D6-Executive Summary

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Mars Surface Platform Capabilities Study (MSPC) Executive Summary

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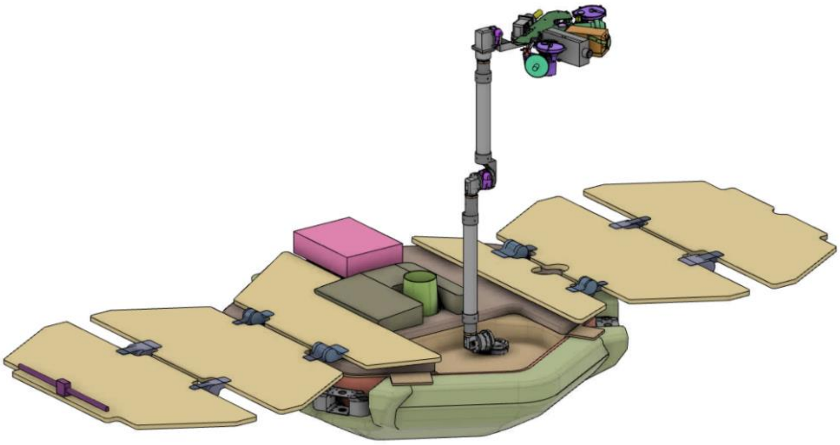


1 AIMS AND OBJECTIVES

The Mars Surface Platform Capabilities Study aims to provide ESA with an assessment of the state of the art Mars Landers using ESA/European technologies with flight heritage. Airbus's Mars lander experience is taken from the Beagle 2 probe launched in 2003 on board Mars Express. The objectives of the study are to:

- Outline the lessons learned from previous development programmes
- Incorporate those lessons learned into a reconfigured version of the Beagle 2 probe for a future, low cost, short turn-around, mission. All major components of the lander should be European.
- Outline the required technology development activities necessary to realise the reconfigured design.

Almost 20 years have passed since the Beagle 2 probe was built and no commensurate mission has been flown since. The MSPC study also assumes the following tacit objectives:

- Rediscover and review information and documentation from the original project
- Capture the knowledge, experience and ideas of those who worked on the Beagle 2 mission

2 STUDY DOCUMENTATION

Applicable documents

AD1	ESA-TEC-SOW020PMHRE01 Statement of Work: Mars Surface Platform Capabilities Study
AD2	ESA-E3P-MSR-RS-001_Margin Philosophy for Mars Exploration Studies
AD3	ESA MSR Sample Fetch Rover Environment Specification - ESA-E3P-SFR-SP-002

Study Deliverables

D1 & D5	Design Report & Final Report
D2	Draft Reference Package
D3	Technology Development Assessment and Roadmap
D4	CAD Model Package, CATIA V5
D6	Executive Summary
D7	Photographic Documentation
D8	Contract Closure Summary
(D9)	Identification and Assessment of Candidate Payloads, MSPC-SUP-TN-01 (supplement to D1)

3 BEAGLE 2 & STARTING POINT

Airbus's Mars Lander heritage is centred on Beagle 2 – a small, low cost lander launched in June 2003 and carried to the red planet aboard the Mars Express orbiter. Beagle 2 was due to touch down on the Martian surface on Christmas Day 2003 but communication with the lander was lost shortly after separation. The apparent failure of the mission and subsequent discovery of the partially deployed lander in 2015 are well documented. Whilst the mission was unable to fulfil its scientific objectives, it remains the only European spacecraft to have successfully landed on the Martian Surface. The lander's design was daring, innovative and heavily influenced by mass and budgetary constraints. The design incorporated many features that are worthy of consideration for future missions and the project provided many valuable lessons learned.

The Beagle 2 probe comprises the eight major elements shown in Figure 1. The spin-up and ejection mechanism (SUEM) retains the probe on the carrier spacecraft during the cruise phase, imparts the linear momentum required for separation and also induces an angular momentum to increase stability during descent. The back cover and heat shield form the aeroshell which encapsulates the parachutes, lander and ammonia gas generator during the cruise phase and early part of the entry descent and landing sequence. The lander itself comprises a base containing the electronic systems, battery and payloads and lid containing the deployable solar panels and the UHF antenna. The two parts of the lander are connected by a hinge forming a 'clamshell' that opens once the lander is at rest on the surface. Prior to inflation, the airbags are folded beneath the lander base which also accommodates the Radar Altimeter Trigger (RAT). When inflated, the Airbags form a ~2 m sphere around the lander.

At launch, the Beagle 2 probe was 924 mm in diameter, had a total height of 523 mm (excluding the spin-up and ejection mechanism) and weighed 68.8 kg. Activation of the pilot chute mortar and pyrotechnic separations was controlled by the probe electronics during Entry, Descent and Landing (EDL). The lander executed two independent pieces of software for EDL and surface operations with all EDL events triggered by the Radar Altimeter Trigger (RAT) and z-axis accelerometer.

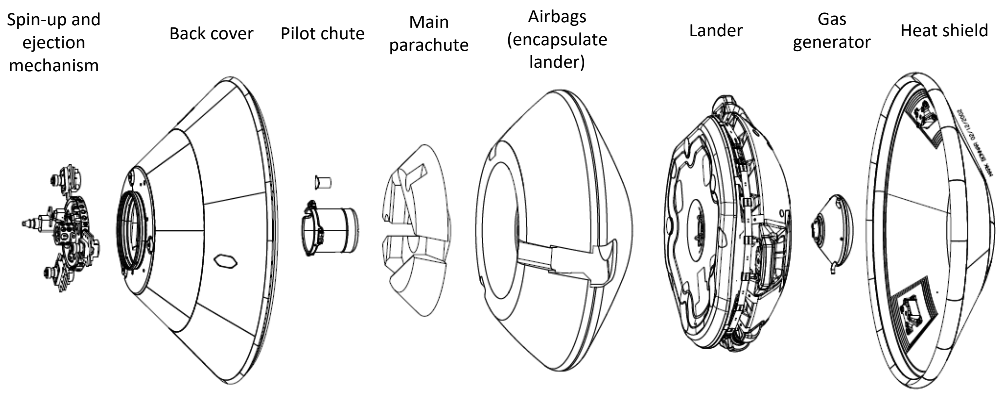


Figure 1. Major elements of the Beagle 2 probe

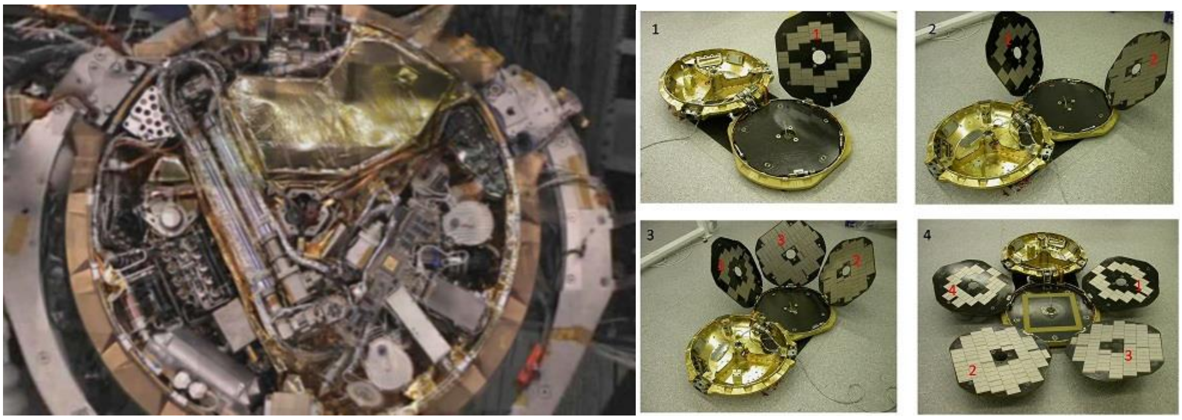


Figure 2. (left) The lander base containing all functional elements of the lander, the internal payloads and the robotic arm. (right) Solar Panel deployment sequence

Once on the surface, the clamshell opens allowing the solar panels to deploy revealing the UHF antenna (Figure 2, right). The base of the lander is densely packed and contains all the functional lander systems (Figure 2, left). The lander had a payload mass fraction of 33% and incorporated multiple instruments into the Payload Adjustable Workbench (PAW) at the end of the robotic arm.

The loss of the lander remains unexplained. Images from the HiRISE instrument aboard NASA's Mars Reconnaissance Orbiter (MRO) appear to show at least three of the four solar panels deployed on the surface with the front cover and parachute suitably displaced form the landing site. The survivability and recoverability of the lander were compromised by two fundamental design flaws:

1. The UHF antenna was obscured until all four solar panels were deployed.
2. Prior to deployment of the solar panels, the lander is dependent on battery power alone, hence the on-surface deployments are time critical and the survival duration finite under anomaly conditions.

Several improved designs were proposed in the immediacy of the Beagle 2 mission through various follow-on studies such as the Beagle Evolution Study. The Beagle Evolution team proposed a Beagle 3 design in 2004; a concept that was not taken forward. The discovery of the probe in 2015 largely vindicated the original design and EDL approach but opportunities for a follow-on mission were not forthcoming. The Beagle 2 engineering team retained an overt enthusiasm for the small-lander concept and many hold fond memories of the original project. Without opportunity to develop Beagle-like landers, much of the expertise and industrial capability was diminished or lost.

The Beagle 2 project produced only a modicum of the documentation and engineering artefacts commonly associated with implementation projects. Of those artefacts which were available to the MSPC study, CAD and finite element models are mostly incompatible with present day software or are aligned to outdated processes. Resurrecting the Beagle 2 server and ascertaining its contents required significant effort during the early stages of the study. The contents included a significant amount of photographs and analytical results but little information relating to design description or justification. In most cases, the validity or relevance of analyses could not be ascertained and methods and assumptions were sparse or undocumented.

In practice, much of the Beagle 2 concept remains in the minds of those who worked on the original mission. The MSPC study depended on contributions form a number of former Bealge-2 team members. Many of those who contributed are now retired and motivated only by their enthusiasm for the Beagle 2 mission and the prospect of a follow-on. Airbus acknowledges the contributions of Arthur Smith, Dave Northey, Andrew Ballard, Stuart Howarth, Giacomo Giovangrossi, Marco Wolf, Hans Strauch and Jerome Bertrand. The expertise and experience of Jim Clemmet (Bealge-2 Chief Engineer) and Lester Waugh (Beagle 2 team member) were invaluable.

4 KEY LESSONS LEARNED FROM THE BEAGLE 2 MISSION AND DESIGN OBJECTIVES

Airbus reviewed the lessons learned documents from the original Beagle 2 mission and re-evaluated them in a modern context. The lessons learned predate the discovery of the Beagle 2 probe on the Martian surface and are written with the underlying assumption that Beagle 2 crashed on landing. Many of the lessons relate to programmatic and management matters that are out of scope for this study. Nearly all lessons and recommendations should be carried forward into future lander programmes The most significant lessons learned (or objectives derived from them) with bearing on the reconfiguration are summarised below. All have been addressed by the reconfigured lander.

- Create more free internal volume in order to ease the AIV, testing and schedule constraints.
- Introduce a low power UHF receive mode required to allow continuous operation.
- Reduce power consumption of processor in operating and non-operating modes.
- UHF communications should be immediately available prior to any deployments on the surface
- The lander must incorporate a battery backed processor clock or an independent battery backed timer (SBU clock).
- Have a non-solar-dependent power source if possible.
- Eliminate uncontrolled bouncing and lander free-fall
- Avoid solar panel and antenna deployment for initial on-surface phase.

4.1 Planetary protection lessons learned

Beagle 2 was one of the very first European missions subject to planetary protection requirements and a lot was learned during the course of the development. The aseptic facility in which Beagle 2 was built no longer exists and it is recommended that a modern day lander be built in a tent within a cleanroom such as the BCF at Stevenage to achieve the ISO-4 cleanliness. Key lessons learned with impact on the lander design include:

- Seal units/sub-assemblies to keep them clean internally and to firm up the internal bioburden budget counts as the build progresses and to protect progress to-date
- Keep integration sequence dependencies to a minimum
    - e.g. several units that must be fitted (or removed) in sequence so that if the one that is first in the pile fails, all the others have to be removed before it can be accessed.

These lessons suggest a more modular and more spacious lander design is required to avoid inter-dependencies between AIT sequences and simplify the overall lander design. The high packing density of the Beagle 2 lander complicated the design and integration of the probe.

4.2 Design Objectives for the reconfigured lander

In the absence of an applicable mission or probe specification for the MSPC study, the following design objectives were agreed with the Agency. The reconfigured probe should:

- Include an EDL sensor suite permitting reconstruction of the re-entry in case of anomaly or failure
- Have the capability to transmit live EDL telemetry to an orbiting spacecraft
- Identify and eliminate all obsolete components from the Beagle 2 design
- Improve management of on-board time
- Incorporate the lessons learned from Beagle 2
- Provide a low cost platform to address different mission concepts and candidate payload suites
- Include a robotic arm hosting a stereo camera pair and volume for additional instruments
- Be compatible with Mas entry via a hyperbolic insertion trajectory
- Eliminate non-European components where possible
- Allow integration of a Radioisotope Heater Unit (RHU) as an optional, mission-dependent component.

4.3 Payload accommodation and volume scaling

The reconfigured lander has been designed to accommodate a variety of payloads but independently from any mission or payload specification. The lander design should provide a low cost, fast turn-around platform that may be adapted to different payloads, mission profiles and landing sites.

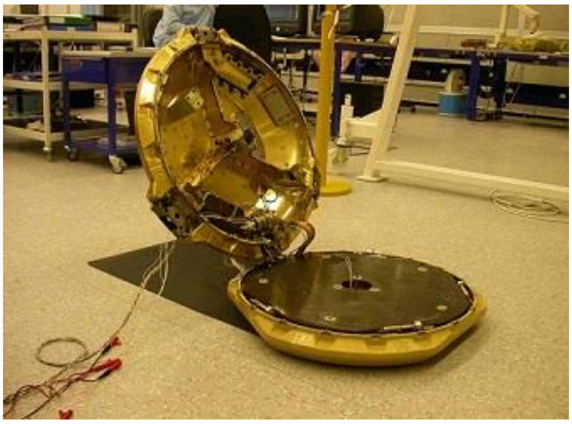
The study team have increased the size of lander (relative to Beagle 2) to achieve ~20% greater payload volume. This change has consequential impact on the probe mass and outer dimensions but does maintains compatibility with a non-propulsive EDL.

5 SIGNFICIANT TRADE-OFFS AND DESIGN CONSIDERATIONS

Reconfiguration of the probe focused primarily on the lander element. It was assumed that the aeroshell geometry and construction could be scaled without changing the fundamental design – an assumption based on successful flight heritage of Beagle 2, Huygens and other similar concepts.. The only change to the aeroshell saw the introduction of a UHF antenna for EDL communications. Similarly, the interfaces to the carrier craft and the Spin-Up Ejection Mechanism (SUEM) remain appropriate for a small lander mission and are not considered within the reconfiguration.

5.1 Pocket Watch vs. Cabriolet Lander Configurations

Perhaps the most fundamental trade study concerned the configuration of the lander itself. The 'clamshell' or, 'pocket watch' configuration of the Beagle 2 lander was mechanically robust and agnostic to landing orientation but also required time-critical deployment of the solar panels.



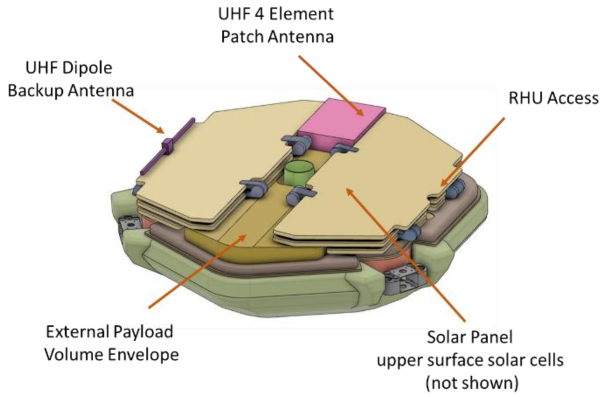


Figure 3. (left) The pocket watch configuration of the Beagle 2 lander (right) The cabriolet configuration with solar cells and UHF antenna available in the post-landing configuration.

Reconfigured lander, whilst looking similar to Beagle 2, remains closed and sealed with the solar panels, robotic arm and UHF antenna on the external, exposed upper surface. It is referred to as the "Cabriolet" version, (Figure 3, right) as opposed to the Beagle 2 "Pocket Watch" configuration (Figure 3, left). Much of the heritage of Beagle 2 is retained. The internal "service module" equipment remain essentially unaffected by this variation in mechanical architecture. Some of the most pertinent benefits and drawbacks of the two architectures are listed in Table 1 & Table 2 below:

Table 1. Benefits and drawbacks of the 'Pocket Watch' architecture

Benefits	Drawbacks
• Maximises heritage from Beagle 2 • Small, high packaging density, high payload ratio. • Flight proven aeroshell front heatshield geometry for small passive planetary landers (Beagle 2 and Huygens), support by a developed flight aerodynamic and aerothermal database. • A choice of both airbag solutions is retained. • Insensitive to final settled location of main and drogue parachutes	• Beagle 2 type airbags requires European development and test with no industrial heritage • Hibernation will require open/ close cycles of the lid hinge • Primary communications dependent on full solar array deployment without change in antenna architecture; • Power generation is dependent on full deployment of the lid and solar panel;

Table 2. Benefits and drawback of the 'Cabriolet' architecture

Benefits	Drawbacks
• Deadbeat Airbag guarantees landing "*right side up*" • The deadbeat airbag system *saves mass*	• Requires commitment to development of deadbeat airbag and gassing system

- The number of *release and deployment functions* after first impact is *reduced*
- The self-righting function is *no longer required*, eliminating the main hinge
- Opportunity for *two external UHF antennas* provides potentially redundant communication *without solar panel deployment*;
- Operational readiness is achieved at much reduced risk of deployment failure
- Retraction of the deadbeat airbag from the workspace of the Robotic Arm is required as a minimum
- The stowed airbag exposes the lander's upper surface during Cruise and Coast phases, increasing thermal losses

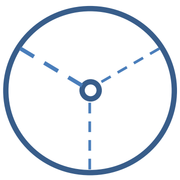
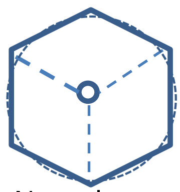
A key difference between the two architectures is that the Cabriolet lander is dependent on vented airbag and subsequent retraction of the deflated airbag if access to the Martin surface is required. The pocket watch configuration may be realised with a vented or bouncing airbag. Ultimately, the Cabriolet configuration was chosen as a basis for the reconfigured lander. The Cabriolet architecture overcomes the most critical flaws identified in the original lander's design.

5.2 Lander shape

Having determined the basic configuration of the lander, the most optimal shape for land base was considered. The Beagle 2 Lander was comprised of a circular bowl with three lugs for connection to the aeroshell. In conjunction with the lid, the bowl contributed to the primary structure of the complete probe, with the lugs transferring launch loads and impact loads. Internal radial webs and a central tube provide additional stiffness and transfer parachute peak deceleration loads. The circular base meant that all internal equipment had to be tailored to the shape of the lander.

An alternative configuration using a hexagon shaped base has been identified as an alternative to provide more linear shapes to ease restrictions on the accommodation of internal equipment and the mounting of external equipment on the lid. Other polygons were considered (see D1) as part of the study with the hexagon becoming baseline. A summary of the benefits and drawbacks of both configurations is given in Table 3.

Table 3. Benefits and drawbacks of a circular and hexagonal lander base

	Circular	**Hexagon**
		
Benefits	○ Heritage ○ Allows symmetry of 3 structural interface lugs ○ No structural discontinuities	○ Natural symmetry of 3 structural interface lugs ○ Regular linear shape lends itself well to internal layout B ○ Straight sides allow inflated airbag compartments also to be linear improving tip-over resistance ○ Provides good linear geometry for accommodation of Lid equipment.
Drawbacks	○ Internal layout places "unfriendly" constraint on payload equipment geometries ○ Internal layout requires service module equipment to be of irregular shapes as with Beagle 2	○ Structural discontinuities non-ideal, possibly needing local structural elements/reinforcements

5.3 Airbag Trade – Segmented non-vented airbags vs. vented airbags & European Developments

The Beagle 2 airbags and gas generator were provided by US industry. The Airbag Gas System was supplied by a separate US company. The airbags were provided by the same manufacturer and using the same technology as those used by NASA for Pathfinder and the Spirit an Opportunity rovers.

The MSPC study considered both the configuration of the airbag and potential routes to European supply of airbags for a future lander mission. Ultimately, the selection of a vented airbag was mandated by the Cabriolet lander architecture and offers the following benefits:

- Lower risk landing
- Immediate operational readiness of lander for Cabriolet Lander
- Compatibility with the Beagle 2 Pocket Watch configuration
- Saves significant airbag mass, (perhaps as much as 5kg for Beagle 2)
- Saves system mass elsewhere e.g. elimination need for self-righting, less harnessing, smaller rear cover, reduction in impact protection;
- Saves system volume benefiting accommodation of other equipment in rear cover,
- Reduction in functionalities/complexities, e.g. reduction in release devices
- Less sensitive to leakage than non-vented airbags
- Less structural impact loading
- UK & European non-space heritage in concept exists (unlike non-vented).

The most significant drawback of the vented airbag is the need to retract the deflated airbag to allow the instrument arm to have access to the Martian surface. Conversely, non-vented airbags are flown at the cost of mass and stowed volume. Their performance is more sensitive to leakage and the magnitude of shocks as the lander falls to the surface. This shock will increase as the mass of the lander increases. Ultimately, the vented airbag is the chosen solution regardless of lander configuration.

5.3.1 European Airbag capability: Summary of Airbag development for ExoMars Schiaparelli Platform at Aero Sekur

The Aero Sekur vented airbag (see D1, [RD-16]) is comprised of six chamber forming a hexagonal shape around the lander test dummy. Each chamber has a dedicated vent valve. A major design requirement for the inflation system is that the lander must avoid any need for self-righting. A passive option for the venting control may be a viable solution, but depends strongly on the landing strategy. An active control was selected for development to maintain attitude control following impact. This was achieved by software vent logic that would control the release of gas through the vent valves but in as quickly as possible. The low Mars atmosphere density and pressure means that this is much more sensitive than on Earth. The only viable solution for the inflation system was the use of pressurized helium. Materials selected are compatible with DHMR sterilization.

Figure 4. 2013 ExoMars Mission - Airbag Prototype tested at Aero Sekur

The venting valve control algorithm requires dedicated sensors. The algorithm that was conceived to stop the airbag up to a near zero vertical velocity and, in parallel, controlling the landing platform attitude. Each sensor was dedicated to independent control of the relevant airbag chamber Accelerometers were selected for the sensing function, one the rigidly mounted the mid-section of the hexagonal landing platform external edge.

The design was supported by extensive analyses using LS-Dyna, simulating the Mars ambient conditions. The analysis development and verification is summarised by the following steps:

- Generate a LS-Dyna model of the airbag system including the implementation of the vent control logic by a Fortran routine running in parallel with LS-Dyna and interacting with it;
- Run several LS-Dyna simulations using that model in Earth ambient condition in order to setup a prototype to be tested in similar conditions;
- Build and test the prototype in the conditions simulated with LS-Dyna;
- Correlate the test results with the LS-Dyna model results;
- Modify the LS-Dyna model correlated to Earth conditions in order to simulate the Mars environment (gravity, the ambient gas, pressure and temperature) and taking into account the result obtained in a vacuum chamber in terms of valve discharge coefficient (completely different compared to that obtained in Earth conditions)
- Run several LS-Dyna simulations using that model in Mars ambient condition in order to optimize the design of the airbag system

The results of the analysis supported the selection of helium as medium for the airbag inflation. The airbag system was positively tested on Earth in a representative way:

- Airbag materials and architecture
- Landing velocities
- Presence of terrain slopes and rocks
- Vent control software (running on a breadboard computer)
- Inflation in a vacuum chamber at Mars ambient conditions
- The discharge of gas was achieved by means of redundant pyrotechnic actuators.

Noting the extent and success of the work undertaken, Aero Sekur consider that the airbag development achieved TRL-6 for ExoMars prior to further work being cancelled.

5.4 Radar Altimeter Trigger vs. Full Range Altimeter

The Beagle 2 probe carried a Radar Altimeter Trigger (RAT) which provided only discrete altitude indications to trigger separation events during EDL. The device was not designed to provide full range altimetry data during the descent. The MSPC study considered whether a full numerical altimeter could be implemented into the reconfigured lander.

The Beagle 2 RAT (Figure 5) was a simplified/modified variant of a numeric output Radar Altimeter. The robust analogue front end was retained from the original design but the radiation-vulnerable Digital Signal Processor back-end was replaced by a simple filtered pulse output to trigger deployment of the airbags. This made it more robust, lighter, simpler and more efficient than the unit from which it was derived. Consequently, the design remains recommended, being robust and mass efficient with minimal component updates needed to deal with obsolescence issues. This makes it a sensible candidate for future MSPC mission candidates, with minimal cost and effort to bring a successful solution up to date.

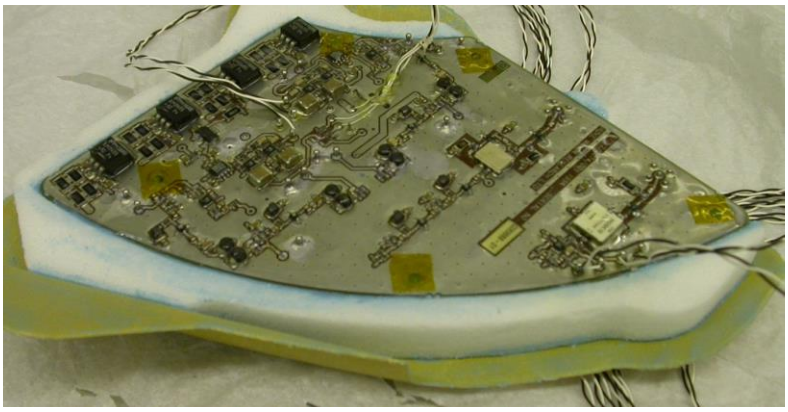


Figure 5. The Beagle 2 Radar Altimeter Trigger (RAT)

A derivative of the Schiaparelli altimeter maybe considered but would require redevelopment and miniaturisation, being too large for a mission of the MSPC class. This is also likely to apply to other candidate units, to make them sufficiently light and robust for space applications. That said, the world of space electronics and avionics is in constant development and it would make sense to re-evaluate the situation nearer the time of need.

To reduce the level of change and development it should be possible to take an intermediate frequency / baseband output from the RAT and feed it to the input of a signal processor unit that computes the altitude and provides the numeric output required from a full altimeter. The back-end processor therefore would complement the RAT, retaining its heritage whilst minimising development costs.

The reconfigured lander maintains the RAT it's the Beagle 2 form suitable for accommodation in the lander base. The opportunity to derive absolute altitude from the existing device (or a derivative thereof) is a concern for future study.

5.5 Benefiting from technical advances and the benefit of the RHU

The reconfigured lander is able to benefit from other technical advancements which have occurred since the Beagle 2 mission:

- Miniaturisation of electronics and component density
- Miniaturisation and availability of camera technology
- Increased availability and performance of MEMS accelerometers and gyros
- Higher performance lithium ion battery cells with improved energy density
- Improvement in solar cell efficiency from 26% to 32% relative to Beagle 2

5.6 EDL sensor suite

The study considered a range of EDL sensors and telemetry for control of the probe during EDL and to monitor the performance of the heatshield during descent. It should be noted that the probe has no propulsion or attitude control system and only the Radar Altimeter Trigger (RAT) and Z-axis accelerometer are required to control the deployment events during EDL.

It was agreed that the EDL sensor suite should be sufficient to allow reconstruction of the spacecraft attitude and attitude as a function of time in case of anomaly or failure. The reconfigured lander includes the capability to transmit EDL sensor data to an orbiting satellite during descent at a nominal rate of 2 kbps. Data rate constrains are mean the transmitted EDL data will be under sampled during descent (and may depend on on-board conditioning of sensor measurements), therefore, it is intended that all EDL raw data is stored on board the lander and transmitted to Earth once on the Martian surface.

As shown in the Table 4, the reconfigured lander augments the Beagle 2 EDL sensors with accelerometers in the X and Y axes and a MEMS gyro. True reconstruction of the EDL sequence would require a full range altimeter. As described previously, Beagle 2 RAT would require substantial modification to provide accurate altitude data and there is no known altimeter of suitable volume and mass for a small lander application. The altimeter is considered an optional instrument for further investigation. The adaptations required to allow full range altimetry data from the RAT require further investigation.

Table 4. Proposed EDL sensor suite

Sensor/data	Application	EDL Critical	Nominal	Configuration
Status Telemetry via UHF	For reconstruction/analysis of EDL	No	Yes	NA
Z-axis accelerometer	Triggers deployment of rear cover & drogue chute	Yes	Yes	2 Redundant
X/Y axis accelerometers	Contributes to EDL reconstruction/analysis dataset	No	Yes	2x1 per axis
3-axis angular velocity	Contributes to EDL reconstruction/analysis dataset (MEMS/small format device)	No	Yes	2x1 per axis

Forward facing camera	For landing site reconnaissance, observing trajectory of the heat shield and for public engagement	No	No	1x non-redundant
Rear facing camera	For observing rear cover deployment and deployment of the main chute	No	No	1x non-redundant
Thermocouples	Heatshield and bioseal temperatures.	No	No	~10
Radar Altimeter Trigger (RAT)	Trigger for deployment of main chute	Yes	Yes	Dual redundant
RAT altitude data	Raw altitude data derived from the RAT (/Altimeter)	No	No	As per RAT

In addition to the nominal sensor suite, forward and rear facing cameras and additional thermocouples for internal components are considered to be optional telemetry that have been accounted for in the number and design of electrical interfaces.

Forebody temperature and pressure sensors were considered for the heatshield but were considered to be too mass/volume and harness intensive to justify inclusion in the nominal sensor suite. The basic geometry and thermal protection system of the aeroshell have been successfully applied to more recent missions and may be considered a proven technology – particularly for a small lander in which mass and volume constraints are critical.

5.7 Radioisotope Heater Unit (RHU)

The reconfigured lander includes a 3 watt RHU housed at the centre of the battery module. The RHU is considered to be an optional item but has been accommodated with the baseline design. The RHU greatly reduces the need for autonomous heating and improves the survivability of the probe in the stowed configuration.

The introduction of the RHU has wide ranging benefits to the remainder of the lander design:

- Reduction in reqeuried battery size and solar panel area
- Reduced heater requirements. Discrete thermal straps rather than dedicated heaters may be an option for future missions.
- Avoids need to power up electronics to contribute to thermal control in non-operational conditions
- Removes risk of battery heater failure
- Reduces sensitivity to environmental extremes
- Reduces impact on design if the lander is deployed to more northerly latitudes and elevations.
- Supports hibernation

It is suggested that an RHU is baselined for a future small lander mission. An eminently suitable RHU is being developed by the University of Leicester under an ESA programme. The development programme aims to achieve TRL-6 in 2024.

6 THE RECONFIGURED LANDER CONCEPT

The MSPC study proposes a reconfigured version of the Beagle 2 lander (Figure 6). The configuration has been optimised to incorporate the lessons learned from the original Beagle 2 mission and realise more recent design optimisations. The design is preferred to the original, “pocket watch” configuration of the Beagle 2 lander whereby the solar panels and antennas are encapsulated upon landing. The design supposes that the lander sits at the centre of a toroidal, dead-beat airbag and removes the clamshell cover used in the original Beagle 2 design. The lander includes a robotic arm which may be configured to specific mission needs. The probe configuration has been rescaled for to accommodate the cabriolet lander although the configuration remains largely unchanged from the original mission. A list of key specifications is given in Annex A of this document.

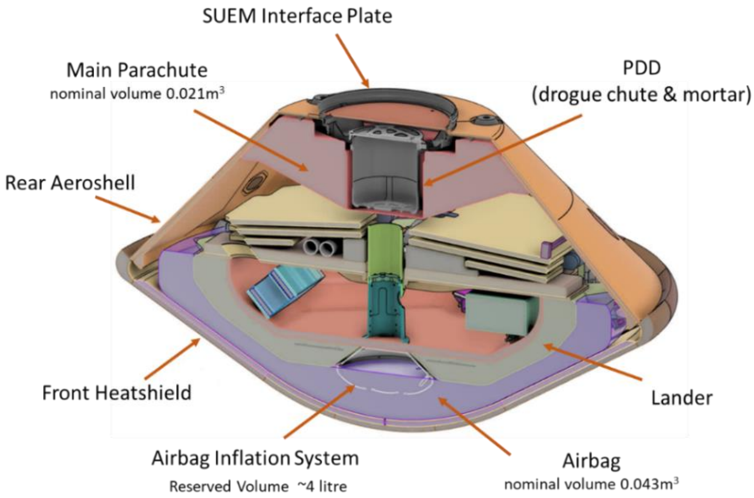


Figure 6. The probe including toroidal airbag and parachutes

In the stowed configuration (Figure 7, left), the probe is powered by its internal battery and supported by the exposed solar cells. The lander has both a four element patch antenna and a back-up dipole. It is foreseen that the lander will have a low power, “wake on hail” mode such that the lander can minimise its power consumption during non-operating periods. The RHU has been accommodated at the centre of the lander's battery module to maximise its effectiveness and allow for late insertion into the lander base.

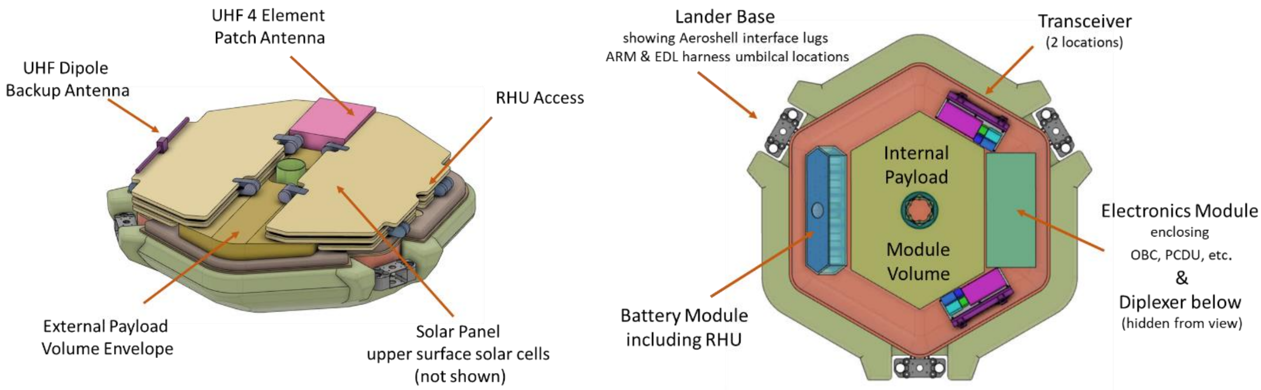


Figure 7. (left) Stowed lander (right) Internal equipment and payload volume

The lander base accommodates all the platform equipment: the battery module, dual redundant transceivers and the electronics module (Figure 7, right). The electronics module incudes the on-board computer, power conditioning unit and all interface circuitry for heaters, deployment initiators and communications with the payload. In principle, the number of panels in the solar array could be adjusted for missions with differing power demands.

The electronics module is based on CubeSat components with dual redundant processors and timer boards. The redundant transceivers are based on those flown for the Beagle 2 mission although some development effort is required to overcome obsolescence. Transfer frame decoding will be performed within the transceiver as for Beagle 2.

The platform equipment may be clocked or moved within the lander base to make best use of the available volume and optimise the mass properties for any given set of payloads. The electronic units shown in Figure 7 (right) are approximated as rectangular volumes but would be tailored to the angled sides of the lander base as part of more detailed design activities.

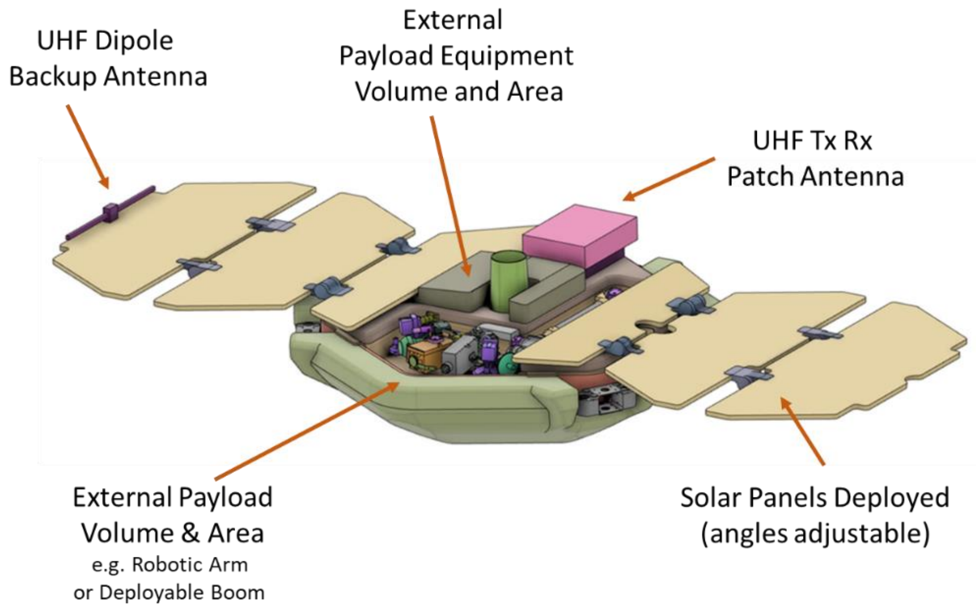


Figure 8. Lander with solar arrays deployed (prior to deployment of robotic arm

The reconfigured lander can host both internal and external payloads. The external payloads and robotic arm sit under the stowed solar array whilst the internal payloads occupy the spare volume in the lander base.

The robotic arm is able to move once the solar arrays are deployed. The PAW concept is retained from Beagle 2 allowing a number of instruments to be mounted to the end of arm (Figure 9). The robotic arm could be substituted by a simple mast in support of instruments not requiring surface sampling or sample gathering.

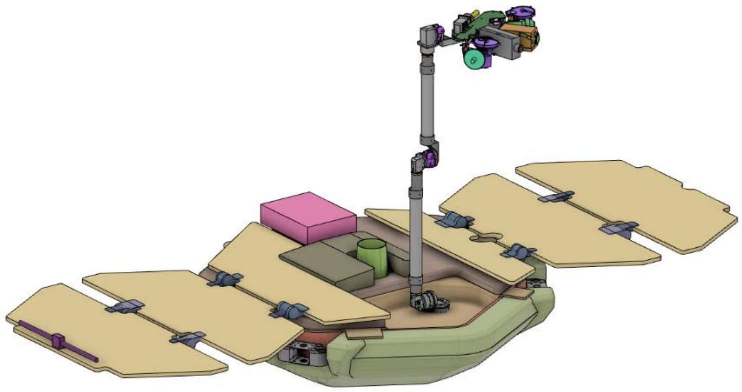


Figure 9. The fully deployed lander with the robotic arm in the mast position

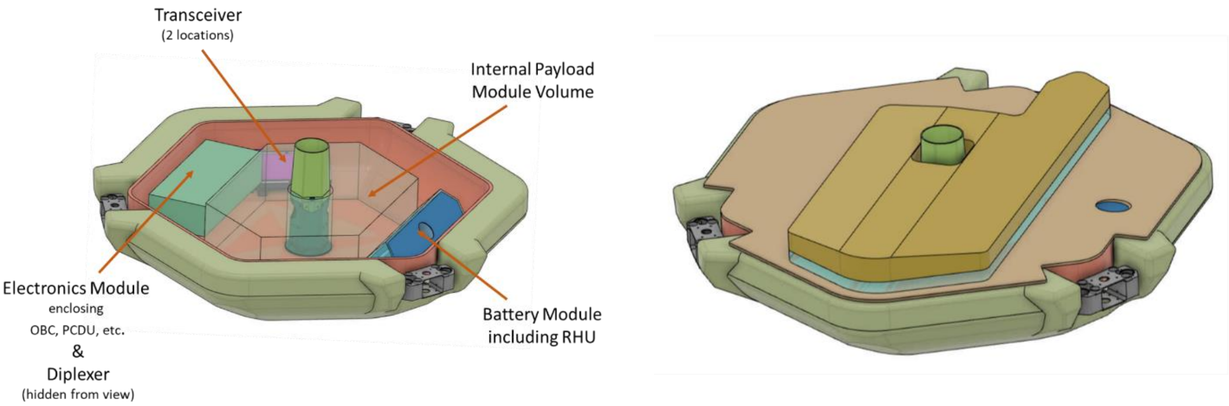
6.1 Mass

The nominal launch mass of the probe (without the SUEM) is 85 kg or 130 kg including all margins. It has been shown that the configuration is extendable to at least 150 kg with resizing of Lander structure and EDLS hardware.

The nominal mass of the lander without payload is 31 kg or 38 k with applied margins. The lander is capable of carrying up to 30 kg of payload mass (internal + external) including all margins. The maximum lander mass including margins is therefore 68 kg.

6.2 Payload Volumes

The total available volume for internal payload (Figure 10) is 0.018 m^3 and the total volume for external payload (Figure 10) is 0.008 m^3. In practice, these values will vary as the number of solar panels, amount of thermal insulation and the electronics & battery modules are tailored to specific mission needs.



Internal volume: **0.018 m^3**

External volume: **0.008 m^3** including the robotic arm (may be increased depending on the solar array configuration and required thickness of insulating foam).

Figure 10. Internal (left) and external (right) payload envelopes and volumes

7 ASSESSMENT OF CANDIDATE PAYLOADS AND INSTRUMENTS

The University of Leicester and The Open University conducted an assessment of the candidate payloads for the reconfigured lander as part of the MSPC study. Their aim was to characterise the typical mass, power, volume, data rates and operational needs/constraints for payloads that could be flown beyond a Mars Sample Return mission. The technical maturity of the payloads were not assessed although many are based on existing instruments. The assessment was based on known characteristics of relevant instruments (previously flown or proposed) but characterised in terms of generic/typical properties.

Five mission categories were considered:

- Geochemistry/astrobiology mission
- ISRU mission – designed to investigate resource availability and accessibility
- Geophysical mission
- Mars weather & lander environment
- Human health

The assessment lists specific measurements in support of each mission category and proposes a payload type for each. Each payload was characterized according to the need for instrument deployment onto the surface, mobility (instruments deployed on small rover or able to roam the surface) and the need for surface and/or atmospheric sampling. The mass, power consumption and volume for each instrument is estimated. The full list of instruments is presented in D9. The outcomes of the analysis may be generalized in the following way:

- Candidate payloads for a future lander mission will have similar mass, power volume and data rate demands to those proposed for the Beagle 2 mission
- None of the payloads produce high data volumes or require significant data processing resources. The need for on-board processing is likely to be driven by image processing associated with the cameras.
- Payload masses vary between 0.5 kg and 15 kg with many in the 0.5 kg range and few payloads with a mass greater than 7 kg.
- Nearly all Geochemistry/astrobiology missions would benefit from mobility and surface sampling
- ISRU payloads would benefit from mobility
- Geophysical payloads typically have low mass (with the exception of sub-surface geology) and are less dependent on mobility.
- Payloads in support of human health and Mars weather generally require access the surface but are less dependent on mobility.

These conclusions suggest that a static lander would be best suited to geophysical, human health and mars weather payloads. Deploying a small rover or mobile instruments from the lander (proposed during post Beagle 2 studies) would increase the effectiveness of geochemistry and astrobiology payloads.

8 ENTRY, DESCENT & LANDING (EDL) SEQUENCE AND ANALYSIS

The EDL sequence for the reconfigured lander is broadly similar to that of the original mission with the exception of vented airbags that cushion the landing. The Bealge-2 mission used non-vented, 'bouncing' airbags that were separated from the probe once the lander reached rest.

This class of lander has no propulsion system and no control loop. Atmosphere entry angle, angle of attack, trajectory and the landing site ellipse are all determined by the carrier/orbiter at the time of ejection.

With reference to Figure 11: During descent (1), the probe software monitors the accelerometer measurements and detects when defined deceleration trends occur. These events are used to trigger the pyros and actuators which initiate the different phases of the EDL. The first event sees the parachute mortar fired along with the aeroshell separation pyro resulting in pilot chute ejection (2) and decoupling of the back shell from the front heat shield. This occurs at approximately Mach 1.4. As the mass on the drogue chute (now attached only to the back shell), is reduced, momentum is lost and the back shell (still attached to the pilot chute) pulls the main chute from its packing bag as the system separates (3). The main chute slows the descent allowing the front heat shield to separate from the probe (4) and fall to the surface.

The probe software responds to the RADAR Altimeter Trigger (RAT) output and commands activation of airbag inflation (5) when the surface is detected. The airbag is vented and the main chute is released on detection of first impact shock (6).

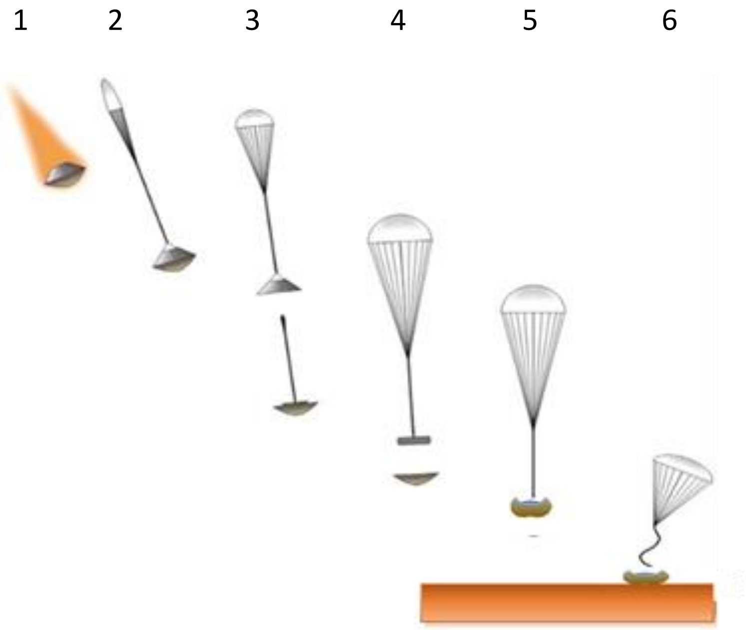


Figure 11. Entry, Descent & Landing Sequence

9 TECHNOLOGY DEVELOPMENT PRIORITIES

This assessment aims to ascertain the technology readiness of the major components and subsystems which constitute the reconfigured lander presented in D1. The MSPC study team has estimated the TRL of all major lander equipment as if procured from European suppliers. The lander shares many design features with the original Beagle 2 lander but presents opportunities for incorporating design improvements and present day technologies.

The Beagle 2 lander design does not exist in a realisable or reusable form and missions based on similar concepts have failed to materialise. If a mission based on the reconfigured lander were proposed, a substantial design and development programme would be required to update the concept, re-engage with a lapsed supply chain and provide engineering artefacts commensurate with modern methods, standards and expectations.

The Beagle 2 supply base was UK-centric and levered suppliers with little or no space industry experience. A markedly different supply chain would be required for a modern, ESA-lead programme. A list of suppliers making up the original Beagle 2 industrial consortium is given in Annex C of D1. Few of the components have been updated or reflown since the original Beagle 2 mission. This assessment conducted during the MSPC study based solely on the state of the technology itself and does not consider the maturity of documentation, analysis or manufacturing processes.

The technology readiness of components from the Beagle 2 mission has been undermined by the fragmentation of the original supply chain and lack of further study. Studies conducted in the immediacy of Bealge-2 such as the Beagle Evolution Study focused primarily on the lander architecture, incorporation of the lessons learned (some of which became less pertinent upon the discovery of Beagle 2) and the opportunities for further exploration of Mars. The industrial capability received little attention. Although the fundamental design of many components remains a valid basis for a future mission, the capability to adapt and manufacture them has either lapsed or diminished. Changes in commercial circumstances, loss of expertise through retirement and the dissolution of development activities result in substantial capability gaps.

The situation is exacerbated by the paucity of documentation from the original mission and the incompatibility of engineering artefacts with modern day software and engineering processes.

Conversely, there are a large number of lander components which could be matured quickly with low programmatic risk. Items such as the lander base, aeroshell and many mechanical items are based on mature and flight proven technologies that require development in a mission or lander-specific form. A broad set of smaller bread boarding and E(Q)M campaigns is a probable component of a future lander development programme.

This study has identified a plausible European source (or route to supply) for all significant lander components. Development programmes for the airbags, parachute mortar and RHU are ongoing or have reached completion. Whilst further development is required to achieve flight-readiness, the foundations of a European supply have been established. Based on cursory information alone, this analysis has not established any reason why the existing European developments should not yield flight products compatible with a future lander mission.

9.1 Key Technology Development items

In practice, the MSPC study was ill-positioned to provide a technology development roadmap for a future lander mission. A more comprehensive technology readiness assessment with the involvement of candidate equipment suppliers and the Agency is a principle recommendation of this study.

1. **Vented Airbags**: Further European development of vented airbags based on Aero Sekur development. The reconfigured lander concept is inherently dependent on vented airbags. Further progress towards a flight-qualified European design is essential.
2. **Parachute mortar**: European development derived from Schiaparelli PDD.
3. **Electronics design:** An electronics module suitable for a Beagle-like lander requires a comprehensive development programme. Whilst appropriate components and electrical sub-systems are contained within existing small satellite and CubeSat designs, the architecture and form factor should be tailored to the lander. The electronics/avionics modules from the existing Mars rover programmes are too large and power intensive for a Beagle-like mission.
4. **Transceiver:** The transceiver presented in the reconfigured lander is based on Beagle 2 and ExoMars heritage. However, further development is required to overcome obsolescence, re-introduce transfer frame decoding into the transceiver (removed for ExoMars) and add support for low power lander modes (wait on hail and hardware reset).
5. **RADAR Altimeter:** (if desired) – Although a full range altimeter is not necessary for successful EDL, a full range altimeter would allow more accurate reconstruction of the entry, descent and landing phases. Such a development could be based on a miniaturised version of the Schiaparelli altimeter and would likely require a comprehensive development programme.

9.2 Lander elements at or below TRL-5

The MSPC study was asked to identify all lander elements with a TRL equal to or lower than TRL-5. The following table lists these items. Note the TRL 1-5 items do not necessarily determine the top priorities for future development programmes and some development needs are dependent on the mission specification.

Table 5. TRL 1-5 items

Element	European TRL	Notated Development constraints, considerations & assumptions
Airbag Refraction Device (if required)	1	• Entirely new development. Detailed concept not yet defined. • Some concepts have been considered during previous programmes. Relatively simple cable retraction mechanism are envisaged. • Further assessment of the retraction need is required. The need for retraction may be payload specific and may depend on reach and capability of the robotic arm.
Altimeter	3	• Possibility of chip obsolescence for Beagle 2 design. • Processor component of the baseline Roke RAT is not radiation hard, thus a delta-qualification is unavoidable. • No European alternatives to Roke unit have been identified. • Schiaparelli altimeter could be considered but thought to be too big for this application

Descent Camera (optional)	4	• Cameras are likely available although the system-level concept requires further investigation. Level of development required will depend on the mission objectives. • Implementation dependent on landing Ls and prevailing illumination conditions. • Target a low-resolution, large pixel camera
RHU (3W)	4	• Existing development programme funded to TRL-5 with University of Leicester • TRL-6 planned for 2024
Probe Software	4	• Advances in software development practices and real time platforms make the existing Beagle 2 software unsuitable for a future mission. Whilst many of the principles and functional approaches may still apply, it is assumed that a full, software development and qualification programme is required. • There is no obvious reason to redefine the boundary between probe and lander software although different architectures should be evaluated as part of further study.
Lander Software	4	
UHF Antennas, Tx & Rx Patches (lander antennas)	5	• TRL-5 for patch antennas although similar concepts have been proven • Fractal antennas at TRL-3/4 offer opportunity for miniaturisation. • Whilst the antenna itself may be relatively simple to design and characterise, the mechanical configuration of the antenna may require proof of concept. • Antenna development considered important but relatively low risk.
OBC and PCDU Electronics (incl. redundancy)	5	• Assumes use of CubeSat components offering relevant functionality but not distinctly qualified for the Martian environment or adapted to the configuration of the lander. • CubeSat boards would prove-space inefficient and this new board layouts and configurations are required. • Repackaging of electronic units required for integration into the lander. • Development of interfaces electronics not offered by existing designs (e.g. pyro drivers)
Transceiver	5	• Transceiver largely based on Beagle/Exomars heritage. • Development required for reconfiguration and obsolescence. • The ExoMars transceiver could be used at TRL-8 if transfer frame coding were performed on the lander's OBC/PCDU. • Considered a low-risk development

10 CONCLUSION

The MSPC study has proposed a reconfigured lander concept for a small lander mission similar to Beagle-2. The reconfiguration has focused mainly on the lander with the assumption that the aeroshell design and geometry remain valid for a future mission. The design has benefited from the lessons learned from the original mission, improved technologies and the ideas and experience of those who worked on the original mission. The Cabriolet configuration overcomes the two major flaws in the Beagle 2 design by ensuring solar cells and the UHF antenna are usable in the stowed configuration. Despite obvious differences between the reconfigured lander and Beagle 2, the lander shares many design features with the original and would operate in a very similar way. Perhaps the most distinct difference between the two landers is the application of a vented airbag that is necessitated by the Cabriolet architecture and offers mass, volume and reliability benefits.

The lander has been resized to increase the available payload volume and alleviate the overbearing constraints of packing density and mass faced by the Beagle 2 team. It is proposed that the electronic subsystems are based on components available from small satellite and CubeSat manufacturers. The EDL sensor suite has been enhanced with additional accelerometers and a MEMS gyro to allow reconstruction of the probe's altitude and attitude during the descent. The probe will transmit live EDL telemetry through the descent and landing phase.

Candidate payloads for small lander missions have been identified. Despite advances in technology, many of the payloads have mass, power, volume and data storage requirements that are commensurate with the original Beagle 2 instruments. The robotic arm will have a similar form to the original mission – more advanced actuation and autonomous operation are likely too mass intensive for a small lander mission.

The Beagle 2 lander design does not exist in a realisable or reusable form and much of the industrial capability has diminished or been lost. Significant development programmes will be required if key components such as the vented airbags, parachute mortar and RHU are to be sourced from European suppliers. The transceiver and Radar Altimeter Trigger require development programmes to overcome obsolescence and modernise designs.

Despite the fragmentation of the Beagle 2 supply chain, many of the mechanical components could be derived from proven designs and manufactured using standard processes. A large number of the components could be developed and qualified at low risk to a future development programme. A Beagle-like lander could be realised relatively quickly if the airbags and other key equipment were sourced from outside Europe.

The next step for lander development could be the combination of Phase A/Pre-Phase A study and Technology Readiness Assessment involving candidate suppliers and a wider pool of experts. Engaging with suppliers and third parties a will greatly increase understanding of the broader systems engineering concerns and provide the inputs necessary for a more detailed assessment of the lander's architecture and performance. Further study will require the resources necessary to reconstruct the analytical basis assess the lander's design.

ANNEX A: KEY SPECIFICATOINS FOR THE RECONFIGURED LANDER CONCEPT

Parameter	
Mission Duration	Ls0 to Ls180 maximum, 360 sols maximum
Landing site latitude	0 - 30N
Landing site altitude	+1 to -3 km relative to geodetic Martian datum
Payload Complement	
Robotic Arm or Boom	Optional, provisioned in top floor payload area and volume
PAW instruments	Mission specific Instrument array + stereo camera pair
Payload Processors	Optional
Probe Launch Mass	85kg nominal, up to 130kg.inclusive of all margins (excluding SUEM) Design configuration extends to at least 150kg but likely to require resizing of Lander structure and EDLS hardware
Lander design	
Total Lander Mass	Up to 68kg inclusive of all margins
Payload Mass	Up to 30kg (internal plus external) inclusive of all margins
Lander Mass (excl. payload)	31kg nominal, 38kginclusive of all margins;
Payload Internal Volume	at least 0.018m^3
Payload External Area	at least 0.008m^3
EDL	
Parachute Configuration	Drogue parachute deployed in 1.8 to 1.4M range Main parachute deployed in 0.6 to 0.4M
Front heatshield and parachute sizing	Sizes particularly dependent on mission specific landing site altitude, selected atmosphere density profile range and Lander payload mass; Heatshield indicative range: 1.1m to 1.3m diameter Main ringsail parachute indicative range: 11m to 13.5m diameter Drogue DGB parachute indicative range: 2.1m to 2.7m diameter
Impact energy dissipation	Deadbeat Airbags, Lander foam outer layer; airbag sized for 38kg Lander at 16m/s terminal descent velocity
Descent and Landing Events	Control - RAT, Z-axis Accelerometer Monitoring – MEMS Gyro, additional Accelerometers as required
Airbag venting function	Venting control algorithm with inputs from X and Y axes accelerometers
Thermal design	
Unit Temperature range	Avionics: Op - -55°C to +45°C Survival: -70°C Transceiver: Op - -55°C to +45°C Survival: -80°C Battery: Op - -30°C to +60°C Survival: -30°C Solar array: Op - -110°C to +20°C Survival: -120°C
No. Heater lines available	12 Zonal Heater
Thermistor Availability	3 per heater circuit, Payload – 10 (ANY/ANP/ANB)
Additional Heat source	Am based RHU – 3W thermal Power
Power	
Power Bus	28V Unregulated/Regulated Bus
Solar Cell Area and type	40mm x 80mm. Total of 198 AZUR32 cells configured into 22 strings of 9 cells each; 2 parallel strings per section, 11 sections,
Solar Array Output Ls0, 10°N OD 0.5	1280 Wh/m^2 with 32% cell efficiency, inclusive of system margin
Battery Cell type	Molicell/ABSL ICR-18650M V3
Battery Design	36 cells arranged as 5 strings of 6 cells each plus 1 string covering cell/string failure and with 3W RHU installed centrally prior to launch.
Battery Capacity BOL	84Ah, 310Wh inclusive of 20% system margin but excluding “spare” string
TT&C	
Antenna design	EDL – UHF Slot Antenna Main mission - UHF Tx/Rx 4 element patch with dipole back-up
Frequency	UHF Tx and Rx Frequencies– as per proximity 1
Target Payload daily data downlink volume	Mission dependant Target value – Rate 256kps, volume 130Mb per Sol
Data Bus	Mil-Bus/CAN bus/CAN-2 bus/UART

END OF DOCUMENT