Beagle-2: Lessons Learned and Management and Programmatics

Editor:
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Contents

Beagle 2 MARS

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Front cover image:	Flight configuration model of Beagle 2
Rear cover images top to bottom:	Flight Model Gas Analysis Package
	Flight Model Position Adjustable Workbench installed in Flight Model lander
	Flight Model Position Adjustable Workbench

Beagle 2 was the UK's first mission to another planet. The project was a partnership between the Open University, the University of Leicester and EADS Astrium (UK). Other funding partners included the European Space Agency (ESA), the Office of Science and Technology of the Department of Trade and Industry, the Particle Physics and Astronomy Research Council (PPARC), the Wellcome Trust, the National Space Centre and the Millennium Commission.

The National Space Centre, supported by the Millennium Commission with National Lottery funding, is the UK's largest attraction dedicated to the excitement of space. Co-founded by the University of Leicester and Leicester City Council; its other funding partners include, the East Midlands Development Agency and BT.

1. Introduction

Beagle 2 the UK led small lander on ESA's Mars Express failed to communicate after its entry, descent and landing of 25th December 2003. It is presumed to have failed during this critical mission phase. A full analysis of possible reasons for the failure is presented separately in the Beagle 2 Mission Report. Many lessons, a large number at a detailed technical design level were learnt from Beagle 2.

This document comments on the Beagle 2 management and programmatics in order to describe and clarify a number of issues and also lists those "lessons learned" with the latter compiled from inputs from the Beagle 2 Operations team as a result of test and operational experience.

The "lessons learned" have been split into logical sections; programmatics, assembly integration and verification etc. Where a lesson learned is applicable to another area for example mechanical design this is referenced. They include points where action was taken and ideas applied during the mission where they could be implemented without adding extra risk, these are marked by a tick in the "done" column. Unfortunately many "lessons learned" could not be implemented during the mission due to a lack of opportunity and resources. The "lessons learned" apply to any potential reflight of a small lander like Beagle 2 and most if not all lander missions to Mars (and elsewhere in many cases), some however are very specific to a "Beagle 2" type design and relate to detailed design issues and lessons from testing etc. and some will strike the reader as very obvious (some perhaps only in hindsight). These are however all included for a complete picture and a full record.

As can be seen many items have been noted and depending on mission constraints it may not be possible or even applicable to apply them to other missions. This long list does not imply however that the design for Beagle 2 was inadequate but rather highlights the routes and ways to improve and make a small lander most robust and to ease the load on any future lander teams in terms of designers, integration and test teams and operations staff. Beagle 2 was severely constrained by mass, volume and schedule and given adequate margins, time and resources many of these lessons would have been implemented on Beagle 2. We firmly believe that small Mars landers in the 60-130kg class are possible given innovative design and engineering, many of the lessons do not require the mass or volume to grow substantially if at all from the 68kg of Beagle 2.

It is important that the knowledge and experience gained from Beagle 2 is passed onto as many people as possible which is why this document has been produced. We hope the document may be of use to future missions and we wish them all success. Any errors within this document are the fault of the contributors and are unintentional.

The set of Lessons presented here were collated from inputs provided by the following:

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2. Beagle 2 Management and Programmatics

Introduction

It is very clear that Beagle 2 was a very challenging mission and only came to fruition because of the motivation and dedication of the team involved in the project. A very complex spacecraft had to be developed within tightly constrained mass limits, in a difficult programmatic environment and on a very rapid timescale.

The Beagle 2 project achieved the following, namely:

- An innovative integrated design
- World class, high return, low mass integrated instrumentation
- Advancement of planetary lander technology in Europe
- Pioneering of industry/academia collaboration
- Delivery of Beagle 2 on time to Mars Express for launch
- Successful Flight to Mars
- Release/ejection from Mars Express
- Unprecedented Public Interest

The following text describes the approach of Beagle 2 and is intended to clarify a number of issues raised elsewhere.

Beagle 2 Management

The Beagle 2 team from project start recognised the probe as a complex spacecraft in its own right, although it remained classified as an instrument by Mars Express in the same manner as the orbiter's other payloads. Mars Express was conceived with the lander being an option only. Consequently with Beagle 2 not being formally accepted as a part of the mission until less than three years before launch (December 2000), Mars Express and Beagle 2 did not comprise a single integrated project of two spacecraft. The Beagle 2 programmatic planning was consistently forced to meet the needs of Mars Express at the expense of its own requirements. It is therefore strongly recommended that any future combined orbiter and lander mission is managed and defined as a cohesive programme, with no part given less than equal priority.

It was always recognised that Beagle 2 was a "high risk" programme but one with the potential to provide world class scientific return. It should be noted that some programmatics and funding constraints resulted mainly in a risk on successful delivery rather than increased risks during the mission. The mission risks were minimised as much as possible given the mission constraints. It was also realised that development problems and solutions might increase the risks, however all efforts were made to minimise risk by first adopting rigorous analysis, followed by comprehensive testing where possible. The possible returns substantially outweighed the risks associated with planetary exploration.

We note that NASA have adopted a policy in MIDEX, Discovery and Mars Scout missions of delegating leadership for delivery of space missions to academic led consortia with NASA retaining oversight, although there are some moves away from this at the present. This previous NASA approach is in fact not very different from that adopted for Beagle 2.

From the start of the project Beagle 2 utilised industry expertise to ensure a viable technical design and management approach. Project management was only led from the University sector, during the feasibility studies, proposal and definition stages. Management for the probe was then transferred to industry for the subsequent development and hardware manufacture phases. Mission operational management was retained by academia.

Following proposal acceptance and initial kick off meetings in April 1999, an industrial project manager was appointed and tasked with development of the probe. The academic groups were responsible for provision of the instruments, science oversight of the design, planetary protection and PR (communications), and following launch, management of the operations.

At first industrial project management was shared with Astrium taking the more senior role; later a more conventional single prime contractor (Astrium) was in charge. In October 2000 following the Casani review, see below, industry was tasked with the complete management of the probe procurement under the control of the industrial project manager, which was further formalised via the "prime contractor" contract placed with Astrium following a cost review in June 2001.

A Beagle 2 Board consisting of high level representatives from the various consortium member organisations was formed at the request of BNSC in late 1999 to monitor technical progress, schedule and cost. The Beagle 2 project referred all key decisions concerning mission-critical cost and technical issues to the Board. ESA and OST were represented on the Board.

Beagle 2 relied on a system team with broad international experience (both US and Europe, both industrial and academic) to address the full range of technologies to design and build a planetary probe. Probe and lander system design was agreed on a collective basis using the advice of all the appropriate and available expertise.

A team culture was strongly fostered with openness and trust encouraged. With such a short time frame to design and develop a unique product care was taken to maintain engineering discipline and management. Standard tools for programme management were employed, typical of those used by Astrium for all its successful spacecraft prime contracts. Many members of the project core team individually had between 15 and 40 years experience in space projects.

Beagle 2 gave ESA full technical visibility of the project through fortnightly management and system engineering meetings and project reviews including internal design reviews as required which were attended by the ESA lander manager who made many valuable contributions to the programme. From 2000, ESA was tasked by BNSC to act as technical advisor on their behalf. In this role, ESA's responsibility was to provide a technical audit of the complete Beagle 2 design and was not confined to simply ensuring that the probe did not jeopardise the success of ESA's own Mars Express orbiter mission. BNSC also attended team meetings and reviews as and when they deemed necessary. Beagle 2 provided all inputs (written and verbal) as requested by ESA and BNSC. At one point ESA was offered the opportunity to take full responsibility for the EDLS (Entry Descent and Landing System).

The Beagle 2 project team responded positively to all those recommendations within its remit from the Casani review (instigated by ESA) in September 2000. These recommendations were translated into actions by the Beagle 2 team. These actions were tracked, with their status regularly reported to ESA and discussed at project management meetings attended by ESA (6 issues of the response summary document were produced and provided). Much was gained by implementing many of the Casani review's recommendations. However the fundamental difficulty associated with the mass and volume constraints remained with no relief being provided by Mars Express.

Beagle 2 was required to fit within a tightly constrained mass and volume limit. Consequently only very limited margins within the project were possible, forcing Beagle 2 to adopt innovative solutions to try and ensure a robust as possible probe design. The entire mass allocated to Beagle 2 was treated as one entity with all members of the project assisting whenever a problem required a consideration of mass allocation. Beagle 2 was initially capped to a mass budget of 60kg ejected mass with a residual mass of 3kg remaining on Mars Express; when a formal request was made (August 2002) to increase this to 69 kg + 5kg no decision was taken by the project, although ESA and BNSC had formally agreed (2001) that a mass of 71kg was acceptable. The Beagle 2 design team were always continually battling throughout the programme to control mass, not knowing whether it would be accepted for launch. The probe mass was eventually only accepted after delivery when it weighed 68.9kg + 4.9kg (March 2003). Under the circumstances any other mass requests were impossible. It is worth noting that the on-surface lander mass was very much as originally conceived, nearly all mass growth occurred in the EDLS, primarily due to the airbags/gasbags.

Beagle 2 Programmatics and Testing

Beagle 2 established a structured development plan. In fact ESA complemented Beagle 2 on its Design, Development and Verification Plan, citing it as an example for the future. Changes to the original plan deemed necessary due to cash flow constraints (through incomplete financing) and escalation in cost (largely related to airbags, parachute redesign and assembly, planetary protection, integration and verification issues) caused the development plan to be revised. Revised plans were consistently reviewed and agreed with ESA prior to implementation.

Given development, schedule and funding problems some key tests originally planned by the Beagle 2 team e.g. lander drop test, and pilot chute ejection and aeroshell release pyrotechnic-shock tests had to be deleted. Priority was given to mission critical key developments, (main parachute, airbags/gasbags, electronics, software), and to the completion of the assembly and test programme. Shock tests were carried out on Beagle 2 components however this was part of the formal mechanical qualification (a functional test before and after) and not under operational conditions. Some shock tests were at higher loads than required because they were completed prior to final revision of the EDLS design (more efficient parachute, final airbag/gasbag design etc.).

The Beagle 2 team fully agree that more testing would have been valuable and would be keen to carry out such a future test programme with appropriate hardware to eliminate uncertainties in developing future lander systems.

Beagle 2 initiated the design of a low mass Entry, Descent and Landing (EDL) telemetry system that would have allowed tracking of the entry and descent until aeroshell release and main parachute inflation, in order to obtain information on some of the key critical events during EDL, much as was done for NASA's Mars Exploration Rovers (MERs) (although their system allowed tracking throughout the whole sequence). A simple breadboard of the proposed system was built and tested. The scheme was not progressed once the Beagle 2 project were advised by ESA that no asset (ground or space based) could be made available to receive such signals. Mass and volume constraints prohibited a system that would have worked throughout the whole EDL sequence.

A high altitude test of the parachute system was considered by the project but not taken forward. The test and qualification approach used for Beagle 2, followed that adopted for several NASA programmes. The extremely high cost of a realistic test (and ultimately schedule limitations) was also a deciding factor. Instead the main parachute was tested at low altitudes using coated fabric to simulate the effects of low pressures on Mars and via extensive mechanical load tests. The pilot chute has Huygens heritage. Some aspects of the Huygens parachute system were tested at high altitude.

US suppliers for critical components (in particular for the entry, descent and landing system) were selected by Beagle 2 to provide maximum use of existing world-wide expertise.

US International Traffic in Arms Regulations (ITAR) and Intellectual Property Rights (IPR) issues however prevented complete oversight of the probe design by the whole Beagle 2 team, particularly on issues relating to the EDLS, the airbags/gasbags, and their gassing system, the pilot parachute and its deployment device. Not until after the Martin-Baker Aircraft Company withdrew from the programme and contracts novated (moved) to Astrium, with subsequent changes in export licenses and ITAR agreements, did Astrium Ltd have full visibility of the detail of these key subsystems and equipment. The Open University was also granted limited visibility during AIV because of their role in planetary protection. This limited oversight of various key issues.

The Beagle 2 Airbags/Gasbags

ILC Dover, who provided the airbags/gasbags for Beagle 2, produced the airbags for Pathfinder and the MER Missions; all these missions using airbags/gasbags have been successful. The same manufacturing and materials technologies were employed for Beagle 2. The successful US technology was however developed for larger landers. Whilst the construction principles were retained for Beagle 2, the actual design is functionally unique and of mainly of UK origin.

The project team believe that the withdraw of the Martin-Baker Aircraft Company (M-BA), from the project in June 2001 although unfortunate, was not of critical significance. The contribution of M-BA to the initial stages of the project is recognised and appreciated. Members of the M-BA Beagle2 team were retained by Astrium as consultants throughout the rest of the assembly, integration and verification programme to ensure transfer of the technology. The M-BA EDLS team leader availability was restricted by M-BA to the end of 2001. M-BA (EDLS) management personnel were excluded from these arrangements by M-BA. Astrium appointed its own EDLS manager following the withdrawal of M-BA, the individual selected has exceptional experience of the space industry, at one time being Engineering Director at BAe Space Systems (now part of Astrium) and having an aerothermodynamics background.

After airbag/gasbag test failures, caused by design specification and development problems, the operational regime for the airbags/gasbags was revised by Astrium. A delay in inflation was introduced to overcome concerns on leak rate and material chemical reaction with the inflation gas. A reduced impact velocity was also defined, allowing a lower inflation pressure to avoid overpressurisation failure. Design detail remained unaffected and the need to introduce new technology or yet more mass growth was avoided. Flight of the original design would have likely led to mission failure. These changes brought the airbag/gasbag operational scenario closer to that of Pathfinder and MER.

Further efforts to make the airbags/gasbags more robust required a large incremental change in mass and volume to accommodate an additional protection layer in the airbag/gasbag structure. This was not feasible within the mission constraints.

Beagle 2 acknowledges that the airbag/gasbag test programme was limited by access to and the cost of US test facilities (none were available in Europe). A series of ten tests were carried out with the airbag/gasbag design. As tests were performed in each case the data from earlier tests were fed back into the programme; the final four tests, reflecting the revised operational scenario, were deemed successful. ESA were provided with all the results but declined an opportunity to view film of the tests because of ITAR concerns. More comprehensive testing could have been achieved with an earlier start to the programme.

The Beagle2 New Main Parachute

It should first be noted that no fault was found with the original main parachute design from M-BA. The purpose of the new main parachute was to provide a reduced impact velocity to promote an environment in which the airbag/gasbag system was more likely to function correctly and survive. The new parachute reduced the terminal descent velocity such that the vertical kinetic energy in the system was reduced to a little more than 60% of the original.

To achieve this in the very short timescale available (April to October 2002), a highly specialised team of renowned parachute experts from Europe and the USA was formed under a dedicated experienced programme manager from Astrium. The team was collocated offsite to maximise focus and communication. The resulting parachute design met all of its specified requirements. Authority to manufacture of the flight hardware was only given after a Critical Design Review where the detail design and development test results were interrogated.

We would like to take this opportunity to commend the new main parachute design and development team for their outstanding contribution to the Beagle 2 project.

Lander Assembly Integration and Verification

Lander Assembly Integration and Verification (AIV) presented new managerial and technical challenges, unique to Beagle 2. The United Nations COSPAR planetary protection agreement requires protection of planets from biological contamination from Earth. Mars is no exception to this but in addition it was imperative that Beagle 2 was also clean of dead biological matter, not just sterilised, if it was not to jeopardise its own science objective of finding life on Mars.

The planetary protection aspects of Beagle 2 were managed by an experienced manager recruited from the medical devices and pharmaceutical industry. Planetary protection was overseen by a committee appointed by the Royal Society, the then signatory of the COSPAR regulations.

This required the design, build and commissioning of a special cleanroom, the Aseptic Assembly Facility (AAF) (at the Open University), and associated working practices. The Beagle 2 assembly team were subjected to special training and health screening. A particular constraint was imposed limiting the number of personnel within the area at any time to no more than four in order to meet the planetary protection requirements.

An interesting example issue that spans systems design and assembly, integration, and verification (AIV) is that of connectors. Mass, and, more particularly, volume constraints within Beagle 2 forced a strategy of reduction of the number connectors internal to the lander. The approach adopted was to minimise the number of connectors by use of solder joint connections whether possible, complicating and extending the build time of the lander electronics. Additional connectors were justified on a case-by-case basis. This occurred to aid AIV in the AAF and to allow remote calibration of the instruments following initial testing of interfaces after an initial integration. All pyrotechnics requiring standard initiators utilised connectors to normal ESA standards.

With only limited time to assemble and verify the build of the Beagle 2 probe (October 2002 to January 2003), careful management was imperative. Working two shifts, seven days per week, required focussed team leadership, clear roles and responsibilities, good communication, clear direction and comprehensive record keeping.

Regular project management meetings were maintained, with ESA and BNSC participation to maintain full visibility to progress and problems. Key reviews were implemented at 'points of no return', e.g. closure of lander lid, closure of aeroshell prior to shipment to acceptance vibration test and shipment to Mars Express at Baikonur, the launch site. The final two reviews were for Flight Acceptance and Planetary Protection – both were successful, with no significant outstanding actions. All these reviews were attended by BNSC and ESA representatives.

Operations

Beagle 2 was flown successfully from launch through to ejection from Mars Express by a combined academic and industrial team. Operations were supported at ESOC during the cruise checkouts with the UK operations centres and teams monitoring the activities and providing support. The post landing search was co-ordinated by the team at the Lander Operations Control Centre (LOCC) at the University of Leicester's facilities at the National Space Centre (a Millennium Commission Landmark Project) in Leicester.

Although operations funding was not available until 14 months prior to launch the operations system was developed and tested at both UK centres (LOCC at Leicester and the Lander Operations Planning Centre (LOPC) at the Open University) prior to launch, although continuing development of the ground system occurred through to ejection. An integral part of the operations was the availability of a Ground Test Model, a full working set of avionics along with critical lander mechanisms (hinge, solar panels, instrument arm) which allowed testing of all operational sequences prior to committing them to the flight probe and preparation of instrument operational sequences planned for post-landing at the LOPC by the instrument science teams (in conjunction with the LOCC).

Summary

The Beagle 2 project was internally managed to high professional standards under severe interface, schedule and financing constraints. Some critical decisions were forced upon the programme due to lack of time to undertake technically preferred tests, following lack of sufficient early funding, however all systems were tested. It should be noted that between formal programme start in early 1999 and June 2001 only 19% of the work was completed due to this, leaving just 20 months to delivery to Mars Express. The operations and ground system were developed successfully under similar schedule and funding pressures.

Beagle 2 was delivered on time to the launch site, being shipped out with Mars Express and was operated successfully throughout the cruise phase to Mars.

3. Lessons Learned: Programmatics (PR)

The **Programmatics** section deals with all aspects of programmatics from concept through to operations.

Ref	Details	Done	Also relevant
PR-01	A Lander is not an Instrument and cannot be treated as such. It is a spacecraft the mission design and constraints should recognise this and landing should have priority if a lander is included.		
PR-02	Build avionics as early as possible in order to validate all interfaces. Ensure sufficient programme resources are in place to achieve this. Ensure early prototype is produced for system design validation.		
PR-03	Have sufficient money at start to go ahead at near full speed avoid the “do it in spare time” syndrome		
PR-04	Start ground segment planning and funding in parallel with s/c build *i.e.* do not think of ground segment as an afterthought. It is an integral part of the system.		Ground Segment
PR-05	Ensure sufficient Operational Staff to avoid overloading one or more key individuals.		Operations
PR-06	Ensure missions and operations rehearsals are identified and planned within the programmatics.	✓	Operations
PR-07	Fully test the communications flight hardware with the all orbiters’ flight hardware before launch.	✓	Communications AIV
PR-08	Ensure Planetary Protection (sterility) is recognised as a System issue (cost, technical and schedule)	✓	
PR-09	SGICD construction should involve software developers from the start.		Onboard Software
PR-10	Plan operations contingency recovery scenarios prior to launch and test as many as possible ideally prior to launch.		
PR-11	Ensure industrial contractor expertise exists within operational team.	✓	Operations
PR-12	Run all coordinated operations (ground, orbiters, *etc.*) in one time system - UTC	✓	Operations
PR-13	Surface operations need to be planned in LTST and correlated to UTC.	✓	Operations
PR-14	Conduct operational science simulations ideally prior to launch.		Operations
PR-15	Ensure trajectory and landing time consistent with visibility of site by Earth-based assets or position/acquire/hire Earth-based or Mars Orbiting assets to ensure this.		
PR-16	Ensure evaluation of all hazards including instrument hazards is done early to avoid problems *e.g.* descope of Mössbauer source on Beagle 2 close to delivery because of unexpected components in emission spectrum.		AIV
PR-17	Conduct EMC tests early and understand emission spectra to avoid interference problems with transceiver. Note: EMC gauze bag used to overcome this problem on Beagle 2.		AIV
PR-18	Test sampling tools with representative samples as early as possible to define operational requirements and possible limitations.	✓	
PR-19	Ensure a detailed search strategy is in place prior to landing, including capabilities and availability of all assets known well in advance.		Operations
PR-20	Ensure that ejection and post-ejection images are available.	✓	

Ref	Details	Done	Also relevant
PR-21	Ensure analysis of ejection and post-ejection images is done rapidly including measurement of velocity, spin and correlation of direction with star images.		Mechanical Design (spin measurement by markings /targets)
PR-22	Ensure colour and optical properties of probe components are well known for any search and consider where possible forcing properties for high contrast *etc.* for location.		Mechanical and Thermal Design
PR-23	Ensure full radiation hardness audit is conducted and that potential vulnerabilities are known and provided to operations team.	✓	
PR-24	Ensure surface operational mode EMC tests are conducted including instruments for both operational mode and search cases (leakage at detectable frequencies) and information is available in an operationally useable format.		
PR-25	Include in radiation analysis work a worst case solar flare (as seen in November 2003).		Electronics Design
PR-26	Conduct shock tests on running and powered systems as during the Mission.		
PR-27	Have sufficient spare components to be able to conduct representative qualification and acceptance shock tests as planned.		
PR-28	Fly multiple probes to maximise chances of success with a delay between landings to allow feedback. Comment: configuration (cruise vehicle(s)) TBD but in reality implies landing from orbit to allow feedback between attempted landings or multiple cruise vehicles. Beware of problems with generic design flaws affecting all systems.		
PR-29	Ensure all co-ordinate systems used are correlated and understood by all parties *i.e.* systems issue.	✓	
PR-30	Ensure all critical tests are performed. The complete lander drop testing was deleted (for the benefit of GTM and schedule).		
PR-31	Consortium approach helped to keep cost down by delegating responsibility to suppliers.	✓	
PR-32	Consortium approach helped to keep cost down: Equipment designed with recognition of the real system need.	✓	
PR-33	Consortium approach helped to keep cost down: Enhance this next time to the level of a real consortium/joint venture approach, with centralised procurement for all direct charges and core project office/system team comprised of collocated staff from participant organisations. *e.g.* a co-located 'Skunk works' team organisation.		
PR-34	Staffing continuity is important. Improve early links between design and operations teams		
PR-35	System test activities should be prioritised and coordinated to ensure that any schedule compression leaves the key tests intact.		
PR-36	The level and type of software operational autonomy should be clearly defined early on.		
PR-37	Ensure System level budgets are reviewed repeatedly *e.g.* Energy budget for Coast, EDL and first Sol to ensure conclusions remain correct and implications to operations *etc.* are understood.		
PR-38	Ensure test models are available in advance of the FM so that faults/design errors can be corrected before becoming critical.		AIV

Ref	Details	Done	Also relevant
PR-39	Improve the documentation structure to show requirements dissemination and tracking. *e.g.* use of DOORS.		
PR-40	Have technologies which are open to all of the project team to avoid problems of ITAR and IPR where possible.		
PR-41	The team of people capable of driving the GTM was not large enough to deal with science payload testing/rehearsing as well as preparation for FM activity. Science planning teams need to have clear understanding of lander in order to actually perform some planning, as well as undertake to learn how to command the GTM.		Operations

4. Lessons Learned: Assembly, Integration and Verification (AIV)

The **AIV (Assembly, Integration and Verification)** section deals with aspects of the construction of the Beagle-2 that are applicable points for future projects.

Ref	Details	Done	Also relevant
AIV-01	Integrate early to allow more system testing to occur.		Programmatics
AIV-02	Test electrical interfaces including at probe level (as early as possible) and understand differences from lander level (re: battery monitoring problem seen on Beagle 2, transceiver telemetry lockout *etc.*)		Programmatics
AIV-03	Create more free internal volume in order to ease the AIV testing and schedule approach. Note Beagle 2 was constrained in volume by Mars Express interface requirements.		Programmatics
AIV-04	Ensure that all assembly facilities are compliant to all requirements, including sterility, cleanliness, acoustic, electrical, ESD protection and RF noise, physical size *etc.*		
AIV-05	Ensure that all assembly facilities are physically large enough for all assembly activities and equipment, including EGSE.		
AIV-06	Ensure that the ground segment and operations staff participate in at least the final stages of AIV.		
AIV-07	Have critical spares ready on shelf in case of damage during final stages of AIV.		
AIV-08	Match AIV shifts to planetary protection team work		
AIV-09	Test all modes of critical systems prior to launch *e.g.* transceiver		Programmatics
AIV-10	Test instrument operational modes prior to launch with representative hardware		Programmatics
AIV-11	Do not solder in FPGAs (or other programmable devices) until full system testing has been completed and contents of device have been fully verified i.e. all inputs and outputs verified.		
AIV-12	Maintaining the battery state of charge at 50% was not required for AIV (or cruise). Do not introduce unnecessary complexity in design.		Electrical Design
AIV-13	Ensure that the AIV facility has a Model Shop to quickly produce Test Aids in-house.		
AIV-14	Calibration of motor potentiometers against actual angles should be performed as accurately as possible, and re-verified as required.	✓	Mechanical Design

Ref	Details	Done	Also relevant
AIV-15	Any test ports e.g. processor should be accessible at all possible stages of spacecraft integration and test.	✓	Mechanical and Electronics Design
AIV-16	Consider making the test port connections available via the umbilical.		Mechanical and Electronics Design
AIV-17	Ease the AIV testing and schedule approach by introducing more lightweight connectors rather than require large numbers of solder joints in confined spaces *i.e.* Design for AIV.		Programmatics Electronics Design
AIV-18	Ensure ESD protection exists on all critical interfaces and ensure AIV including planetary protection takes this into account.		
AIV-19	Ensure that ESD protection is continuously monitored and managed		
AIV-20	Ensure AIV and PP monitoring is effective by viewing (both visual and camera based) from appropriate angles and heights		
AIV-21	Test or understand effects on atmosphere in terms of possible coronal discharge		Electronics, Mechanical Design and AIV
AIV-22	Test effects of dust on RF transmission.	✓	Electronics, Mechanical Design and AIV
AIV-23	Test or understand effects of atmospheric dust on parachute systems.	✓	EDL, Mechanical Design and AIV
AIV-24	Ideally conduct full lander deployment sequence using flight or flight identical systems utilising all FM critical components e.g. electronics, mechanisms etc.		Programmatics

5. Lessons Learned: Electronics and Electrical Design (EL)

The **Electronic Design** section presents lessons learned in the design and implementation of the electronics subsystems of Beagle-2. These include the Common Electronics, the Interfaces, the main computer and storage, the communications hardware, and the power supplies. Communications-specific lessons learned are listed separately.

Ref	Details	Done	Also relevant
EL-01	Must have a big enough battery and solar panels to allow transceiver (Rx) to be powered throughout the day and night until at least nominal operations are achieved.		Onboard Software
EL-02	A low power UHF receive mode required to allow continuous operation. Look at reduction in power consumption of processor operating modes. Investigate mobile phone technologies - 'pulsed mode' of 5ms/45ms duty cycle' allowing continuous receiver operation		
EL-03	Must have a battery backed processor clock or an independent battery backed timer (SBU clock).		
EL-04	Redundancy for critical functions / circuits.		
EL-05	Keep Pyro/ELM batteries separate until after S.A. charging has started and voltages are about the same. (Avoids current pulses).		

Ref	Details	Done	Also relevant
EL-06	Ensure all internal buses *e.g.* PPI Bus (CEP<->CEM) work correctly and are tested sufficiently early to allow rework and modification if required.		
EL-07	Ensure CEM performs Power-On-Reset state correctly.		
EL-08	Have a robust independent beacon for location.		EDL
EL-09	The APS should not be affected by a glitch such that it can be switched off.		
EL-10	Division of power switching registers into related functions reduces scope for error (including commanding TxRx off) and would add additional switchable channels.		
EL-11	PPS power switching should be rationalised and uniform to simplify operations.		Onboard Software
EL-12	Current sensors to be in supply lines not returns – *i.e.* Use LCL's therefore can have a true Gnd. Ref. Point (Star).		
EL-13	Must be able to switch OFF probe (Beagle (APS)) without s/w. (PSW or LSW) running *i.e.* directly from the MLT.		
EL-14	RFI/EMC issues to be taken into account in the design.		S/C Design
EL-15	EEPROM needs enough area to support 2 versions of software (PSW / LSW) with a fail-safe mechanism for choosing which version to load.		
EL-16	Ensure CEP FPGA correctly acquires Camera Images.		
EL-17	Find a non-volatile memory with a higher 'write cycle' limitation (EEPROM ~1000)		
EL-18	All 13 bits of the Coast Timer to be telemetered (not just 10 bits)		
EL-19	Trickle Charge to operate over all Battery voltage range.		
EL-20	SBU clock interface to CEP to be corrected (add 330pF Capacitor to MISO) or use a different chip.		
EL-21	Umbilical link to work at all required speeds of MLT.		
EL-22	Improve or replace opto-coupled umbilical link.		
EL-23	'Idle' detection on UART CE link anomaly to be detected correctly in MLT.		
EL-24	'Wait Flag' anomaly to be corrected in MLT.		
EL-25	Separate software between memory chips so failure of a single chip is not catastrophic.	✓	
EL-26	Ensure spare RAM is available.	✓	
EL-27	Ensure mass memory allocation is well understood along with operational implications.		
EL-28	Direct memory addressing via hardware decoder in MLT required to overcome potential software crashes *i.e.* reload s/w without s/w running.		
EL-29	Hard-coded direct telecommand for reboot required to overcome potential software crashes		
EL-30	Digital and analogue readout via umbilical link of critical data *e.g.* all timers.		
EL-31	SGICD must be PUS-compliant.		
EL-32	Monitor a solar cell output to monitor power generation, cell efficiency, dust coverage *etc.*		

Ref	Details	Done	Also relevant
EL-33	Look at susceptibility of design to large solar flares during cruise. Ensure active radiation measurement during cruise by for example RADFET. Noting Beagle 2 RADFET inoperable under PSW due to wiring error		Programmatics
EL-34	Include known light source for calibration of colour target references.	✓	
EL-35	Understanding earthing in all "forms" of probe.		AIV
EL-36	Consider a separate primary battery for pyros.		
EL-37	Alternative to electro-mechanical relay - seek alternative that is not sensitive to mechanical shock or to power surge.		
EL-38	Battery temperature constraints – examine new battery technologies to ensure low survival and operating temperatures.		
EL-39	Improve electronics design by updating the technology applied. Review design rules with input from UoL and other companies.		
EL-40	Improve electronics design through greater use of COTS. Review practice elsewhere.		
EL-41	Improve electronics design: employ a redundant processor		
EL-42	Serial interface implementation should be rationalised.		
EL-43	Provide more voltage/current/temperature/status TM. Note that spare channels were available. Gassing System for Beagle 2 did not have any temperature sensing.		
EL-44	Test and understand ESD effects on all 'assemblies' of probe as it enters, descends and lands.		EDL
EL-45	Secondary power supplies should be rationalised.		
EL-46	Avoid relying upon a successful deployment for all power generation.		S/C Design
EL-47	Consider alternative power sources and thermal heating (primary batteries, RTG's, fuel cells, RHU's etc.) if possible within mission constraints.		
EL-48	Ensure good margins on power systems *e.g.* include solar cells on exposed surfaces and if necessary consider primary battery for EDL and other critical operations *e.g.* deployment and initial operation.		Mechanical Design
EL-49	Ideally have a design that can shutdown overnight by using appropriate low temperature technologies and a "sealed" lander which doesn't open up.		Mechanical Design
EL-50	If possible carry a descent camera so landing location can be rapidly ascertained following initial communications.		Mechanical Design
EL-51	Understand shock test problems with individual components and understand possible variation of response within a given type and batch of components.		Mechanical Design / Programmatics
EL-52	Provide EDAC for Mass Memory to protect science data.		Onboard Software
EL-53	Power arm pots separately from motors, so you can work out where the arm is without having to move it.		
EL-54	Review the use of latches, umbilical links, *etc.* with regard to safety. The solution was driven by MEX.		
EL-55	The SBU clock could be a simple counter.		
EL-56	If possible ensure sufficient power margins that stay-alive power can be applied to critical instrument components to ease operations		Payload and Interfaces

6. Lessons Learned: Mechanical Design (MD)

Ref	Details	Done	Also relevant
MD-01	Ensure failure modes and implications understood for all mechanisms and deployment. Avoid one critical mechanism potentially blocking another, *e.g.* lid blocking deployment of solar arrays.		
MD-02	Replace airbag system - reduce mass and volume consumed – *e.g.* deadbeat airbag system.		EDL
MD-03	Eliminate (uncontrolled) bouncing.		EDL
MD-04	Eliminate (uncontrolled) lander free fall.		EDL
MD-05	Main chute release - release before impact.		EDL
MD-06	Main chute release - lengthen lanyard - consider use of Radar Altimeter as a trigger - determine benefit in reducing pendulum mode.		EDL
MD-07	Reduce first impact shock - e.g. examine design with more parachutes - check performance of multiple chute configuration and/or lighter lander.		EDL
MD-08	Design architecture - avoid solar panel and antenna deployment for initial on-surface phase.		
MD-09	Design architecture – if possible eliminate self-righting requirement.		
MD-10	Centre of Mass position - increase front shield diameter; target $Z_{cg}/D = 0.22$ - check on any constraints on shape, size; revise mass properties		EDL
MD-11	The pilot chute current design was constrained to <M1.5. Consider ≥M1.8 and examine potential instability problems.		EDL
MD-12	Understand implications of structural deformations from any cause temperature shock *etc.* on all mechanisms		Thermal Design
MD-13	Shiny surface(s) on lander to reflect the sunlight (glint) to aid location from orbit.		Programmatics
MD-14	Have additional verification of ejection: laser rangefinder, and a target on MLI to verify spin rate.		Programmatics
MD-15	Controllable heater on SUEM if required.		
MD-16	Ensure that all parachutes are understood and if possible tested in a low pressure atmosphere or equivalent in terms of test regime.		EDL
MD-17	Use a non corrosive gas for gasbag/airbag inflation if gasbags/airbags used. Gas should not interfere with science measurements.		
MD-18	Ideally, as mass and other constraints allow, use an active system to counteract winds. Understand effects and implications of gusts and near surface turbulence.		EDL
MD-19	Understand pressurisation limitations of systems (including purging) and implications of over-pressurisation. Have true purge or not at all - review the need for HEPA/bio-seal.		
MD-20	ARMs-3 separate actions - replace by single function, *e.g.* clamp band or Line Charge Connection Device (LCCD) - need to determine method of clamping lander.		EDL
MD-21	Collision avoidance margin - introduce additional controls, *e.g.* introduce (10m) strop between back cover and main chute pack, deploys before main chute strip out - pilot chute/main chute transition.		EDL
MD-22	Calibrate mechanism motion *e.g.* instrument arm fully and have VR modelling in place including sun angles *etc.*	✓	Ground Segment

Ref	Details	Done	Also relevant
MD-23	Harness design to be co-ordinated with Mechanical design to avoid routing issues during AIT. - get a good harness designer.		

7. Lessons Learned: Onboard Software (SW)

Ref	Details	Done	Also relevant
SW-01	Ensure probe, lander and software constructed with operation in mind.		
SW-02	Ensure on-board power monitoring or safety mechanisms cannot lock you out in a critical situation. Check in particular for programming errors and conversion errors e.g. Hex/Dec.		
SW-03	Develop and test backup software modes fully and understand all implications of them.		
SW-04	Have auto-transmit mode immediately after landing and then recover to a standard operational mode.		Operations Programmatics
SW-05	Software should be given a higher profile within system development activity. A dedicated system software engineer is required within the Systems team.		Ground Segment Software
SW-06	Ensure critical data including science data can be downloaded by minimum number of commands.		
SW-07	Must have an independent TC access without CEP and PSW / LSW – in order to restart s/w – *i.e.* MLT needs some limited TC decoding for 'critical' functions *i.e.* Processor reboot, PSW / LSW reboots, APS OFF / ON. Prox-1 already supports this.		Electronics Design
SW-08	Re-examine the hand-over point between PSW and LSW.		
SW-09	Ensure PSW and LSW use compatible timing		
SW-10	Ensure SW supports MELACOM SSTSP on Umbilical and OTC and SBU clock.		
SW-11	AutoTransmit (expedited) function must be made to fully work.		
SW-12	PSW TM packets should be simplified – *i.e.* same both pre and post separation.		
SW-13	Onboard software systems (PSW and LSW) should try to use compatible TM packets.		
SW-14	Allow the transceiver software to be updated during flight if possible. and tested of course with reversion (to old version) capability. Consider use of patches within transceiver software.		
SW-15	Check critical software data tables via multiple data routes.		
SW-16	Have on-board software disable battery state of charge monitoring if no communications reached within a TBD number of days.		
SW-17	Have ability for on-board activity sequences to be replicated automatically to minimise commands loads particularly in contingency situations.		
SW-18	LSW needs to auto-revert from EGSE to RF mode if no comms for 24 hours on EGSE port of MLT (Avoids lockout).		
SW-19	Add support for self-replicating Activity Sequences with an iteration limit.		

Ref	Details	Done	Also relevant
SW-20	Parameters in Full and Summary Lander Status packets to be optimised.		
SW-21	No need to automatically Reset Context every 1 second during Cruise.		
SW-22	All Timer TCs (Perform Activity of Function – 238,3) to be supported.		
SW-23	Desensitise PSW-LSW handover to shock reboot - can PSW and LSW overlap? Will multiple processors help?		Electronics Design
SW-24	Ensure time references correlated at all control centres use atomic clock references if possible.		Ground Segment Software
SW-25	Ensure software load procedures are well tested including memory dump on flight hardware and fully representative GTM.	✓	Programmatics
SW-26	Arm angles for angle manoeuvres are always absolute and calcurve dependent. An option to move through a relative angle would be useful, and would accelerate sequence development and testing. Attention is needed to error build up.		Operations
SW-27	Implement File-based Data Management		Onboard Software
SW-28	Ensure LSW does not declare Comms session successful until after receipt of TC, SSTSP packet or other.		
SW-29	Ensure battery protection (BSC) logic is not activated until after first communications session.		Operations
SW-30	Improve the use of TC 238,3 'Perform Activity of Function' for other complex tasks.		
SW-31	Make LTST determination more robust in LSW and use for MET.		
SW-32	Implement a NO-OP command.		

8. Lessons Learned: Entry, Descent and Landing (EDL)

The **Entry, Descent and Landing (EDL)** lessons learned are perhaps the most important, and this is the most risky part of the mission, and the time during the Beagle-2 mission that it *probably* failed. Note that the lessons learned are not in any particular order, and in no way form a failure scenario that has been linked with the loss of the Beagle-2 mission.

Ref	Details		Also relevant
EDL-01	Must have live 'data' during EDLS – not necessarily actual TM, but a carrier & some indication of processes through EDLS phases – needs something to receive signals in right place / time (orbiting spacecraft or radio telescope)		Programmatics
EDL-02	Software shall not be dependent on correct polarity of accelerometers only magnitude.		
EDL-03	Eject as close to planet as possible to ensure accurate targeting.		
EDL-04	Model extremes of weather and understand effects on EDL. Have weather measurements and forecasts up to and beyond landing.		
EDL-05	Look at possible backup modes for EDL where reliant on one measurement system for example parachute release.		
EDL-06	Have ability for operational staff to test EDL with simulated inputs.		

Ref	Details		Also relevant
EDL-07	Have entry angles *etc.* verified by external review.	✓	
EDL-08	Use DDOR tracking to minimise navigation errors and landing ellipse size.	✓	
EDL-09	Delivery from orbit - identify launch vehicle and upper stage options; consider introduction of low cost orbiter; conduct trade-off ballistic entry or descent from orbit/aerobraking?		
EDL-10	Coast phase targeting - Introduce accurate/controlled targeting.		
EDL-11	Efficient separation control - replace SUEM by spinning up and back off upper stage.		
EDL-12	Intelligent EDLS algorithm - consider intro of real time sensors in addition to accelerometer OR react to deceleration profile.		Mechanical Design
EDL-13	EDLS communication - introduce ability to update EDLS parameters just prior to TOA		
EDL-14	Understand TPS performance due to roughness potential breakup *etc.* - need to think about effect of TPS roughness on FS ballistic coefficient.		

9. Lessons Learned: Payload and Interfaces (IF)

Ref	Details	Done	Also relevant
IF-01	Verify instrument interfaces including power requirements as soon as possible.		
IF-02	Ensure Instruments can communicate with CEP while MLT is active.		Electronics Design
IF-03	Microscope operations would be simplified with some position encoding.		
IF-04	Filter wheel design should eliminate end-stop bouncing.		
IF-05	Microscope design should include end-stop sensors.		
IF-06	Install as required additional (wide angle) cameras to allow imaging of critical operations e.g. mechanism motion, sample collection tool docking with sample inlet ports etc.		Mechanical Design

10. Lessons Learned: Thermal Design (TD)

Ref	Details	Done	Also relevant
TD-01	Thermal design to optimise use of 'Heat dissipating elements' *i.e.* pcbs APS/PPS/CEP/CEM/MLT as well as heaters. Scope for improvement on approach taken for Beagle 2.	✓	
TD-02	Ensure temperature sensors for landed phase operations are closely coupled to requirements of thermal management and modelling. Scope for improvement.	✓	
TD-03	Understand burn off characteristics of MLI during entry minimise potential for hang-up *etc.*		

11. Lessons Learned: Electrical Ground Support Equipment (EGSE)

Ref	Details	Done	Also relevant
EGSE-01	Ensure EGSE correctly simulates all interfaces		c.f. EGSE-04
EGSE-02	EGSE S/W should be completed & properly tested (with SCOS *etc.*) and with MLT.		
EGSE-03	Ground Segment database must be simplified and optimised, and preferably implemented early enough that the AIT database and operational database are identical.		
EGSE-04	All MLT interfaces to be supported *i.e.* UHF, Umbilical and EGSE.		
EGSE-05	Build EGSE with AIV and Operational testing in mind		
EGSE-06	Ensure EGSE is compatible with planned Ground Segment *e.g.* utilises SCOS	✓	
EGSE-07	EGSE error handling should be robust.		c.f. EGSE-02
EGSE-08	Ensure commands for probe can be easily transferred to Orbiter(s) transceiver EGSE so full end to end test and post launch operations testing can be conducted *i.e.* EGSE compatibility from sub-probe to System level.		Ground Segment

12. Lessons Learned: Communications (COM)

Ref	Details	Done	Also relevant
COM-01	Review comms redundancy, in particular with suitable management and watchdog philosophy.		
COM-02	Revise Comms Search Modes - in terms of modes; operation scenarios took too long, auto-transmit faulty, correct use of battery BSC thresholds.		Electronic Design Onboard Software
COM-03	Base comms search modes on calculation of orbiter orbit information.		
COM-04	Ideally build into the RF system a direct-to-Earth mode even if at the level of transmit only system of 'morse' data words post-EDL and tones during EDL.		Electronic Design
COM-05	Look at alternative signalling methods in case of transmitter failure or alternative frequency bands.		
COM-06	Have radio "searches" cover a wide as possible frequency band to allow for possible detuning problems.		
COM-07	Try to arrange your fallback comms to be controlled by LTST so that if the on-board time gets corrupted you know when you can expect any process to occur *e.g.* autotx relative to mid day		
COM-08	Review the use of the hail sequence with orbiters. Consider avoiding command loads in the leading transfer frame. Alternatively choose to ensure commands are in the first frame to increase chances of successful delivery.		
COM-10	Give the orbiter the capability of blind commanding		Programmatics

Ref	Details	Done	Also relevant
COM-11	Retain the auto-transmit mode but limit its life perhaps to avoid interference with future missions.		
COM-12	Use PROX-1 to relay and resynchronise the time - the features are now in the protocol.		
COM-13	Put an image (picture) into the list of auto transmit data – even if low-res and highly compressed.		
COM-14	Review the use of all available telemetry. Need all watchdog signals/functioning reflected in spacecraft telemetry.		
COM-15	Simple SSMM operation on cruise stage is required with all modes understood.		

13. Lessons Learned: Operations (OP)

The **Operations** section presents is concerned with operational aspects of the lander and probe, as well as operations aspects of the ground segment and the team involved in controlling the spacecraft.

Ref	Details	Done	Also relevant
OP-01	A lander technical specification operations resource to be completed and held at LOCC. (Location of thermistors, trip values of power subsystem protection logic *etc.*)		
OP-02	Closer involvement between operations team and software / instrument teams during development of instrument operations. Operations team must have an understanding of instrument operation to ensure instrument safety on surface.		
OP-03	Operations team to be closely involved in definition of requirements for and development of ground segment operations resources.		
OP-04	With an operations team remote (*e.g.* at ESOC) from the operations centre it is essential that an exact record of all commands sent, along with release times and any other critical operations information is passed in real time to the remote operations team.		
OP-05	Commanding teams to consist of two engineers at a minimum. All stacks to be checked independently before despatch.	✓	
OP-06	A dedicated period of time must be allocated to the development of surface operations planning (creation of operating procedures *etc.*) and training / preparation of operations team for landed phase.		
OP-07	Size of operations team is a spacecraft safety issue. Lack of manpower redundancy causes risk. A solid foundation of direct spacecraft operations experience should be evidenced in a larger operations team.		Programmatics
OP-08	GTM configuration to be fully compliant to Ops validation tasks including procedure preparation and database products for System and instruments.		
OP-09	Ensure any ground test model software reflects latest flight standard and ensure software is loaded via "identical" procedures.	✓	Programmatics
OP-10	GTM to be available in time to allow Ops team to validate all in-flight procedures, nominal and contingency before usage.		
OP-11	GTM should be a specific build and not shared with other development activities.		
OP-12	An "as operational" mode of the Ground Test Model, configured as close to the real time status of the spacecraft as possible, should be maintained at all times when offline testing is not being carried out.		
OP-13	Ensure instrument data formats and extraction requirements and software are in place pre-launch to allow testing of basic components of ground system. This would be simplified with PUS compliance.		Programmatics / Ground Segment

Ref	Details	Done	Also relevant
OP-14	Ensure operational system flexible enough for command file generation and use at short notice (re: problem with MPS at ESOC overcome by intense manning).		Programmatics
OP-15	All spacecraft commanding to be performed from validated and configuration controlled operations procedures.	✓	
OP-16	A daily log of all commands sent, changes in spacecraft status, spacecraft events, spacecraft observations and spacecraft health as indicated by telemetry to be kept.	✓	
OP-17	A greater proportion of the operations team should have competency in producing command stacks and analysing telemetry.		
OP-18	The operations protocol developed for commanding should be rigorously adhered to.		
OP-19	LOCC is a control centre. All other tasks are secondary to commanding / analysing telemetry. Support facilities (ie video conferencing) to be elsewhere if possible.		
OP-20	Core operations team on the day has final say over non-operations staff admission and location within LOCC.		
OP-21	A formal procedures system should be agreed before procedures are created.		
OP-22	A formal configuration control system should extend over all operations files and data.		
OP-23	Ideally run operations in UTC during cruise and LTST on surface.		
OP-24	Operations teams should be sufficient large to run two shifts on a 24 hour basis or per Sol basis		Programmatics
OP-25	Make sure you have a comms pass track map and keep it up to date.		
OP-26	Early discussion with mission planning teams (MPS, MEXPOS) will clarify requirements and give some insight into which aspects of ICDs will be disregarded/changed ahead of time, before they become expensive deltas.		
OP-27	Relative event timing (relative to previous command in sequence) would simplify MET preparation and validation, and make activity sequences and timeline events less sensitive to LOBT errors.		
OP-28	Have a strategy for calibration of all moving mechanisms post landing in case of deformation due to any cause.		
OP-29	SCS_acquire_*_image_* could assign image ID instead of leaving LSW to automatically assign one. this will simplify the implementation of compression/postprocessing/downlinking. *i.e.* user specifies how to label an image, and refers to same label in all relevant commands. Avoids need to get image reports ahead of images in telemetry passes.		Onboard Software
OP-30	Other subsystems in addition to LSW to be documented in the Lander Operations Manual.		
OP-31	All operations resources should be finalised and implemented in a mission ready configuration well before rehearsals to ensure operator familiarity.		
OP-32	A mechanism of extraction of TM from SCOS into analysis tools required. Must be able to extract both raw and engineering data. A tool to aid data 'browsing' would make observation and trend analysis much easier.		
OP-33	Expected status and limits to be defined and implemented in MCS.		
OP-34	All command loads should be tested on the GTM before being sent to the spacecraft.		
OP-35	All critical planning work; comms session selection, power modelling *etc.* should be checked independently.		
OP-36	Method of calibrating arm angles post landing, independent of pot readings required. For example, repeating a test image of a known geometry from a known position.		
OP-37	Avoid over-complicating solutions to problems. A calculation by hand may be quicker than solving by computer.		

14. Lessons Learned: Ground Segment (GS)

The **Ground Segment** list of lessons learned include ground segment architecture decisions and implementation, hardware, software and support issues, and interface and team management where these are not covered in another section.

Ref	Details	Done	Also relevant
GS-01	If possible configure ground test model so RF testing is possible. Have transceiver as integral part of a ground test model along with corresponding Orbiter(s) transceiver.		Operations
GS-02	Computer systems with critical functions should be specified properly with regard to issues like hardware clock drift/reliability/storage access times rather than by availability/cost.		Operations
GS-03	Make sure you have a model of the on-board state and make sure that the on-board *i.e.* the state transition sequence is determinable or state will not change without ground acknowledgement.		
GS-04	Complete TM/TC database should be a key deliverable along with calcurves from technotes/testing as appropriate, well in advance of rehearsals/simulations.		Programmatics Operations
GS-05	Have appropriate tools to understand relationship to landing site LTST and Orbiter orbit numbers *etc.*		
GS-06	GS database must be simplified and optimised.		
GS-07	Include a fax machine near console.		
GS-08	Use magnetic whiteboards.		
GS-09	Large area of pinboard would be useful, or halfheight panels behind consoles to allow quick reference to key information.		
GS-10	Beagle MCS should be capable of separating simulated data from real FM data. Solution: multiple installations/home directories, *e.g.*: sops23e - normal account, development, analysis, checkouts, database stuff *etc.* sops23e-fm - real, pure, not to be messed with FM commands and telemetry only, never cleared out, always available. sops23e-sim - simulations only		
GS-11	MCS backing-up activity could be implemented at script level but should be a scheduled server running in the MCS control panel. (*i.e.* archiving and config 'snapshots')		
GS-12	SCOS-TMprint needs to be fixed/replaced as soon as possible.		
GS-13	Allow MCS user to override time correlations, *e.g.* force new clock value locally or for incoming telemetry files.		Operations
GS-14	A centralised, structured, repository for all stacks, LORs, command binaries, logs, and telemetry files should be implemented. All MCS systems should have access to the same set of stacks *etc.*	✓	Operations
GS-15	MCS user database should be centralised, and needs to not use 4 separate plain-text files to implement user/role functionality. A single XML file with encrypted passwords, driven by a User Manager front-end would be safer, simpler, and cleaner.		Operations
GS-16	FTS concept needs to be redefined to perform multiple copy/transfer/backup actions for each file. A staggered schedule does not correctly achieve this.		Operations

15. Lessons Learned: Landing Site Selection (LS)

Ref	Details	Done	Also Relevant
LS-01	Survey potential landing site(s) to metre and ideally sub-metre type resolution and understand all potential hazards prior to selection.		Programmatics
LS-02	Have ability to change landing site and time en route if conditions change.		Mission S/C Design
LS-03	To maximise chances of SOL1 survival land at dawn. Check the environmental benefits (reduced wind, *etc.*)		Modelling
LS-04	Survey landing site(s) if possible with potential search assets prior to landing to have a "before" data set.		Programmatics

16. Lessons Learned: Cruise Phase (CP)

Ref	Details	Done	Also relevant
CP-01	Separation detection should be changed from heater and trickle charge to H/W separation links – no need for separate switching OFF of TM.		S/C Design
CP-02	'In-Flight' test all Cruise and EDLS functions during checkouts prior to actual use in the mission.		Operations
CP-03	Ensure cruise phase telemetry can be seen 'live' at appropriate support centres, not just via data recall later.		Ground Segment
CP-04	Direct TM link to TTC DHS as well as via SSMM.		S/C (MEX) Design
CP-05	Have cruise phase databases distributed to all support centres so all parties can easily view all telemetry data		Ground Segment
CP-06	Look at potential outgassing in cruise and take where possible preventative measures to protect MLI surfaces mechanisms *etc.*		
CP-07	Ensure space weather data is available and used during cruise including measurement where possible of achieved dose during flares *etc.* and take protective counter-measures for predicted problems.		Mission Operations
CP-08	Ensure temperature sensors for cruise phase operations are placed at all necessary points.	✓	S/C design
CP-09	Understand material properties and possible variation in performance and effect of vacuum storage during cruise phase	✓	
CP-10	Plan the mission plan to precede dust storm season. Check the orbital mechanics, and consider a prolonged cruise phase via a non-optimum transfer trajectory if necessary.		Mission Planning
CP-11	Understand any potential offsets during cruise navigation due to thermal distortion of carrier vehicle		Thermal Design EDL

17. Lessons Learned: Miscellaneous / Facilities (MF)

Ref	Details	Done	Also relevant
MF-01	Ensure heating / air conditioning / hot water work overnight if people are working overnight.	✓	

18. Abbreviations and Glossary

AIT Assembly Integration and Test (=AIV)

AIV Assembly Integration and Verification

AOCS Attitude and Orbital Control System

APS Auxiliary Power Supply

ARM Aeroshell Release Mechanism

BCR Battery Charge Regulator

BEE Back-end Electronics

BNSC British National Space Centre

BS(O)C Battery State of Charge

CEM Common Electronics Module

CEP Central Electronics Processor

CoI (ESA) Commission of Inquiry

COTS Commercial Of The Shelf

CSM Communications Search Mode

DHS Data Handling System

DoY Day of Year

DTI Dept. Trade and Industry (of the U.K. government)

E2 See EEPROM

EDAC Error Detection And Correction

EDL(S) Entry, Descent and Landing (System)

EEPROM Electrically Erasable Programmable Read-Only Memory

EGSE Electrical Ground Support Equipment (for controlling the GTM)

ELM Electronics Module

EMC Electro-magnetic Compatibility

ESA European Space Agency

ESD Electrostatic Discharge

ESOC European Space Operations Centre, Darmstadt, Germany

ESS Environmental Sensor Suite

FPGA Field Programmable Gate Array

FTS File Transfer System

FW Filter Wheel

GAP Gas Analysis Package

GS Ground System

GTM Ground Test Model (full set of working avionics along with critical mechanisms)

HEPA High Efficiency Particulate Filter

ITAR International Traffic in Arms Regulations (USA State Department)

JPL Jet Propulsion Laboratory (of NASA, Pasadena California)

LCL Latching Current Limiter

LMST Local Mean Solar Time

LOBT Lander On-Board Time

LOCC Lander Operations Control Centre, National Space Centre, Leicester

LOPC Lander Operations Planning Centre, Open University, Milton Keynes

LSW Lander Software

LTST Local True Solar Time (time of day on Mars at the landing site)

MBS Mössbauer Spectrometer

MCS Mission Control System

MER Mars Exploration Rover

MET Mission Event Timeline

MEX Mars Express

MIC Microscope

MLI Multi-Layer Insulation

MLT Mars Lander Transceiver

MPS Mission Planning System

MTL	Mission Timeline
NASA	National Aeronautics and Space Administration (USA)
NEV	Near-Earth Verification
NSC	National Space Centre (Millennium Commission Landmark Project Leicester)
OBC	On-board Clock
ODY	NASA Mars Odyssey
PPARC	Particle Physics and Astronomy Research Council
PPS	Payload Power Supply
PROX-1	CCSDS Communication Protocol for Landers
PSW	Probe Software
PUS	Packet Utilisation Standard (ECSS-E-70-41A)
RADFET	Radiation (sensitive) Field Effect Transistor
RCG	Rock Corer Grinder
RF	Radio-frequency
RFI	Radio-frequency Interference
SBU	Switch and Backup Unit (Clock and Memory)
SCOS	(ESA) Spacecraft Operating System (Software)
SCS	Stereo Camera System
SGICD	Space to Ground Interface Control Document
Sol	Solar martian day
SPICAM	Spectroscopy for the Investigation of the Characteristics of the Atmosphere of Mars (a spectrometer onboard Mars Express)
SSMM	Solid State Mass Memory (on Mars Express)
SSTSP	Standard Spacecraft Time Source Packet
SUEM	Spin Up and Eject Mechanism
TM/TC	Telemetry, Telecommand
TOA	Top of Atmosphere
TPS	Thermal Protection System
UART	Universal Asynchronous Receiver Transmitter
UHF	Ultra-high Frequency
UoL	University of Leicester
UTC	Universal Time Coordinated
WAM	Wide-Angle Mirror
XRS	X-Ray Spectrometer