Beagle 2 on Mars – The Discovery Assessed

Principal Author:

Dr Jim Clemmet (Beagle 2 Chief Engineer)

Affiliation: Retired, previously of Astrium Ltd, Stevenage, (now Airbus Defence and Space UK)

Contact Address: 154 London Road, Biggleswade, Bedfordshire, SG18 8EH

Email address: jim.clemmet@ntlworld.com

ABSTRACT *(200 words)*

With no contact following landing on Christmas Day 2003, the Beagle 2 mission was declared lost February 2004. A glinting object seen in Mars Reconnaissance Orbiter HiRISE camera images has been identified as the Beagle 2 late 2014. This paper presents the evidence that the objects seen are indeed Beagle 2 through a series of evaluations of the objects identified on the surface.

How the hardware may appear on the surface is presented. Size, reflectivities, location and dispersion on the surface are compared with expectations and the natural terrain.

A virtual modelling technique has been developed to simulate the HiRISE images to enable determination of the state of deployment of the Lander.

Based upon the outcomes from these analyses, an impressive list of mission successes has been compiled together with the potential causes for the loss of the mission.

Although not possible to identify the cause for the loss of mission, these assessments provide strong evidence for Beagle 2 having reached the surface of Mars, releasing the Lander and deploying three of its solar panels and possibly all four.

Beagle 2 is the UK’s and Europe’s first mission to land onto the surface of another body in our Solar System.

Key Words

Beagle 2, Mars, Express, HiRISE, lander, discover

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Jim Clemmet[1], Mark Sims[2], Nick Higgett[3], Teodora Kuzmanova[3], Eric Tatham[3]

Derek Pullan[2], Jan-Peter Muller[4], John Bridges[5], Judith Pillinger[6]

[1] Beagle 2 Chief Engineer (Airbus Defence & Space)
[2] Space Research Centre, Dept. of Physics and Astronomy, University of Leicester, LE1 7RH
[3] Digital Design Lab, School of Design, De Montfort University, Leicester, LE1 9BH
[4] Mullard Space Science Laboratory, University College London, Surrey RH5 6NT
[5] Institute for Space and Earth Observation, Dept. of Physics and Astronomy, University of Leicester, LE1 7RH
[6] The Open University, School of Physical Sciences, Milton Keynes

1. Introduction*:* The Beagle 2 Mission

Following the discovery of the Beagle 2 Lander late 2014, just 5km from the centre of its last predicted landing ellipse on Mars (Ref. 1), it is of course necessary to understand why it is indeed Beagle 2. An evaluation of the objects identified on the surface has been conducted from an engineering perspective and the outcome can now be described with high confidence. The state of Beagle 2 hardware on the Martian terrain, the successes and the potential causes for the loss of the mission have been identified.

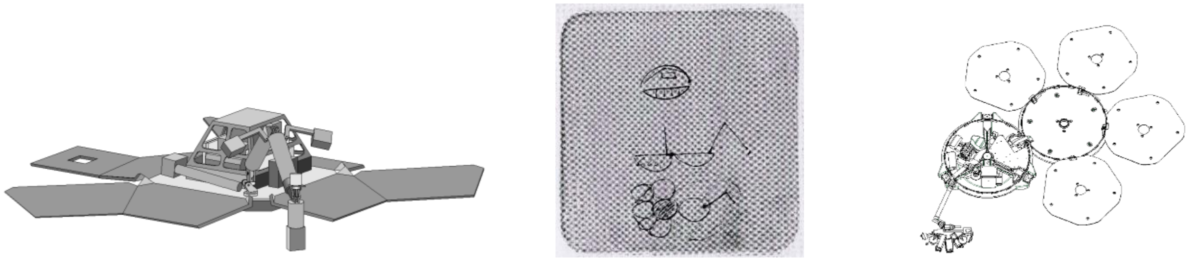
Launched in June 2nd 2003 on European Space Agency's Mars Express Orbiter, the UK's Beagle 2 is Europe's first Mars Lander project and the first controlled or otherwise to land onto the surface of another body in our Solar System.

In 1997 the late Professor Colin Pillinger from the Open University persuaded the European Space Agency (ESA) to include a lander in its Mars Express mission. Initially ESA provisioned 100kg but later reduced the allowable mass to just 60 kg. A revised Beagle 2 proposal was conceived and finally accepted by ESA in 1998 (Figure 1).

With Beagle 2 formally accepted as part of the Mars Express mission late 1999, a comprehensive engineering team was pulled together, led by Airbus Defence & Space, Stevenage. The University of Leicester co-ordinated the engineering of the overall science package and had responsibility for the flight operations and mission management. The Open University led the mission science and developed the critical GAP (Gas Analysis Package) instrument. Many UK academic groups and industrial companies contributed to Beagle 2, with specialist technology contributions from elsewhere in Europe and the USA.

Carrying a comprehensive world-class science package, the principal objective was to search for extinct life. Surface, sub-surface samples would have been analysed using GAP's miniaturized mass spectrometer. The complete science package would enable the study of organic, inorganic chemistry and mineralogy, the weathering, composition and age dating of rocks, the search for water and methane and the microscopic and multispectral imagery of the terrain. A suite of environment sensors were also included. All this within an 11.4kg payload, including the 5-axis robotic arm.

It was soon recognized that the original lander design configuration as proposed would not be viable. A new configuration for in-depth assessment was sketched on the back of a beer mat! This became the new baseline. The team had just a little more than 3½ years to design, build and test before delivering Beagle 2 to the launch site absolutely no later than February 2003. With a fixed launch window, June 2003, Mars Express would go with or without its passenger.



(a) The 1998 Lander (b) the Beer Mat (c) the 1999 Lander

Figure 1: Beagle 2 60kg Probe Lander Configuration

Beagle2 was successfully ejected from Mars Express on Dec. 19th 2003. All pre-ejection telemetry showed the probe to be in good health, with the exception of a fault in the hardware back-up clock.

Entry into the atmosphere was due in the early hours of Christmas Day, 25th December 2003. No Mars orbiting spacecraft was available to receive any signal during EDL. First data transmission from the surface was expected just a few hours after successful deployment of all solar panels, uncovering the antenna. No signal was received.

After four months and 24 attempts at communication, via NASA's Mars Odyssey and ESA's Mars Express orbiters, the lander was declared lost and unable to communicate with Earth.

The reasons for the loss remained unclear and, until late 2014, there was no knowledge of Beagle 2. An ESA enquiry (Ref. 2) placed emphasis on collision between the back cover and the main parachute, failure of the ultra-lightweight main parachute or failure of airbags and potential entanglement of the parachute and airbag during bounces. We now know none of these occurred. But lacking any information on the status of Beagle 2, it was not possible to eliminate any of the many potential causes.

The target landing site was in Isidis Planitia at 11.6° N, 90.74° E. The landing ellipse at 174 km x 106 km had an area of 14,500 km^2 posed a considerable challenge to any attempt to locate Beagle 2 hardware. Updates using mission data following the Mars Express launch and Beagle 2 separation events progressively reduced the size of the landing zone as uncertainties were removed. The revised ellipse at just 57km x 7.6km made the search a little easier

More than a decade after being declared lost, the discovery of Beagle 2 was announced on 16th January 2015. This find, at 11.52ºN, 90.43ºE, just 5km "upstream" of the centre of the last predicted landing ellipse, shows that the Entry, Descent and Landing (EDL) sequence for Beagle 2 worked. The lander did successfully touchdown on Mars on Christmas Day 2003 but it appears that it may not have fully deployed, preventing radio contact, although there is some limited evidence that suggests that deployment may have completed. Investigations are continuing.

2. Beagle2's Martian Descent and Deployment

The image below (Figure 2) shows the probe installed on the top floor of the Mars Express Orbiter (MEx). The small size of Beagle 2 is very evident. At just 68 kg, including the lander itself at 33kg, inclusive if the science 11kg payload, the Probe and Lander within were extremely compact and very challenging to first design and then assemble in the highly aseptic cleanroom at the Open University.

Six days after leaving MEx and 2.5 hours before reaching the top of the Martian atmosphere, Beagle 2 woke up automatically, booted up the Probe software ready to start the EDL sequence, Figure 3.

With the imposition of severe restraints on mass and volume, Beagle 2 was designed with no redundancy with the exception of the sensing accelerometers and the electric circuits for some hold-down and release devices.

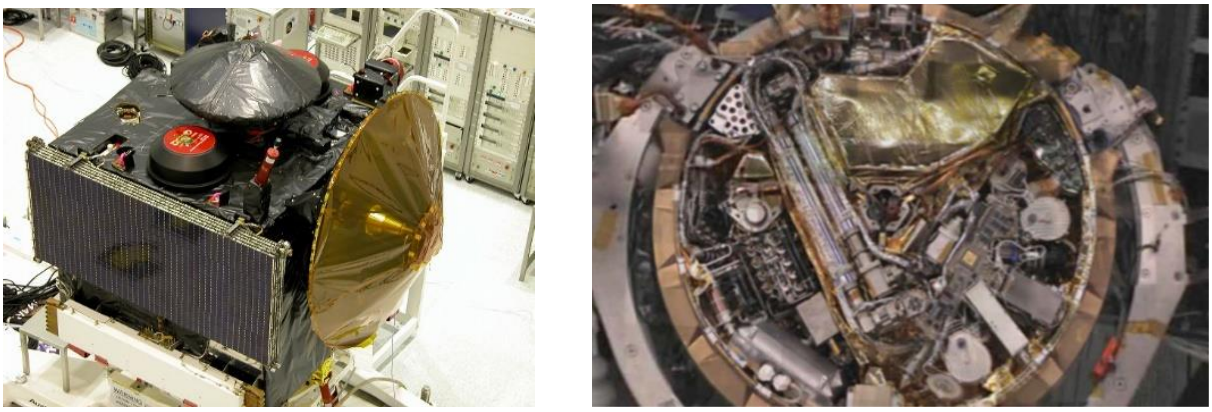


Figure 2: Beagle 2 On Mars Express Top Floor & the Lander Base Interior

The Probe entered the thin Martian atmosphere at an altitude of 120km with the correct entry angle, angle of attack and 14rpm spin rate, all set by Mars Express trajectory and orientation at the point of separation and Beagle 2's 3.5kg Spin-up and Ejection Mechanism. The combination of the aerothermal performance, pilot parachute and main parachute was designed to slow the lander down to first impact with the surface of Mars at 16 m/s in a little less than 5 minutes, under the control of the Probe software.

From Top of Atmosphere, the descent trajectory was planned with 3 main phases. The first is defined by the deceleration from 20,000 km/h with aerodynamic heating peaking at a temperature of 1700ºC. During this phase the probe was protected by its aeroshell front heatshield and back cover incorporating ablative tiling. Software continuously monitored the output from the 2 accelerometers to sense the deceleration profile and commanded the mortar to fire and deploy the 1.9m pilot chute. The speed decelerated from supersonic to subsonic values, and the aeroshell was then released from the lander, with the small pilot chute pulling back the rear cover. The momentum of the lander pulled out the 10m main chute and full inflation occurred a 2.6 km altitude, 340 km/h. The resulting drag separated the lander from the front shield. At approximately 280 m above the ground travelling at 16m/s, the landing sequence was initiated by the Radar Altimeter Trigger (RAT) sensing the Martian surface, leading to inflation of the airbag assembly, encapsulating the lander. First surface impact occurred minutes after main parachute inflation. The main chute was autonomously released by sensing this 200g shock and would collapse close to this point of impact.

The airbags continued to bounce along the descent trajectory, the distance depending on descent velocity, terrain characteristics, surface wind and airbag pressure. After detecting that Beagle 2 was stationary, the 3 segments comprising the 2m diameter airbag assembly were released simultaneously by the probe software and the lander fell to the surface to survive a 400g impact shock. The distance travelled by each segment depends upon their residual gas pressure and terrain topology and is predicted to be no more than 10m from the lander. Finally the Probe software released the lander clampband and central bolt before handing over to the Lander on-surface operations software.

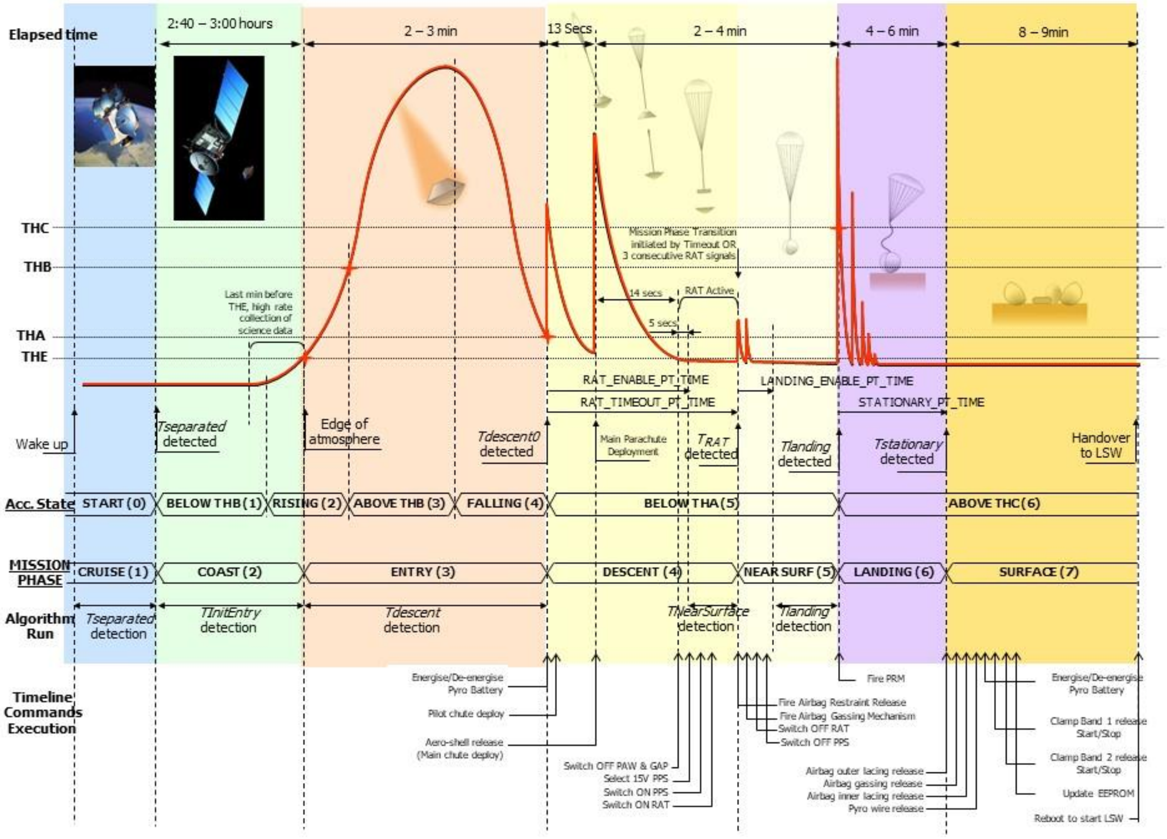


Figure 3: Entry, Descent and Landing Sequence for Beagle 2

The immediate task for the Lander software was to boot up and start in operating in the correct mode. The software then autonomously commanded deployment operations (Figure 4), starting with the lid hinge to open up the “clam shell”. On completion, the software would then command separation deployment of the stack of 4 solar panels.

The lander software commands the non-redundant deployment motor of each of the 4 solar panels, following a pre-defined sequence seen in Figure 4. Panel deployment is managed through a series of angle thresholds. Obstruction monitoring is initiated at 110°, followed by an illumination check at 130°. If this proves negative, deployment continues to a maximum initial deployment of 160°. If a panel fails to deploy to at least 130°, that deployment will timeout and the deployment of the next panel will be commanded. Failure to deploy at least beyond 90° would block an adjacent panel.

To transmit and receive signals, the UHF antenna embedded in the lid required all solar panels to deploy successfully. With Mars Express having a highly elliptical orbit and Beagle 2 only communicating through it once every four days, it was imperative that the antenna design would provide the necessary performance to communicate with the spacecraft at the orbital extremes. Heavily constrained by the allowable volume and mass, antenna designs configured into the lander base had been investigated but the required performance could only be achieved with the final antenna configuration.

This complete sequence from wake-up to readiness for surface operations is composed of 78 individual high level tasks, conditions and events. With many of these being multiples, for example the simultaneous release of 3 heatshield pyrotechnic release bolts and of the order of 8 high energy surface impacts, this approaches nearly 200 potential opportunities to induce failure.

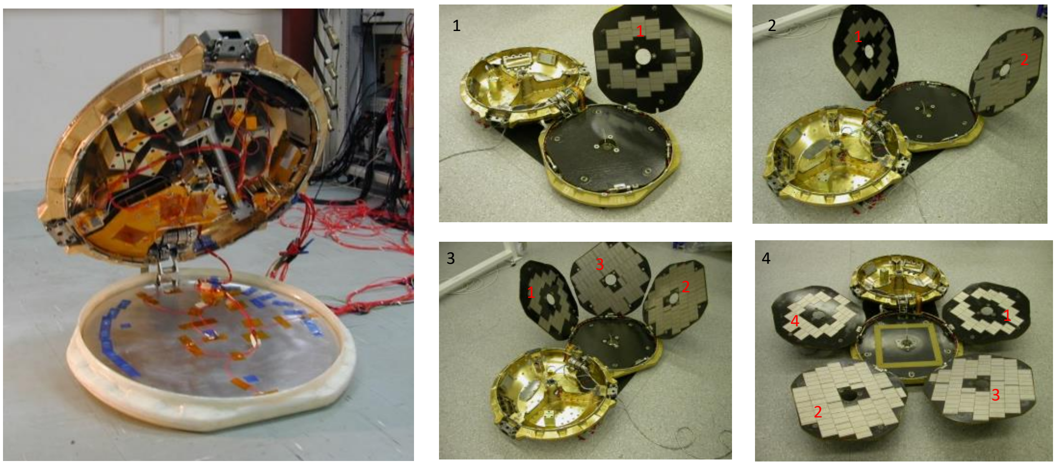


Figure 4: Beagle 2 Lander Deployments (Development Model)

3. Beagle 2 on the Surface of Mars

3.1. The Discovery of Beagle 2

A number of images across the updated landing ellipse had been acquired over time by the HiRISE camera on NASA’s Mars Reconnaissance Orbiter (MRO), (Figure 5). Since the loss of Beagle 2 many individuals had been scanning HiRISE images but without any joy. In 2014 Michael Croon, previously a part of ESA’s MEx operating team, recognised that there was a gap in the imaging of the landing ellipse and asked for a new image. Once available, Croon identified an unusual glint and requested an overlapping image. The glint was there again and Beagle 2 had been found (Ref.1). Subsequent evaluation lead to the announcement of the discovery of Beagle 2 on the surface of Mars in January 2015. The Beagle 2 Lander, the rear cover and the main parachute can be seen (Figure 6). With a HiRISE image comprised of a billion pixels, each of about 300mm and a fully deployed lander fitting inside a 1.8m diameter footprint, spotting Beagle2 was a remarkable discovery.

Zooming in on the Lander indicated the shape of the deployed lander with at least one solar panel deployed. Similarly the pilot parachute appeared to be attached to the rear shell. There was some uncertainty about the main parachute candidate and the front heatshield and airbags had not been located.

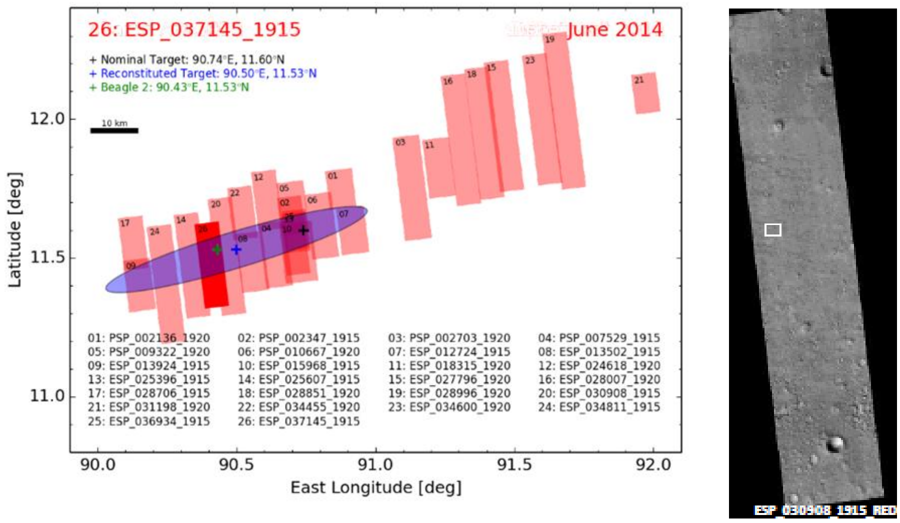


Figure 5: HiRISE Images: Updated Landing Ellipse & ESP_030908_1915

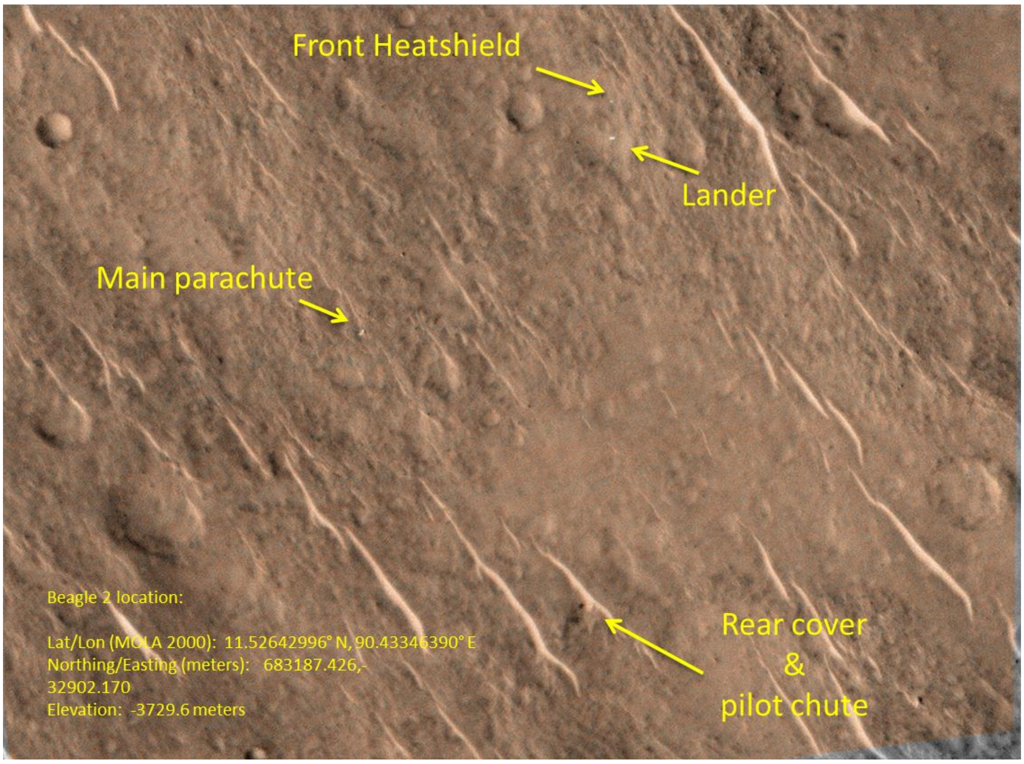
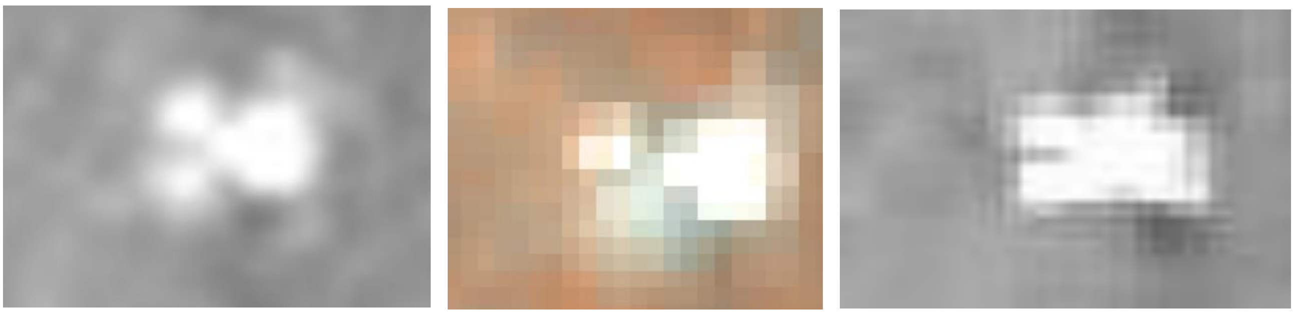


Figure 6: MRO HiRISE RGB image showing Beagle 2

Subsequently, more images have been taken by HiRISE consistent with these initial observations under different sun illumination conditions and variations in MRO relative position. These images have been analysed individually and in combination confirming that these objects are alien to Mars and have generated more detail of the shape and state of the objects of interest, including the front heatshield. The airbags have still not been located.

Initially two images were simply overlayed by The Jet Propulsion Laboratory (JPL) using geological reference features to give a better appreciation of the lander, Figure 7(a). Two other techniques have been used to combine images more rigorously to prove a better appreciation of the Lander. Figure 7(b) uses a process employed at JPL and is used to evaluate the state of NASA's hardware on Mars, including the Curiosity rover. Figure 7(c) is a super-high resolution image using methodology developed at University College London (UCL). The three outputs are consistent.



(a) 2 HiRISE Images overlayed (b) JPL (incl Colour) (c) University College London

Figure 7: Combined MRO HiRISE image showing Beagle 2 Lander

3.2. Description of Beagle 2 Hardware

To aid the interpretation of the HiRISE images it is important to understand how the hardware may appear on the Martian surface: size, colour and particularly reflectivity.

With a successful landing and deployment, any examination of orbiter images will be looking for four main objects: the lander itself, the main parachute, the back cover with the pilot chute attached and the front heatshield. Each may be sufficiently distinguishable from the natural terrain to make their discovery possible. The airbag segments, given their tan colour, present a much greater challenge.

Table 1 summarizes the relevant characteristics of these items, shown in Figures 8 to 12. In searching for Beagle 2, it should be noted that a typical dimension just 600mm to 900mm, just two or three HiRISE camera pixels. The footprint of a fully deployed lander fit a 1.8m diameter circle.

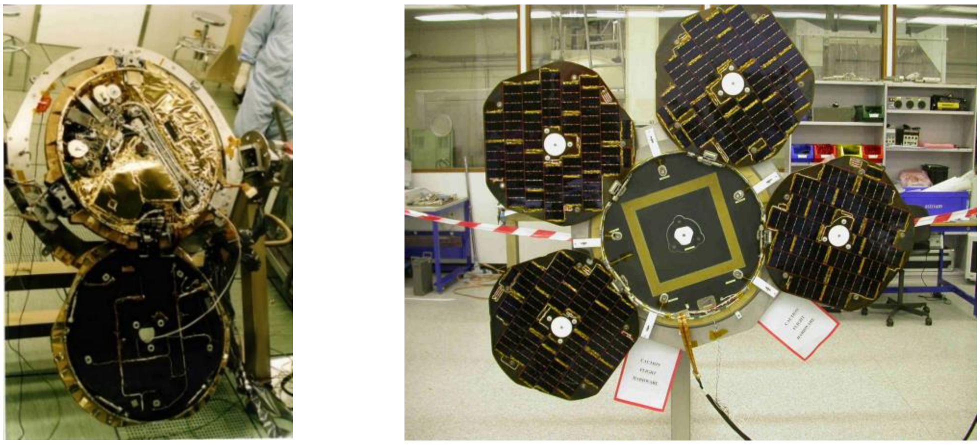


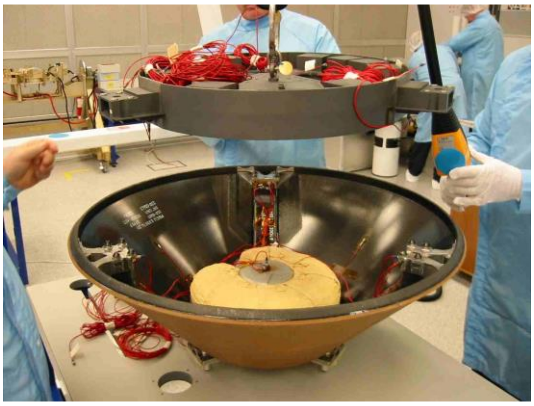
Figure 8: Lander and Solar Panel & Lid Assemblies

Figure 9: Main Parachute Structural Load and Drop Tests

Figure 10: Airbag Assembly

(a) Probe Ablative Tiling

(b) Front Heatshield with Internal MLI



(c) Interior View of Back Cover

Figure 11: Exterior and Interior Views of Aeroshell

Figure 12: Pilot Parachute on test (inflated by wind)

Item	Key Dimensions	Surface finishes	On-Surface Appearance
Lander Base	shallow bowl 660mm diameter and 80mm deep	GAP & Electronics : goldised kapton thermal blanket Robotic Arm & PAW: Aluminised tape & natural metal finish	once opened up: 2/3rd highly reflective specular finish 1/3rd diffuse surfaces.
Lander Lid	660mm diameter and 30mm deep,	Once solar panels deployed: Smooth resin rich carbon fibre composite with embedded antenna	reflective specular finish
Solar Panels Stowed in a stack in Lid, rear surface upper most	4 pentagon shaped solar panels nominally 570mm across	Front: 85% solar cell. Rear: resin rich carbon fibre composite (cfrp), bleed cloth texture imprinted during manufacture	Front: highly reflective specular glass finish Rear: shiny but more diffuse
Front Heatshield	shallow cone 930mm diameter and 225 mm deep	Exterior black kapton thermal control blanket. Expected to detach or burn up during entry. Exterior: ablative cork tiles Interior: aluminised kapton thermal blanket covering resin rich cfrp.	Exterior: non-reflective burnt/charred surface Interior: highly reflective specular surface.
Rear Cover	truncated cone , maximum diameter 930mm; length of 310mm.	Exterior blanket as front heatshield. Exterior: ablative cork tiles Interior: resin rich cfrp.	Exterior: non-reflective burnt surface. Interior: reflective specular finish
Pilot Parachute	inflated diameter 2m 8.5m strop and rigging.	white nylon fabric	Heavier weave, less translucent than the main parachute. Remains tethered to rear cover.
Main Parachute	10m diameter when fully inflated	white nylon fabric	Translucent Expected to collapse to 3 or 4m sized object.
Airbags	Each inflated segment has a length of 1930mm (airbag diameter) and 965mm	The outer layers of the airbag are constructed from a yellow/tan woven fabric with diffuse reflectivity	Airbag leak will result in collapse. Max 10m from Lander.

Table 1: Hardware Characteristics

4. Engineering assessment of the HiRISE images

4.1. Location

The entry and descent analysis was rerun using Mars Express flight dynamics data provided following the ejection of Beagle 2. Figure 13 presents the output of this work and shows Beagle 2, located through the HiRISE images, incredibly just 5km from the centre of the revised landing ellipse and 20km from the original target.

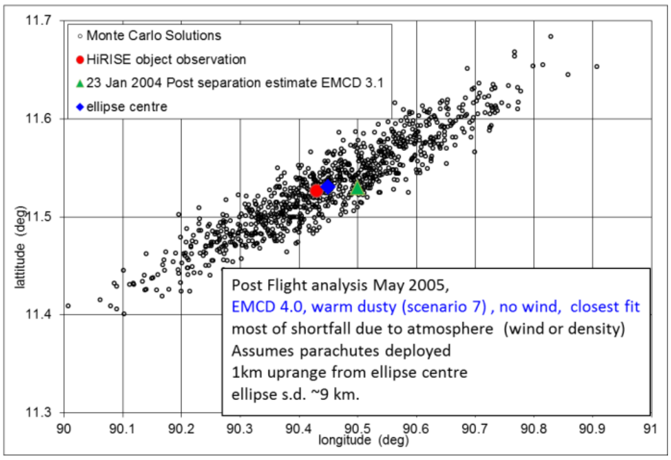
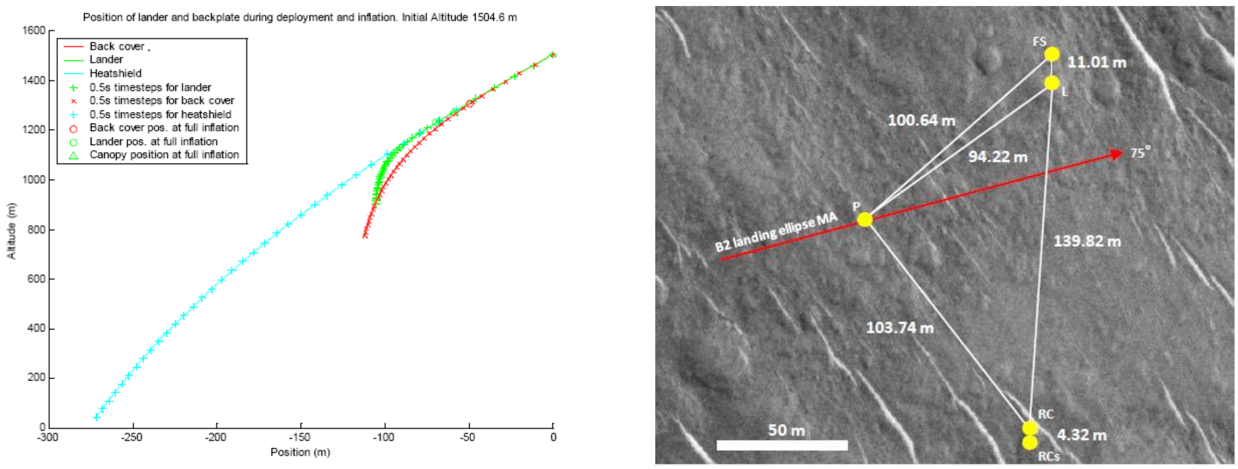


Figure 13: Location in updated Landing Ellipse (May 2005)

4.2. Dispersion of Hardware on the Martian Surface

Output from the analysis conducted to assess the potential for re-contacts between main parachute and back cover during the descent sequence, Figure 14, also provides an indication of the distribution of the hardware on the Martian surface.



(a) Recontact analysis (b) Distances between object on Mars surface

Figure 14: Dispersion of Hardware on Mars Surface

The analysis was only performed in the 2D plane of the landing ellipse major axis and stable behaviour had been assumed. Heatshield tumbling from high altitude, altitude sensitive cross-winds and residual spin during descent under parachutes and asymmetry in airbag bouncing can all result in deviations away from the nominal trajectories but have not been accounted for in these predictions. Some care in interpreting this data is necessary.

Referring to Figure 14(a), the distance between the first impact of the lander (nominal location of the main parachute) and the heatshield would be at most 160m, probably significantly less when accounting for instabilities. Measurements of the HiRISE image (Figure 14(b)) shows a distance of 100m between the first impact site (i.e. main parachute) and the front heatshield.

The back cover would be approximately 30m downstream from the lander first impact/main parachute site. The downstream distance of the back cover is approximately 44m but accompanied by a significant lateral drift under the pilot chute of 90m caused perhaps by high altitude winds. These separations compare well with the simplified predictions.

From a Monte Carlo analysis performed during the mission design phase, the final location of the lander, once the airbags have come to rest, may be in a wide range up to 600m further on from the site of first impact, cases 1 to 4 in Table 2. Beagle 2's arrival at Mars occurred not long after a late dust storm event which resulted in a reduced but not abnormal atmosphere density profile. Consequently, with key EDL events occurring at lower altitudes, the descent velocity under the main parachute may have been higher at first impact than the nominal prediction and, with the dust settling, the potential of low wind speeds, the descent trajectory may also have been more vertical. Variations in the distance travelled while bouncing may be represented for example by cases 5 to 8. Incomplete airbag inflation at first impact or high leakage would result in a lower damping factor (i.e. lower coefficient of restitution). Airbag leakage rates had led to the late introduction of the 10m parachute, a delay to airbag inflation and the RAT. Cases 4 and 7 in particular compare well with the measured separation of 94m in the HiRISE image, Figure 14b. This suggests a relatively low horizontal speed and a higher than nominal descent rate compared with the mean condition, consistent with post dust storm conditions.

Range of Travel from First Impact to Rest		case 1	case 2	case 3	case 4	case 5	case 6	case7	case 8	case 9
		mean	mean +2sigma	mean -2sigma	mean + low wind	warm/thin atmosphere + low wind				
descent rate at first impact	m/s	15.6	19.6	11.6	15.6	19.6	19.6	19.6	19.6	19
horizontal velocity at first impact	m/s	9.9	17.5	2.3	5.5	2.3	2.3	5.5	5.5	5.5
Kinetic Energy at first impact	kJ	8.2	16.5	3.3	6.5	9.3	9.3	9.9	9.9	9.4
airbag damping factor		65%	75%	55%	65%	65%	75%	65%	55%	62%
total bounce travel along surface	m	153	552	17	85	45	73	107	71	94

Table 2: Airbag/Lander: Range of Travel from First Impact to Rest

4.3. Spectral Analysis

A spectral analysis has been conducted of the Beagle 2 hardware candidates by the team at University College London, natural objects and local surface terrain found in the series of the HiRISE images of the Beagle 2 landing site. The HiRISE camera has Infrared, Red and Blue-Green channels only and IRB rather than RGB images have been recommended for this purpose by HiRISE.

To allow comparison, the analysis has also been repeated for NASA's Spirit and Opportunity Rovers, both having significant solar cell areas. A visual summary of the results from a well illuminated image of Beagle 2 is presented in Figure 15. Differences between the selected objects and the local surface are clear. Comparison of the Beagle 2 highly reflective elements and NASA's Opportunity rover show a similar decreasing Red:BlueGreen ratio characteristic relative to their adjacent terrains. Actual values may differ due to different latitude/longitude locations, atmospheric borne dust and seasonal lighting conditions. This characteristic is consistent with solar cells designed to absorb the red end of the spectrum. In contrast, a sunlit rock shows an increase in the red content.

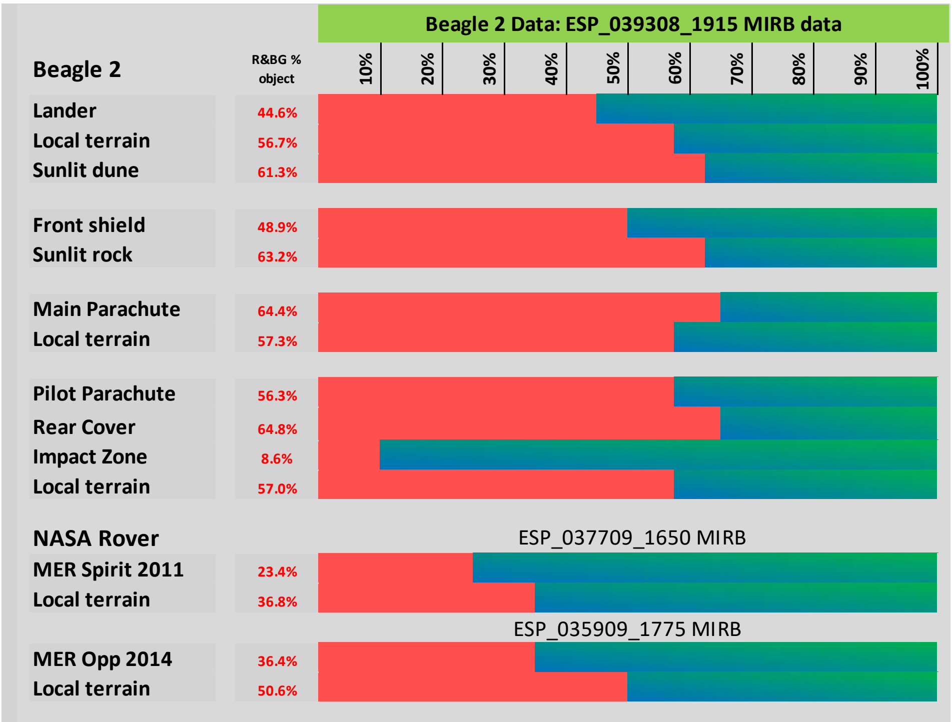


Figure 15: Comparative Red:BlueGreen Ratios of light reflected from Object Surfaces

The main parachute is also distinguishable from sunlit Martian rocks but with a larger relative increase in red content due to its high reflectivity (being white) of ambient light on Mars with its predominant red tinge noting that the parachute will also have accumulated wind borne dust on its smooth fabric surface. The tiled surface of the rear cover appears more alike to the main parachute while the tethered pilot parachute share R:BG ratio with its local terrain. This is not surprising since the HiRISE images show their movement across the terrain resulting in their smooth surfaces being contaminated by the Martian soil and dust. Both are very distinctive from the dark disturbed impact surface, which has a very low red content. The R:BG ratios for natural objects are common within the search region. The R:BG ratios for the more highly reflective and alien Beagle 2 and MER hardware are unique.

4.4. Lander Interpretation: Overlays of lander geometry

The Lander should be showing the base, lid and four solar panels each of the order of 2 HiRISE camera pixels width. With panels deployed to either 130° or 160° it is unlikely that all would be reflecting light towards HiRISE simultaneously, making it difficult to assess the exact state of deployment of the lander. Combining images of the lander taken under differing lighting conditions and from differing orbital locations allows for a better understanding to emerge, not simply from artificially creating higher resolutions but by combining those elements reflecting light on different occasions .

First assessments of both individual and combined HiRISE images give a strong indication of the lander with at least one or more solar panels deployed. The airbags separated, the lander fell to the surface, the airbags moved away to some extent and the clampband released. The Probe Software has handed over to the Lander Software and, following boot up, the main hinge successfully opened the lander and the solar panel stack released.

An outline of the Lander with various states of solar panel deployment has been overlaid on these resulting images. It is clear that with just one panel only fully deployed, there is no fit to the images.

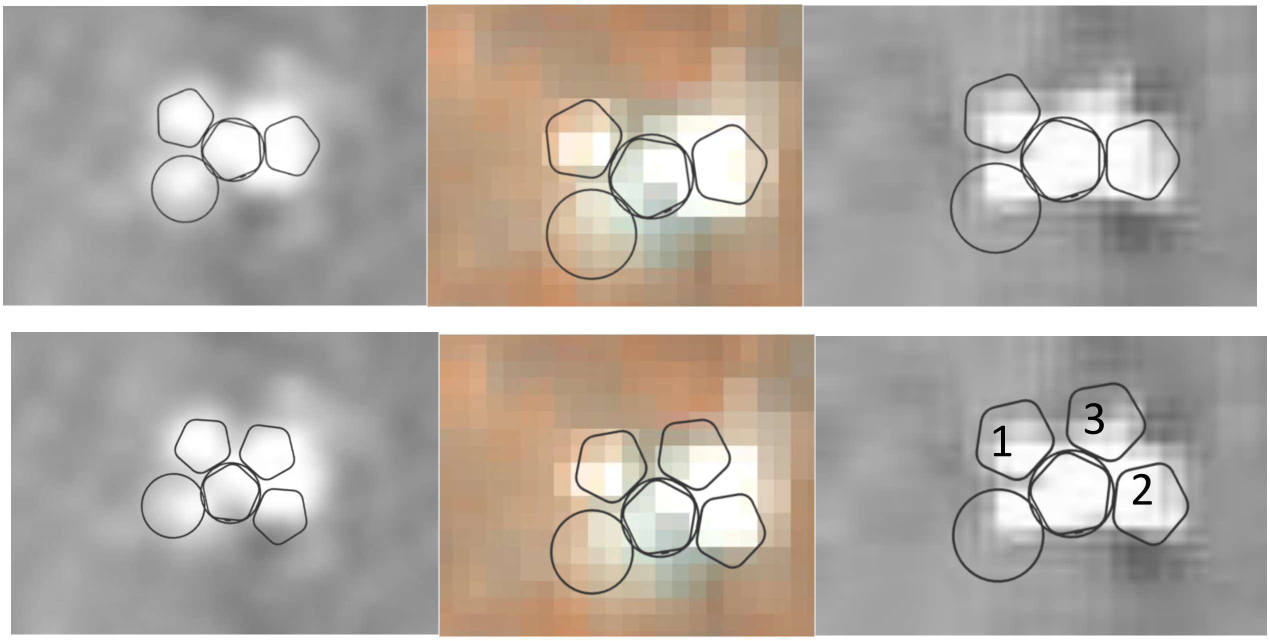


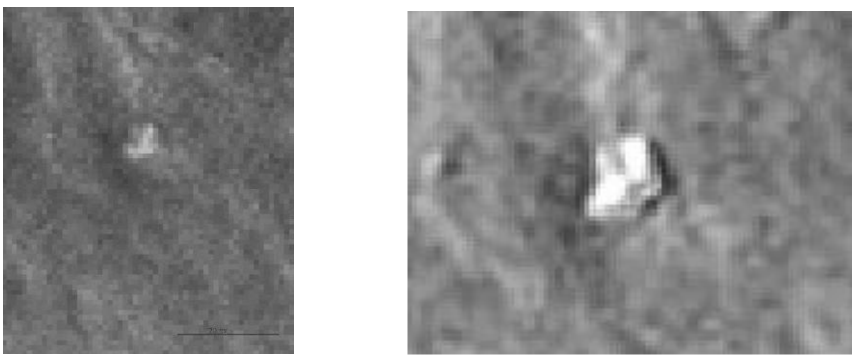
Figure 16: Early Lander outline overlays (2 and 3 solar panels deployed)

Figure 16 presents overlays of the lander with either 2 or 3 panels deployed. A partial deployment of the fourth panel cannot yet be ruled out even by lack of radio communication. An investigation of differing orientations of the lander has not resulted in viable fits. In positioning the lander base it should be noted that part of its surface near the lid hinge only will appear highly reflective (refer to Figure 8). Pixel saturation on the right hand side of the image could be induced by just the second panel only. Three solar panels deployed appears to provide a better overall interpretation than two but a firm conclusion is not possible from this exercise.

Whilst potential candidates for the three airbag segments have been identified in the vicinity of the lander, none have proven sufficiently distinguishable from the terrain at this time to warrant further comment.

4.5. *EDL Hardware Interpretation*

The main parachute is shown as a collection of bright pixels (Figure 17) with an irregular shape as expected. With dimensions of approximately 4m by 2m, the size is consistent with Earth drop tests.



(a) HiRISE image extract (b) UCL super resolution

Figure 17: Main Parachute on Mars

The front heatshield shows only as a small collection of bright pixels less than its 960mm diameter above the lander (Figure 18) and can only be distinguished under certain sun angle illumination conditions. This suggests that the shallow conical disc has come to rest with its exterior surface down. Only under certain combinations of sun angle and MRO orbital position will reflections from the heatshield's internal thermal blanket be captured by the HiRISE camera.

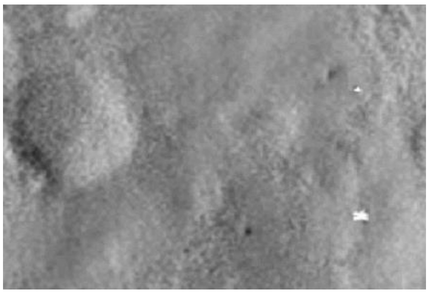
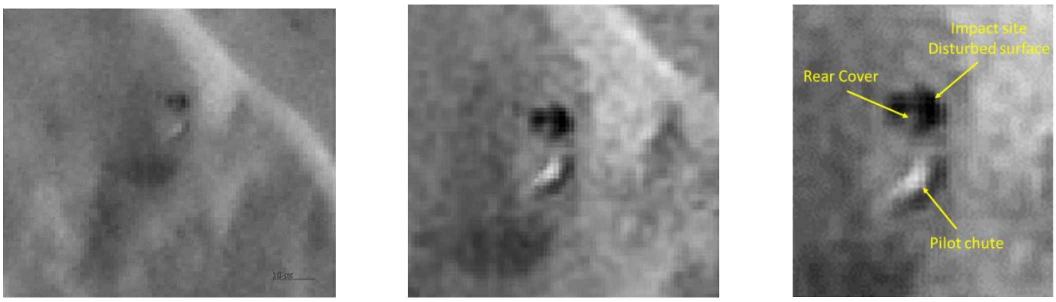


Figure 18: Front Heatshield above the Lander

Animations of EDL hardware and the Lander have been compiled and can be found via Ref 3. Generally these show the items under the differing illumination conditions associated with the HiRISE images.

Figure 19 shows a dark area with a small lighter object within the impact zone. Below this, a more reflective object can be seen about 4m away. The animation of these objects is particular interest showing both the reflective object moving across the surface with the smaller object moving within the dark patch. These are the pilot parachute and the rear cover respectively. The movement of the parachute across the Martian surface can only be due to surface winds. With the tether still in place, the rear cover is pulled across the disturbed surface of the impact zone. With the wind induced movements of the rear cover and the pilot chute, contaminating their surfaces with Martian dust, a similar R:BG ratio to that of the terrain as seen in the spectral analysis can be expected.



(a) HiRISE image extract (b) UCL super resolution (c) Object Identifications

Figure 19: Back Cover and tethered Pilot Parachute on Mars

4.6. Virtual Modelling

Based upon an idea from Sims, a technique has been developed at De Montfort University, Leicester to give a more objective interpretation of the lander and front heatshield images (Ref. 4).

This involves constructing virtual models of the lander and its front heatshield, based on CAD data, and incorporating associated surface reflectivities. The initial work assumed that the lander lid deployed through 180° and solar panels through to 160°. Subsequently an animated sequence was introduced to allow variations in lander lid and solar panel deployment state and numerous orientations of both lander and heatshield to be compared to selected MRO HiRISE image. The modelling simulates the specific view of the target in the HiRISE image, as seen along the camera boresight under the actual combination of sun illumination and orbital location conditions. Details of the work are to be presented in greater depth in the future.

Three HIRISE images with differing Sun azimuth illumination angles, ESP_030908_1915_RED (136.68°), ESP_039519_1915_RED (139.76°), ESP_044332_1915_RED (203.76°), have been selected for their variation in the appearance of the object surface reflections seen. Outputs from the virtual model are then compared to HiRISE images of the objects on the Martian terrain. A total of 11 lander simulated images covering 1, 2, 3 and 4 panels at 160° and 4 open at the 130° default angle have been compared to the 3 satellite images. A common solution for the lander configuration has then been sort consistent with all 3 HiRISE images and similarly for the front heatshield.

The virtual model provides strong evidence that the base is "south-west" of the lid and that it is tilted up at 12 degrees towards the "north-east", Figure 20. Other orientations do not result in successful matching. Figure 21 and Figure 22 present an example of the results for the lander with 3 solar panels deployed and the 4 panels at 130° case, respectively.

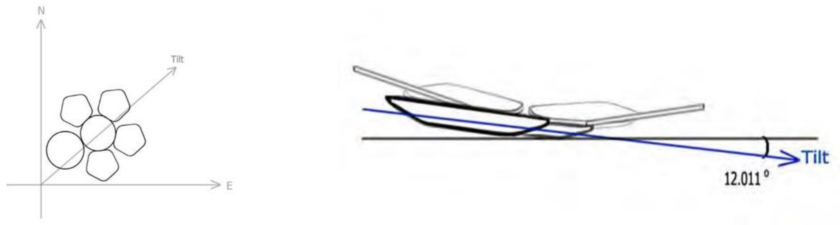


Figure 20: Lander Orientation on Mars Surface

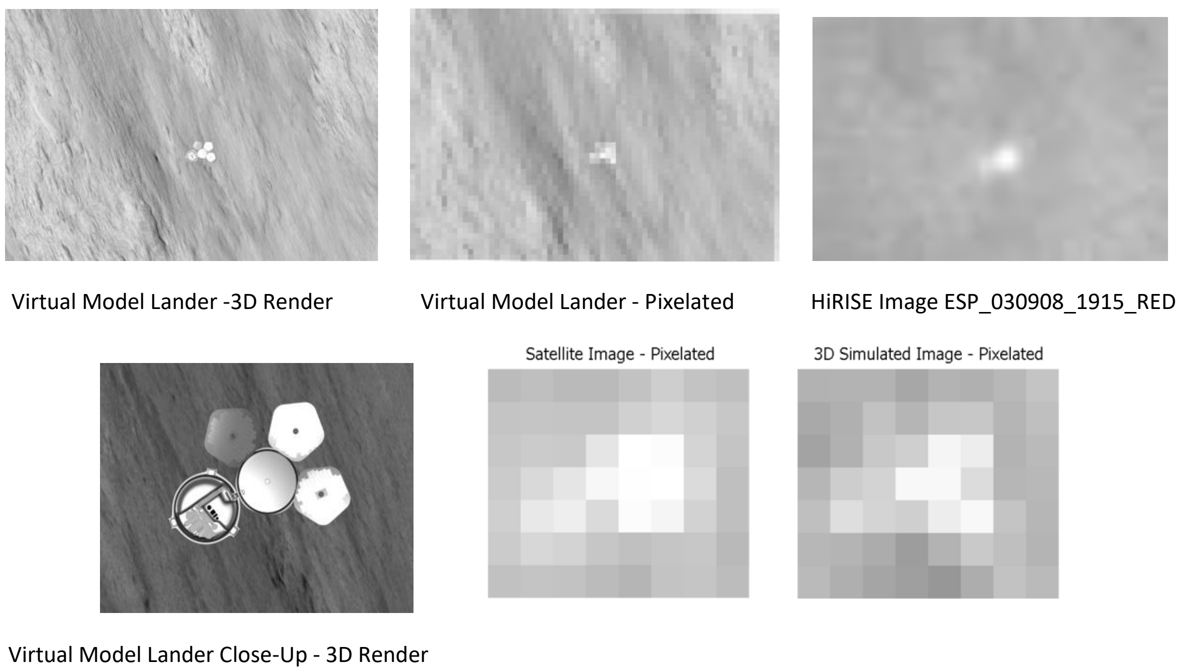
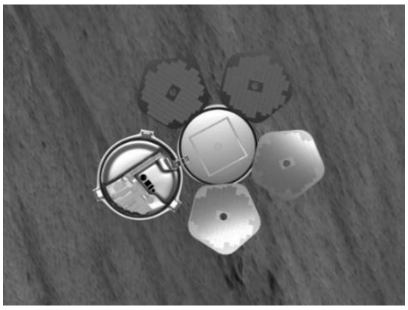
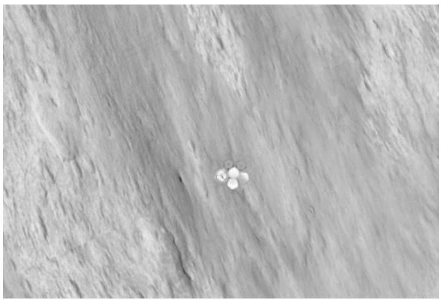


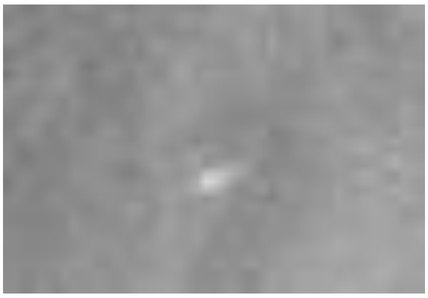
Figure 21: Comparison for Lander with 3 panels deployed:

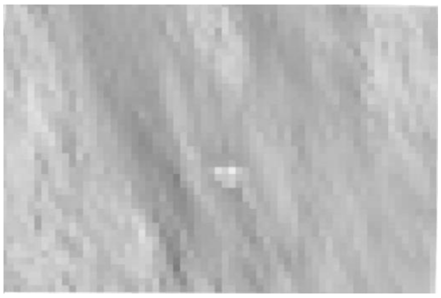
Virtual Model and HiRISE Image ESP_030908_1915_RED (136.68° Sun Angle)





Virtual Model Lander Close-Up Renders 203.76 ° Lander_203.76_RED_4_Pan_3D Render)





ESP_044332_1915_RED (203.76 °) Lander_Pan_203.76_Z_4_ RED_Pixelated

Figure 22: Virtual Model results for Lander with 4 panels deployed at 130°

Focusing on the area local to the target, the satellite and simulation images were normalized to give a maximum pixel value of 1. The similarity of the images was then compared using three approaches: correlation, the mean pixel value of a subtracted image (simulation image – satellite image) and finally the mean pixel value of a ratioed image (satellite image/simulation image).

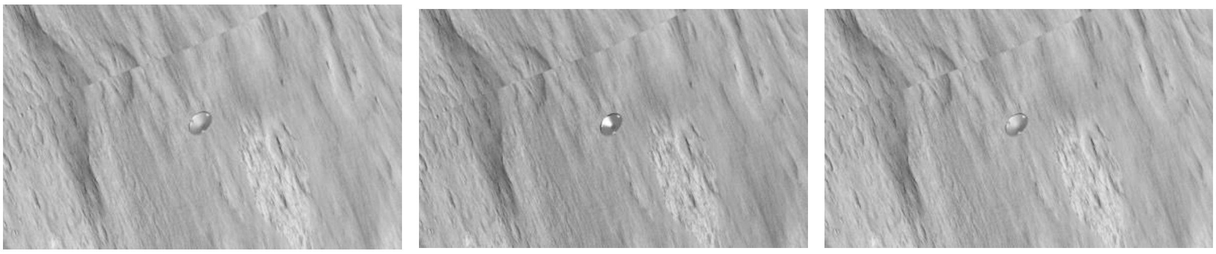
The results presented in Table 3 summarise the number of times each panel configuration provides the best match, across all tests. Also given is the average number of pixels included within the used image area in each case where that panel configuration was considered the best match. The most common results were configurations with 3 panel deployed at 160° and 4 panels at 130°.

Whilst a strong indication, it is not sufficient to be certain that solar panel 4 has deployed. Further images with higher value Sun azimuth values for improved illumination of panel 4 are required to provide confirmation.

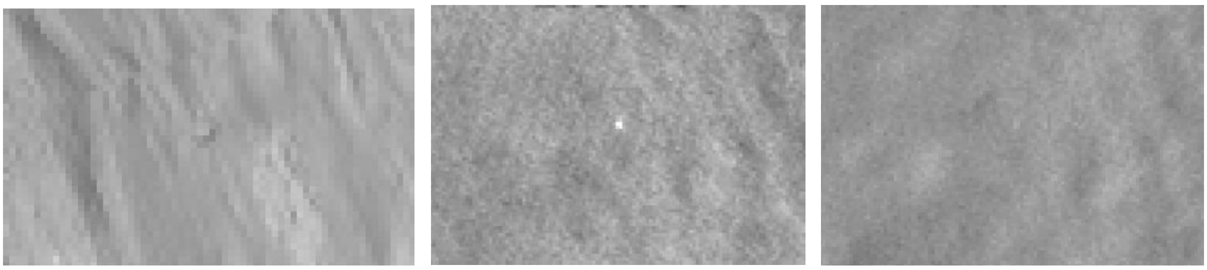
Panel configuration	$\mu_b + 3\sigma_b$		$\mu_b + 5\sigma_b$	
	Number of times most similar	Mean number of pixels	Number of times most similar	Mean number of pixels
1	1	12	2	8
2	0	-	0	-
3	4	20.25	3	18
4	1	12	0	-
4 at 130°	3	14	4	10.25

Table 3:Virtual Model results for the Beagle 2 Lander

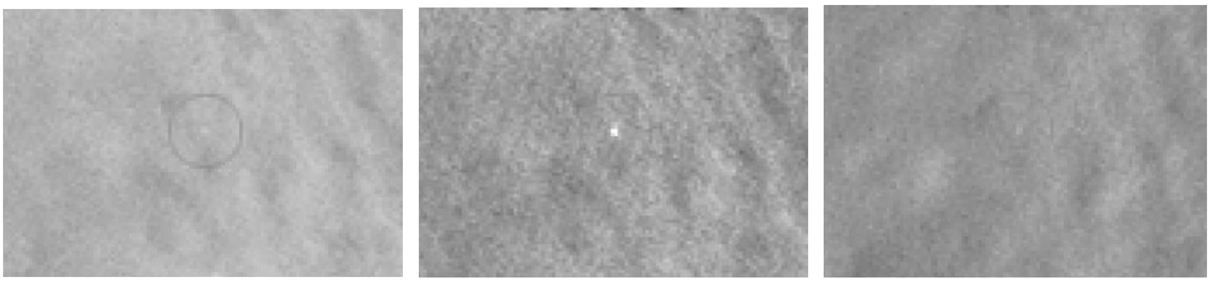
Figure ***23*** presents the results for the front heatshield, demonstrating that the inner thermal blanket is exposed and visible under limited illumination conditions. The orientation of the heatshield, concave face uppermost, is shown in Figure 24.



Front Shield Render _136.68° Front Shield Render _139.76 Front Shield Render _203.76



Front Shield _136.68_Pixelated Front Shield _139.76_Pixelated Front Shield _203.76_Pixelated



ESP_040363_1915_RED (136.68 deg) ESP_039519_1915_RED (139.76 deg) ESP_044332_1915_RED (203.76 deg)

Figure 23: Virtual Model results for Front Heatshield

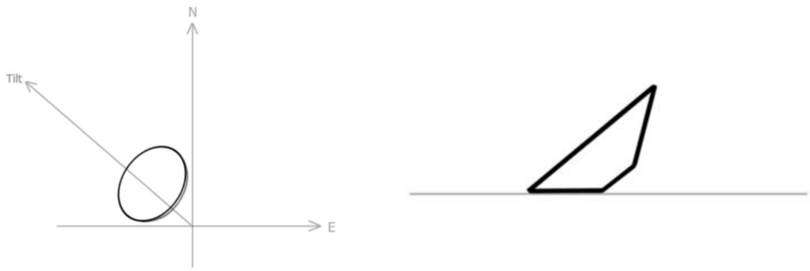


Figure 24: Front Heatshield Orientation on Mars Surface

5. Successes and Mission Loss Scenarios

Based upon the interpretation of the HiRISE images that three or four solar panel have deployed, an impressive number of successes can be identified. These include:

- The Beagle 2 spacecraft separated from the Mars Express spacecraft with the required stability, velocity, attitude and trajectory.
- The primary software based On-board Clock automatically woke up the computer and the Probe Software booted up and initiated correctly.

- The spin stabilized probe entered the atmosphere at the correct entry angle and with the correct angle of attack
- The aerothermal performance through the supersonic phase of descent was stable and provided the deceleration profile expected..
- The aeroshell front heatshield and back cover provided the required thermal protection and withstood the structural loadings of entry and descent.
- The pilot parachute deployed correctly, inflated and sustained the aerodynamics loadings, including through the transition to subsonic conditions.
- The front heatshield released, with all three pyrotechnic release bolts being cut simultaneously and separation took place without disruption to the stability of the probe.
- The lander and airbag assembly and the front heatshield separated from back cover, pulling out the main chute.
- The ultra-lightweight main parachute deployment and inflation completed and structural loads sustained; there was no re-contact with heatshield which moved ahead under its own momentum.
- Radar Altimeter sensed the Martian surface and triggered correctly leading to operation of the Airbag Gas Generator resulting in Airbag inflation prior to impact.
- Main parachute released at first impact with no re-contact with the bouncing airbag assembly.
- The accelerometer sensed coming to rest and the Airbag Gas Generator and Airbag releases initiated successfully.
- The three airbag segments moving away under the residual strain energy in the system, pulling the AGS clear.
- The clampband and central lid hold-down released permitting opening of the lander without hangup.
- All EDL non-redundant hardware, including electrical harnessing, and functions operated as intended.
- Redundant accelerometers operated and provided correct data for EDL control throughout this sequence of events.
- The central computer functioned correctly and the power system delivered the required power during the EDL phase.
- The Probe Software managed the Entry and Descent phase of the mission correctly, all algorithm control parameter values correct. Software updates during Cruise phase successful.
- The UHF transceiver baseband operated successfully during the Cruise phase, in support of checkout during the journey towards Mars, providing two way communication via Mars Express.
- All sensed temperatures and voltages during Cruise were nominal.
- Software updates and revisions to parameter values loaded during the cruise phase operated successfully.
- The Probe Software successfully performed the handover to the Lander Software for on-surface operations to commence.
- Lander Software booted up and initiated correctly following the handover from the Probe Software.
- Main Lid hinge operated, lifting either the lid or the heavier base, and opened the lander

sufficiently for solar panel deployment to occur.

- All solar panel hold-downs functioned and released the solar panel stack. Note that no one panel could deploy unless all hold-downs operated correctly with the fractured bolts withdrawing.
- Solar panel deployment proceeded, resulting with at least three panels deployed to the default angle or greater.
- Correct operation of the Lander Software solar panel control algorithm has been demonstrated.

The thermal analysis shows that the first night required 20Wh of battery self-heating (cold case) or ~0Wh for the hot case. These values increase to 26Wh and ~1Wh respectively for subsequent early nights. The electrical energy budget for the first day on the Martian surface shows that the lander should survive the first night even with no solar panels deployed. This is on the basis that the battery is at the expected 69% state of charge on completion of deployments. Energy level should have been adequate, provided that all operations consume nominal or near nominal demands.

So what may have gone wrong? Consideration of all mission phases from launch, through the near 7 months of Cruise, 6 days of Coast and the 8 minutes of Entry, Descent and Landing and On-surface deployments, identifies 78 high level functions or naturally occurring events. Many of these include multiples, for example the simultaneous release of the 3 heatshield bolt cutters or the 5 solar panel hold down mechanisms. But not all are so easily quantifiable, such as the numerous impacts of the airbags with the surface or the number of parts susceptible to damage by a single high shock event. This results in at least 188 identifiable opportunities for loss of the mission. Accepting the successes listed above and with 3 solar panels only deployed, these opportunities reduce to 24 relevant functions, tasks or events and at least 99 opportunities respectively that may have led to the incomplete solar panel deployment or other reason for communication failure (Table 4 and Table 5). The primary cause of failure is not necessarily to be found within the solar panel assembly or associated software or electrical system.

If all panels have in fact deployed, a number of these are no longer relevant, but others come into consideration, in particular those relating to operation of the RF section of the transceiver and viability of the antenna hardware. The possible listing of reasons for mission loss for this alternative scenario reduce to 21 relevant functions, tasks or events and 52 opportunities.

Examination of Table 4 suggests that a recurring cause during the eight month journey to the surface unsurprisingly relate to release events, either shock loads or hang-ups. But airbag performance is also a concern. This is not necessarily an equipment problem, i.e. leakage higher than expected, but simply under-inflation due to lack of time before first impact. This may be due to higher descent velocity or late triggering of the Airbag Gas Generator.

Item	Function/Tasks/Events	Possible Causes of Mission Loss	Applicability	
LAUNCH Phase			3 Panel	4 Panel
Launch Environment	vibration & shock loads	local damage prevent correct functional operations at later point in sequence	Y	Y
EDL: supersonic				
Battery reconfiguration for pyros	operate relay cycle (ARM On)	relay malfunction due to shock loads; setting reversed by shock loads removing protection to Central Electronics	Y	Y
PDD mortar	charge firing	high shock causes lander electronics component failure	Y	Y
EDL: subsonic				
front shield ARM	ARM bolt cutters	high shock causes lander electronics component failure	Y	Y
RAT & Airbags	inflate airbags	insufficient time: only partial AGS burst disc malfunction incorrect supply pressure high leakage	Y	Y
EDL surface: kinetic				
Atmosphere density profile	impact velocity	reduced design margins due to post dust storm atmosphere warmer temperature/lower density (not abnormal)	Y	Y
Airbags	survive impacts	high velocity (KE>1J), high 'g': structural failure; above nominal leakage reducing internal pressure/damping	Y	Y
Lander Structure & Mechanisms	survive impacts (200g)	high 'g': structural distortion	Y	Y
Lander Harness	survive impacts	high 'g': breakage	Y	Y
EDL surface: static				
Release devices	Airbag inner lacing release	lacing snags	Y	
	Pyro wire release cutter	wiring snags	Y	
	AGS/Airbag manifold quick release	release device fails, airbag segment(s) remain attached to lander	Y	
	airbag ejection	insufficient stored energy lacing hangup lander catapulted due to asymmetric residual airbag pressure	Y	
	AGS pulled clear	hangup: airbag insufficient energy to pull clear	Y	
Lander	survive drop to surface (400g)	high 'g': distortion of structure or actuators rock penetration - antenna damage	Y	Y
Clampband	clampband moves clear	hangup; local terrain	Y	
PSW	PSW/LSW hand over	time corrupted at PSW/LSW handover		Y

Table 4: Potential Causes of Mission Loss –Launch and EDL

On surface operations (Table 5) may have failed due to EDL or surface impact shocks up to 400g and again release events feature. But there are other more individual and unique possibilities such as loss of Lander On-Board Time or lack of power. Whilst an end-to end test of the communications system was conducted with both ESA's Mars Express and NASA's Odyssey Mars Orbiter systems, perhaps there was some unidentified design or implementation error.

Behind each there are numerous causes, some of which are listed. Each individual item may be assessed in depth but, unless communication contact can be established, it is unlikely that the actual cause, for example a broken wire or damaged coax cable, will ever be identified and others may yet be recognised.

Item	Function/Tasks/Events	Possible Causes of Mission Loss	Applicability	
Surface operation			3 Panel	4 Panel
Lander deploy't pots/sensors	survive impacts	wiring/sensor failure	Y	
	lid hinge motion	self-righting high 'g': breakage	Y	
Release devices	operate s/panel frangibolts	hangup due to loss of clearance	Y	
	cup cone seperations	cold weld	Y	
Battery configuration unified	operate relay cycle (ARM Off)	failed relay	Y	Y
Solar panel hinge actuators	panel hinge motion	local damage, harness failure; sensor failure; airbag obstruction	Y	
Battery	State of Charge	lower than predicted SoC at start of sequence; higher than expected demand for deployments, including Lid	Y	Y
Terrain	blockage	local terrain: rocks, partial burial of lander	Y	Y
LSW Comms control software	comms sessions management	incorrect design or coding error; software bug		Y
LSW loss of time	comms session timings	time corrupted at PSW/LSW handover Hard Rest causing processor clock rests to zero and reconstruction methodolgy not adequate (backup clock malfunction noted during cruise)		Y
Antenna	RF Cavity	loss of integrity (vib'n, impact, thermal cycles; multipaction in Mars atmosphere		Y
	Coax cables	loss of connection/continuity; damaged shielding; damaged by rock penetration		Y
Transceiver	baseband section	damaged by impact/s		Y
	RF section	electronics malfunction; internal software malfunction; damaged by impact/s		Y
	Diplexer	damaged by impact/s; multipaction in Mars atmosphere		Y

Table 5 Potential Causes of Mission Loss – Surface Operations

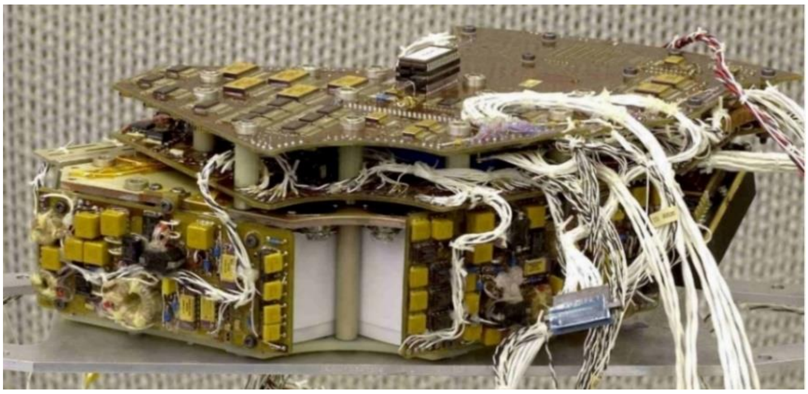


Figure 25: Electrical Assembly

(Incorporating Computer and Power PCBs, Transceiver and Battery)

The complex assembly of the lander electrical hardware is unconventional as can be seen in Figure 25. Whilst every consideration was given to this extremely compact design, including Paschen breakdown voltages, perhaps some undesired behaviour occurred during early operations or perhaps induced by the prevailing Martian atmospheric conditions.

But if all four panels have deployed and uncovered the antenna to an extent to allow communication, one particular candidate for mission failure deserving more attention is loss of time.

A fault in the hardware based back-up clock was found after launch but this required a hardware modification, and hence could not be corrected. In the event that Lander On-Board Time had been lost for whatever reason, transceiver communication session switch-ons would not have been synchronised with the orbiting spacecraft. The system design incorporated a back-up strategy to recover local time by using solar panel output to sense dawn and dusk. However the accuracy would depend upon the tilt vector of the lander base and the angle to which the panels deployed. The lander software also included two communication search modes. The second of these powers on the transceiver in near-continuous mode during daylight and intermittently during the Martian night, sending out the low power carrier signal whilst waiting for a hail. It is apparent that these strategies did not result in either recovery of LOBT or suucessful links with an orbiting spacecraft. But this may be as a consequence of constraints on orbiter operations.

6. Conclusion

Beagle 2 did not crash into the surface of Mars as some individuals have speculated. The Entry, Descent and Landing System worked from start to end. But the previous suggestion from the Beagle 2 project that the first impact may have been more severe due to a warm, less dense but not abnormal atmosphere or higher than expected airbag leakage leading to less damping on impact remain amongst the possible causes for mission loss.

The location of the candidate objects on the Martian terrain and their dispersion across the surface together with their characteristic Red:Blue ratios output by the spectral analysis provides conclusive evidence Beagle 2 successfully performed a ballistic atmospheric entry and controlled descent and landing.

Analysis of the numerous HiRISE images shows that the lander itself deployed but perhaps not fully, demonstrating that the Entry, Descent and Landing hardware functioned as required and that all probe software operated correctly.

The Lander software was initiated and correctly operated with regard to opening up the Lander and commanding and controlling solar panel deployments.

Individual HiRISE images and artificially created super-resolution images have provided a consistent impression of the hardware on the surface of Mars. The virtual modelling has provided a strong analysis of the state of the lander and with near certainty that three solar panels successfully deployed. The fate of the fourth panel is less definite but there is good indications that this also deployed to its default position.

More HiRISE images with different illumination conditions and at different orbital coverage may help in reducing the numbers of identified failure scenarios to something more manageable and may confirm full deployment on the Martian terrain. But until then or a future mission providing higher resolution photographs, it is unlikely that it will be possible to be more conclusive as to the cause of mission loss.

The reality is that even the very best images will only confirm the deployed state of the Lander. Unless we find a way to communicate with it, we will never know whether it is a broken wire, a structural distortion, a hang-up or a flat battery or one of the many other scenarios.

But what we do know is that Beagle 2 reached the surface and got frustratingly close to being able to conduct its highest quality science mission. An achievement of which all involved can be extremely proud. Beagle 2, a low cost mission, is the UK and Europe's first landing, controlled or otherwise, on another body in our solar system – not bad for the very first attempt.

And, finally, if the "loss of on-board time" scenario is the reality, if all four solar panels are deployed, if the battery still has sufficient capacity and if the lander has been able to maintain its health, could there yet be a way to rescue the mission?

Acknowledgements

The Beagle 2 Engineering Team, for their dedication, determination, professionalism and enthusiasm.

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And of course the late Professor Colin Pillinger for his enthusiasm, imagination, determination, interrogation and encouragement.

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Figures and Tables