ‘desperate’ mode of commanding was conducted on sols 7, 36 and 37.

Lessons Learnt

Test representative flight communications hardware in ALL modes before launch

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5.3.8 Software requires reboot

Very much as a ‘last resort’ strategy, reboot commands were despatched on sols 36 and 37.

None of the preceding recovery activities yielded any improvements, and attention naturally turned to analysis rather than recovery.

6. THE SEARCH

The search for a Beagle-2 signal post-landing was supported primarily by 3 different organisations (in time order):

- NASA JPL via Mars Odyssey
- Jodrell Bank (and other radio telescopes)
- ESA via MEX

Jodrell Bank was used to listen for a UHF Carrier at or close to the Beagle-2 transmit frequency, while the orbiters were attempting to hail and establish duplex communications. To validate the orbiter UHF systems, tests were performed between the UHF unit on MEX and the NASA MER-A (Spirit) rover - successfully completed on 11th January 2004.

6.1 Imaging the landing site

Shortly after the anticipated landing, a campaign was established to image the landing ellipse, led and kindly supported by Malin Space Science Systems using the MOC camera on Mars Global Surveyor. This focussed on the downrange (eastern) half of the ellipse, as both MERs landed downrange of the centres of their respective uncertainty ellipses owing to elevated global temperatures affecting entry dynamics.

A total of 10 images were acquired, covering slightly more than 72% of the downrange half of the ellipse. Figure 6 shows a much reduced version of the mosaic of eight images acquired of the eastern ellipse on top of the planning mosaic. Raw, cosmetically-cleaned, and map-projected versions of each image were provided to the Beagle-2 team for evaluation. Scientists at MSSS also inspected the images for indications of the lander or its components. Based on their experience in previous searches for landed vehicles (Viking-1, Pathfinder, Polar Lander, MER-A and MER-B), only one candidate feature was identified in the mosaic. In the original image this feature is about 20m in diameter, dark, roughly circular, and appears to have some interior structure, and does not seem to be a natural impact crater. However, 20m is rather larger than expected from the impact of Beagle-2 hardware (see 6.2). Based on this imaging campaign and subsequent analyses, no evidence of the missing lander was found within the coverage of the downrange half of the landing ellipse.

6.2 Beagle 2 crater sizing

In support of the image analysis work, an estimate was required of the size of crater that Beagle-2 would have made on impacting if all or part of the Entry Descent and Landing sequence failed. Crater size was calculated using the Schmidt & Holsapple method [6], scaled from empirical terrestrial cratering data. Impact velocity and flight angle were determined from EDL modelling. The following results are statistical expectations:

- Crater rim diameter ~ 2m
- Ejecta field radius 1.4 - 2m
- Total feature size 5 - 6m diameter, upper limit 9m.

7. INVESTIGATION OF FAILURE MODES

The focus of investigations was necessarily limited and driven by the availability of evidence. Each following subsection outlines the analysis carried out and findings, in no particular order of importance or chronology.

7.1 Electrical Performance during Cruise

The behaviour and performance of the Beagle 2 probe was monitored throughout cruise phase. A dedicated additional review of cruise phase telemetry was carried out as part of the post-operations investigation, culminating in a report on the electrical behaviour during cruise.

All telemetry collected from the probe during cruise phase was reviewed. The analysis was directed towards identifying and eliminating any circumstance which may have contributed to the loss of mission. The following are the main results of investigation.

- Battery charge at ejection was over 98%. Supply voltages were healthy and within tolerances for the duration of cruise; no overall trend was observed.
- There were no unplanned software resets during cruise, and no multi-bit errors in memory. 10 single-bit errors occurred in RAM, and were fixed.
- All changes in timer telemetry were correlated with MEX command history. No timer anomalies were found in any test or related activity.
- Three anomalies occurred during the upload of the new software image. The successful load of the image was finally confirmed by verification of checksums..
- An “Integrity Check” procedure was executed following all memory operations in order to verify the continued integrity of critical sections of EEPROM.

The behaviour of all probe subsystems during cruise was as expected with the exception of a number of understood spacecraft anomalies. None of these anomalies are considered to impact the survivability of Beagle-2 on the surface of Mars. No evidence to support *any* failure hypothesis was discovered in probe telemetry returned during cruise operations.

7.2 Thermal Performance during Cruise Operations

The Rutherford Appleton Laboratory, responsible for the thermal design of Beagle-2, provided an assessment of the cruise phase thermal performance, and found that the thermal subsystem performed very close to expectations, and no suggestion of a failure mode from the thermal behaviour. Minor deviations from the model were identified, but within tolerances.

7.3 EDLS and Mars’ atmosphere

The EDL system was designed in coordination with modelling performed by Fluid Gravity Engineering Ltd (FGE). The modelling was revisited in the post-operations phase in light of possible evidence that the atmospheric density profile above Isidis on the day of arrival may have differed from that used in the design phase model.

Both MER rovers reported a significant delay in parachute deployment. The atmosphere as experienced by the MERs was within NASA’s specifications. The MERs utilise a much more complex EDL system capable of recovering from late sequence initiation; the Beagle-2 system was unable to respond to changed circumstances as the sequence is purely time-driven once the deceleration trigger has been detected. Extensive re-modelling ensued, to determine any change in ballistic properties. No conclusions were found that lead to a mission failure scenario.

7.4 VMC Image Analysis

Beagle-2 ejection was imaged by the MEX Visual Monitoring Camera (VMC). Eight images were captured at known times, and images 3 to 6 were analysed in detail by Virtual Analytics Ltd. with context information from the Beagle team. Analysis concentrated on determining the ejection velocity and solar aspect angle (SAA), and identifying a bright image on the probe body in image 3. Purely from the image processing performed, the following results were obtained, independently verifying expected and known values of ejection parameters.

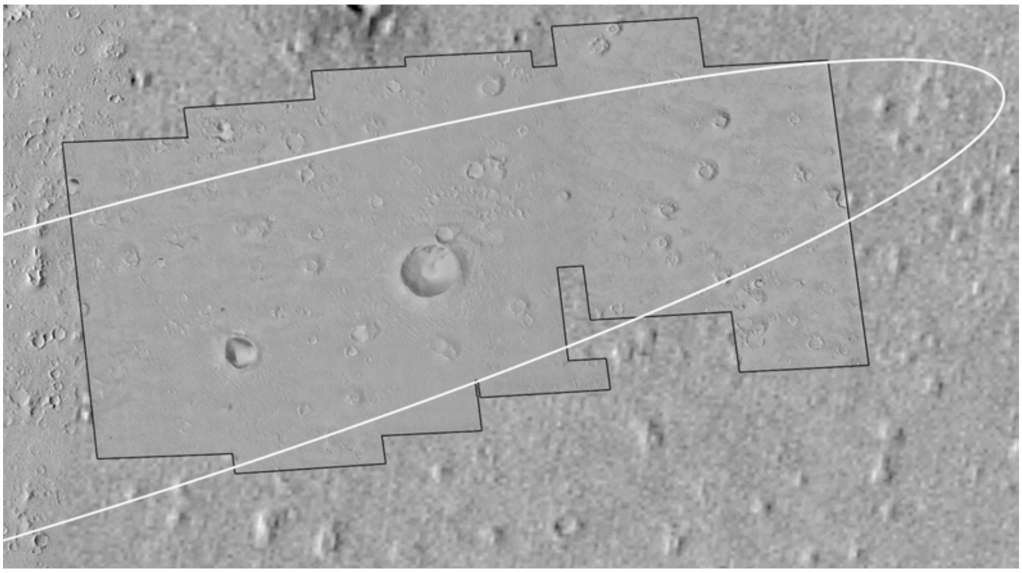

Figure 6: Landing site imaging coverage

Ejection velocity was calculated at 0.3025 ± 0.0083ms^{-1}. A solar aspect angle of 133 ± 10° was estimated, in agreement with ESOC's stated value of 124°.

7.5 Aeroshell release mechanism cover dis-bond

Three aeroshell access points on the probe were closed with bonded covers during the final phase of AIV. The possibility was considered that one or more of these became dis-bonded during flight. This would lead to a lack of complete isolation of the probe internal volume from the severe environment during EDLS, and possibly to catastrophic failure. The bonding process and possible failure cases were examined in detail, but no conclusions relevant to overall failure were drawn.

7.6 Outgassing

During the cruise phase, MEX experienced an unexpected δV. The cause was positively attributed to outgassing from the +Z face (where Beagle was located). Consideration was given to whether the outgassing could lead to 'icing–up' of the ejection mechanism and consequently non-nominal ejection, or if the outgassing resulted from a leak in the Airbag Gassing System. Once again, no evidence was found to support any failure mode.

7.7 Parachute deployment, heatshield separation

All aspects of the EDL modelling were revisited, with particular attention to the difference in ballistic coefficients of the parachute, heatshield, and rear cover. The possibility of re-contact between the main parachute and the airbags after the first bounce was also considered but found extremely unlikely. However, analysis showed that an additional 10m of strop length would have significantly reduced the probability of re-contact even further.

7.8 Ejection

The MEX operations team analysed the response of the attitude control subsystem to the ejection event, and FGE revisited the Monte Carlo determination of the landing ellipse based on the entry interface state and covariance provided by ESOC. The results indicate that ejection was nominal with slight over-performance of 1.29% and uncertainty of ±0.5%. The analysis concludes that Beagle-2 was perfectly targeted by Mars Express with only a very small error in entry parameters and landing location.

7.9 Design failure modes and summary

A collection was maintained of potential failure modes in the design itself. This attempted to evaluate all potential failure modes for Beagle-2. For any given failure case, the variants and consequences are given; risk mitigation steps taken and any relevant comments are also included where appropriate. The team assigned two parameters to each case on the basis of analysis and engineering judgement.

The first was look at any possible evidence for or against a particular case and assign a weak or strong label if possible. Then, for each mode a probability statement, *e.g.* 'Low', of this case being the cause of mission loss is also assigned. This is naturally subjective and represented a collective view. Only remaining failure modes with some evidence for them, and those which are 'unknown' are considered possible scenarios.

While it is not possible to define a most likely failure mode, it is very probable that failure occurred during entry, descent, and landing (EDL), or surface deployment. The following potential causes have been identified, and are not in a priority or probability order.

- Electronics too cold for start up after coast phase due to MLI damage during cruise
- Lander electronics malfunction and failure to operate one or more systems during EDL
- Excessive velocity during entry due to unusual atmospheric conditions

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Lessons Learnt

The atmospheric model needs to be updated during orbiter missions in order to prepare for future landed missions. Understanding of the Martian atmosphere is weak.

- Front heatshield break-up or aerodynamics corrupted leading to hypersonic failure
- Parachute envelopes airbags after first bounce leading to problems with bag release and deployment
- Airbags fail on impact, during subsequent bounces, or are punctured
- Thermal protection tiles detached from aeroshell during entry
- Parachute(s) inflation problems
- Airbag/gassing system leak at connection point resulting in incomplete inflation
- Airbag jettison failure or damage to lander as part of release process
- Damage to lid or clampband following impact of lander with ground, causing failure of release or deployment of lid and solar panels
- Antenna damaged on impact
- Return or forward link failure causing an unknown protocol problem, or random component failure.

A vast number of failure modes are possible, and only a limited subset have been identified by the team as being more probable than the remaining causes. The main results established from the broad and thorough investigation are therefore the lessons learned.

8. LESSONS LEARNED AND CONCLUSIONS

A large number of programmatic, design and technical lessons have been learnt from Beagle-2 which will need to be applied to future missions. The primary lesson is that a lander cannot be treated as an "instrument" *i.e.* as a payload addition to an orbiter. Appropriate priority to funding, schedule and resources must be considered, at system level, for lander elements in any future mission.

A 'lessons learned' report [3] was produced that captures in a fairly raw form the main lessons learned, contributed by a wide range of teams involved. These are categorised by mission or system aspect, *e.g.* software, operations, communications, AIV, *etc.* Some may be impractical given mission constraints. We also indicate which lessons were applied and were successful, and those that were derived from experience or hindsight, and were not applied to Beagle-2. Significant overlap can be seen between this 'LL' report, and the ESA Commission of Inquiry Recommendations [4]. Combining the lessons learned [3], with the Commission of Inquiry report [4], the B2 Mission Report [2], and including the governmental support inquiry findings [5], a comprehensive record is created of Beagle-2 that could be very valuable to future probe missions.

The Beagle-2 mission was known to carry high risk, but could have delivered an outstanding science package to the Martian surface. It is hoped that in contrast to the many reports and analysis outlined and referenced above, this paper highlights the lower-level technical actions and considerations of the teams responsible for designing and operating Europe's first lander.

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NOTE

Neither the Mission Report nor the Lessons Learned document are endorsed in any way by PPARC, by ESA, or by any organisation other than the engineering and flight operations teams involved. Conclusions and mistakes are our own.

Images: EADS Astrium (UK), Logica, European Space Agency, University of Leicester, and Malin Space Science Systems.