Beagle 2: the Exobiological Lander of Mars Express

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In late 2003, the Beagle 2 lander component of the Mars Express mission is planned to touch down in the Isidis Planitia region of Mars (265.0°W, 11.6°N). Once safely deployed on the surface, Beagle 2 will conduct an intensive and exhaustive programme of surface operations for about 180 sols (equivalent to about 6 months on Earth). The principal objective is the detection of extinct and/or extant life, or at least to establish if the conditions at the landing site were ever suitable for life to have evolved in the planet's history. To achieve this goal, a systematic set of experiments using a complementary suite of instruments will perform *in situ* geochemical, mineralogical and petrological analysis of selected rocks and soils. Studies of the martian environment will also be conducted via chemical analysis of the atmosphere, local geomorphological assessment of the landing site and measurement/monitoring of dynamic environmental processes, including transient events such as 'dust devils'. Further studies, unique to Beagle 2, include analysis of the subsurface regime using a ground penetration tool and the first attempt at *in situ* isotopic dating of rocks on another planet.

The complete experiment package weighs less than 9 kg and requires less than 40 W of power. With a probe mass limit of 69 kg, imposed by mission constraints, and a landed mass of 33 kg, Beagle 2 thus aims to fly the highest mass ratio of payload-to-support systems of any mission to Mars. This is achievable only by adopting an integrated design approach and employing minimal or zero redundancy.

1. Introduction

Beagle 2 is named to honour the ship used in the epic voyage of Charles Darwin and Robert FitzRoy during 1831-1836, which led to publication of Darwin's *On the Origin of Species*. Nearly a century and a half after the publication of the first edition of this volume, Beagle 2 aims to discover whether the theory of evolution extends to a second planet in the Solar System. Darwin's more famous biological works means that the contributions made by him to geology (and those of FitzRoy to meteorology) are often forgotten. Beagle 2, like its predecessor, addresses a wide range of subjects: the life question, of course, but also the geochemical and mineralogical characterisation of the immediate landing site and the chemistry of the atmosphere. To fulfil these goals, Beagle 2 has the following remit:

- geological investigation of the local terrain and rocks, especially their light-element chemistry, composition, mineralogy, petrology and age;
- investigation of the oxidation state of the martian surface within rocks, soils and at protected locations beneath boulders;
- full characterisation of the atmospheric composition to establish the history of the

planet and the processes involved in seasonal climatic changes and diurnal cycling;

- search for key criteria deemed to demonstrate that life processes could have operated in the past;
- determination of trace atmospheric gases, indicative of extant life at some location.

The above list, in many respects, exceeds what has been achieved by previous missions. It goes far beyond the goals stated for other Mars landers under consideration and transcends the Science Definition Team's ambitions for Mars Express itself. Rock dating, atmospheric characterisation, climatic change monitoring and the search for possible biologically-derived trace constituents are all among the most important aspects of the study of Mars, and are envisaged as firsts that could be achieved by Beagle 2. Presumably none of these was thought to be possible or within the scope of small landers, as envisaged at the conception of the Mars Express project.

In its original form, Beagle 2 was conceived as a 'large' (108 kg) lander that carried additional instruments to enable it to act as the third node in a geophysical network. Following the imposition of more stringent mass constraints (60 kg only available for a landing craft), a network of several stations was no longer feasible. As a result, the additional elements of the Beagle 2 payload became redundant and were therefore deleted. Likewise, the earlier version of Beagle 2 had provision for a small rover to transport sampling devices some distance from the lander, but the discovery that the subsurface sampler (the 'Mole') had inherent lateral mobility also allowed that element to be discarded. It is encouraging to note that, throughout the challenging period from proposal to delivery, the scientific goals (reflected in the payload) remained intact. This has been achievable only through the skill and dedication of the Beagle 2 team of engineers and scientists.

1.1 Background

In 1976, two Viking spacecraft landed on Mars with the prime objective of searching for evidence of life on a second planet in the Solar System. Results from a package of biological activity experiments and a pyrolysis gas chromatograph-mass spectrometer (GC-MS) were interpreted, by majority verdict rather than unanimous consent, as negative. The one positive result that suggested operation of a martian metabolism was subsequently interpreted as a chemical artefact. The intervention of an oxidative surface chemistry on the planet rather conveniently explained the inability of the GC-MS to observe any organic matter above the detection levels, in spite of some theories that predict the presence of meteorite debris, and hence carbon compounds, even in a sterile environment.

Although the findings were disappointing, Viking provided the first close-up images of the martian surface, major element chemical analyses of soil samples and meteorological information, a feat duplicated at considerably less cost and with simpler technology 20 years later by Pathfinder. An unexpected bonus of Viking was that an exploratory compositional and isotopic study of the atmosphere enabled a link to be made with a previously poorly understood group of meteorites: the Shergotty, Nakhla and Chassigny association or SNCs (Bogard & Johnson, 1983; Becker & Pepin, 1984; Carr et al., 1985). The number of SNC-class finds has now grown to more than 20 specimens; their genetic relationship has been confirmed by exceedingly precise oxygen isotopic measurements: $\delta^{17}O$, $\delta^{18}O$, where $\delta^{17}O = [(^{17}O/^{16}O_{\text{sample}}/^{17}O/^{16}O_{\text{standard}}) - 1] \times 1000$, per mil, or ‰; and so on for other δ values. In detail on a plot of $\delta^{17}O$ versus $\delta^{18}O$, the so-called 'cap-', 'cap-delta-', or 'big-delta-' ^{17}O value ($\Delta^{17}O = \delta^{17}O - 0.52 \times \delta^{18}O$) for martian meteorites is 0.321±0.013‰ (Franchi et al., 1999). The presence in some of the meteorites of six atmospheric species having the same abundance ratios and isotopic systematics (e.g. high $\delta^{15}N$) as values measured in the martian atmosphere, points indubitably to Mars as a provenance (Pepin, 1985). The young geological age (1.3 Ga to 180 Ma) of all but one (4.5 Ga) of the SNC meteorites (Wood & Ashwal, 1981; McSween, 1985; 1994) provides circumstantial evidence of their being from a body sufficiently large (planetary-sized) to show recent volcanic activity. Although some scepticism remains, there is almost universal belief that SNCs are martian. Data from SNC research, in conjunction with Viking and Pathfinder results, guided the scientific goals of Beagle 2, which are harmonised rather than being a series of uncoordinated efforts from a group of disparate investigators.

Although all the SNC samples are igneous in origin, Nakhla, EET A79001 and ALH 84001 show good evidence of low-temperature hydrothermal alteration, producing carbonate and other mineral deposits (Carr et al., 1985; Gooding et al., 1988; Wright et al., 1988; Mittlefehldt, 1994). These discoveries have proved highly beneficial to the study of the martian environment and to understanding the chronological sequence of events. For 75 years, however, petrologists failed to recognise the presence of carbonate in these igneous meteorites. In 1985 geochemical analyses (Carr et al., 1985) uncovered the existence of carbonates, a vital facet of martian meteorite research. Eventually, Gooding et al. (1991) demonstrated unequivocally the presence of inclusions microscopically. For a while it was argued that carbonate in martian meteorites must be a terrestrial artefact, but $\delta^{13}C$ measurements strongly suggest otherwise (Carr et al., 1985; Wright et al., 1988). Interpretations based on the ^{14}C content of carbonates in EET A79001, that such minerals were terrestrial (Jull et al., 1992), may be erroneous owing to experimental problems (Wright et al., 1997a).

Notwithstanding the above, carbonates in ALH 84001 are isotopically distinct from all similar species on Earth, and have $\delta^{13}C$ values consistent with those expected for the martian atmosphere. Debates concerning their origin have now switched to the interpretation of models used for calculating carbonate formation conditions (Wright et al., 1992). Techniques that rely on major-element abundance, measured by electron microprobe in selected areas, invoke a high-temperature (600°C) formation event (Harvey & McSween, 1996). Bulk oxygen isotope and, to some extent, carbon studies of carbonates by chemical dissolution require a scenario involving liquid water and temperatures in the range 0-80°C (Romanek et al., 1994). Other studies, at high spatial resolution, indicate a mixture of origins at a variety of temperatures, for different generations of carbonate, none of which exceeds 250°C (Valley et al., 1997; Leshin et al., 1998; Saxton et al., 1998).

The origin of the carbonates in SNC meteorites is of vital importance because they are accompanied by organic matter (Wright et al., 1989). Also identified within the mineral, at least in some samples, are features that are interpreted to be nm-sized fossils (McKay et al., 1996). Thus it has been suggested that biological processes have been acting on Mars. A view that all the organics are a result of contaminants derived from percolating Antarctic melt waters (McDonald & Bada, 1995; Bada et al., 1998) can be refuted on a number of grounds. For example, oxygen isotope and D/H results (Wright et al., 1997b) would have been disturbed by inundation; as these remain recognisably different from Earth values, they must be very little affected by terrestrial water exchange. Although each of the martian meteorites contains some Earth-generated contamination, specimens where the organic matter is in excess of 1000 ppm, e.g. EET A79001 (Wright et al., 1989), are considered to host some pre-terrestrial martian carbonaceous material.

Whether the existence of nanofossils or indigenous organic matter in martian meteorites is genuine or not, the inescapable fact remains that conditions conducive to life prevailed on Mars in the past. Furthermore, in the years since Viking, investigations into the viability of terrestrial organisms have demonstrated their adaptability and tenacity. It has been shown that they can thrive and multiply in acid, alkaline and highly saline conditions, apparently unaffected by pressure, capable of living at temperatures ranging from –12°C to 113°C, with the simplest and most ancient forms being the most tolerant (ESA Exobiology Team, 1999). How long organisms may lie dormant and survive at even greater extremes, particularly at the low-temperature end of the scale, is unknown. Microorganisms have been shown to inhabit Antarctic dry valleys, the nearest equivalent on Earth to martian conditions. It follows that the decision to conclude that Mars is totally hostile to life, on the basis of the very preliminary results from Viking, was premature.

According to theories proposed after Viking, a problem that must be considered with respect to carbonaceous matter is its survival on the surface. The planet's regolith is highly oxidised, a property believed to arise from hydrogen peroxide in the atmosphere. Models exist relating to this question (Bullock et al., 1994; Stoker & Bullock, 1997; Zent & McKay, 1994). One suggests penetration of the oxidant to less than a few metres in soil, the other assumes a vast turnover so that all material down to 150 m is oxidised. The martian rocks examined by the Alpha Proton X-ray Spectrometer (APXS) on Pathfinder's Sojourner rover showed evidence for a weathering rind (Rieder et al., 1997) but the depth of this layer was not ascertained, and the oxidation state was not recorded. One way to address this issue would be through an *in situ* investigation that determines the concentrations of certain components (especially oxidation-sensitive organic compounds) with depth in the regolith.

Unfortunately, SNC meteorites, being of deep-seated mafic origin, are not able to elucidate directly the problem of oxidation within the regolith. However, we note here that martian soils are sulphur-rich, possibly due to volcanic exhalations, and that SNC meteorites contain sulphides and sulphates (Burgess et al., 1989) and even nitrates (Grady et al., 1995). Furthermore, from geochemical data it appears that SNCs and the Viking and Pathfinder soils are related, possibly two-component mixing, with one end-member being SNC-like and the other being andesitic.

It should be borne in mind that all the rocks investigated by Pathfinder were igneous and of the same petrological type, with the exception of one 'rock' that was possibly a soil clod. This was disappointing because it was thought that the Pathfinder landing site (a washout area) would be a good place to find rocks of sedimentary origin. Perhaps Pathfinder was unlucky; future missions should continue to search for rock types from sedimentary formations. Note that the Pathfinder APXS attempted to measure carbon abundance, and hence recognise carbonates (widely thought to be present at, or near, the martian surface) but none was found. The problem with this approach is that atmospheric CO_2 intervenes between the uneven rock surfaces and the detector, resulting in a major background signal. Furthermore, although some close-up images of rocks were taken by the camera on Sojourner (Smith et al., 1997), these were obscured by dust, which also affected the APXS data. As yet, no microscopic imaging studies have ever been made on Mars.

Although regions on the martian surface have been assigned relative ages derived from crater counts, the only absolute dates available for martian rocks come from SNC meteorites, and, of course, *their* exact provenance on Mars is unknown. In this respect, it should be noted that the APXS made measurements that revealed the average potassium content of the 'soil-free rock' to be 0.7±0.1%; the age of such a rock could have been estimated from a knowledge of the ^{40}Ar content had the noble gas abundance been measured.

While the abundance and isotopic compositions of martian atmospheric constituents have been used to such good effect in identifying martian meteorites, these values, particularly the isotopic ratios, are not well constrained. The data quoted for $^{14}N/^{15}N$ (165, $\delta^{15}N = +650‰$) and $^{12}C/^{13}C$ (88, $\delta^{13}C = +11‰$) were for a limited number of measurements, which were made using an instrument that was never envisaged as a dedicated isotope mass spectrometer or, indeed, calibrated in this respect. In consequence, there is a ±50‰ to ±100‰ (i.e. ±5% to ±10%) error attached to the figures. Neither the ill-fated Mars Polar Lander (including the Deep Space 2 microprobes) nor the Mars Surveyor mission carried a mass spectrometer that could have provided more precise data. A totally independent assessment of the full isotopic composition of carbon dioxide on Mars, both its carbon and oxygen, is still required employing instrumentation designed for that purpose. The same applies to the crucial measurements of $\delta^{15}N$ and $\delta\Delta$.

The noble gas isotope ratios of martian atmospheric constituents are even less well defined than those for carbon and nitrogen. A key value for argon, the third most abundant constituent in the atmosphere of Mars, is $4 \leq {}^{36}Ar/{}^{38}Ar \leq 7$, described by some authors as matching the terrestrial value, which happens to be 5.3, conveniently around the mean of the Viking measurements. Quite unaccountably, SNC meteorites have a ${}^{36}Ar/{}^{38}Ar$ of 4.1±0.2 (Wiens et al., 1986), a value distinct from all other meteorites and hence a possible diagnostic indicator of a martian provenance. Other intriguing noble gas results from Viking and the meteorite clan concern ${}^{40}Ar/{}^{36}Ar$ (3000±500, c.f. Earth 296) and ${}^{129}Xe/{}^{132}Xe$ (2.5±2, c.f. Earth 0.97). Both ratios imply a much greater abundance of radiogenic elements (${}^{40}K$ and ${}^{129}I$, respectively) in the martian surface than Earth, or that an early martian atmosphere was lost and replenished from crustal outgassing.

Water is another intriguing trace constituent (volume mixing ratio 3.0×10^{-4} mol.) in the martian atmosphere. No D/H ratios were measured by Viking, but some have been afforded by astronomical observations at infrared wavelengths from ground and airborne telescopes, and the ratio is believed to be about 5.0±0.2 times the terrestrial value of 1.6×10^{-4}. The quoted error, if applied to the Earth, would suggest all terrestrial D/H ratios were the same, which is not true; D/H on Earth varies in a predictable way and reveals much about the hydrological cycle. Measurement of the equivalent parameter on Mars has the potential to provide information on equivalent planet-wide phenomena, including seasonal climatic effects, and addresses the issue of Mars' warmer and wetter past.

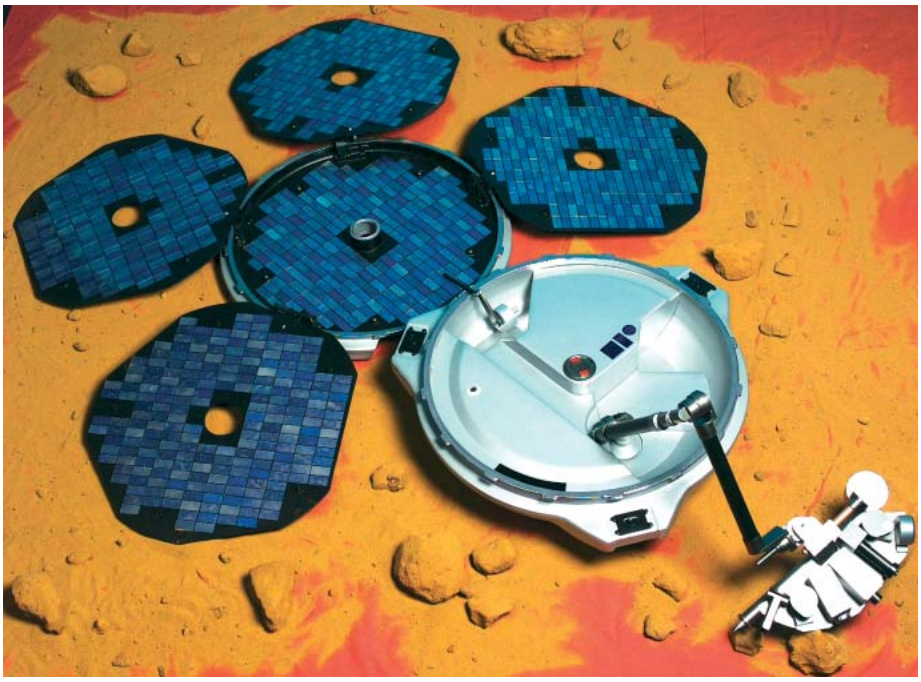
Looking in greater detail at the effects of fluids on Mars, the oxygen isotopic composition of water released from the hydrated silicates of martian meteorites (Karlsson et al., 1992; Baker et al., 1998) do not fall on the Mars line defined by high-temperature minerals. The results predict that water in the martian atmosphere is not in equilibrium with the surface of the planet and has been, or is being, isotopically affected by photolytic or exospheric loss processes. Clearly this needs to be studied further by future space missions.

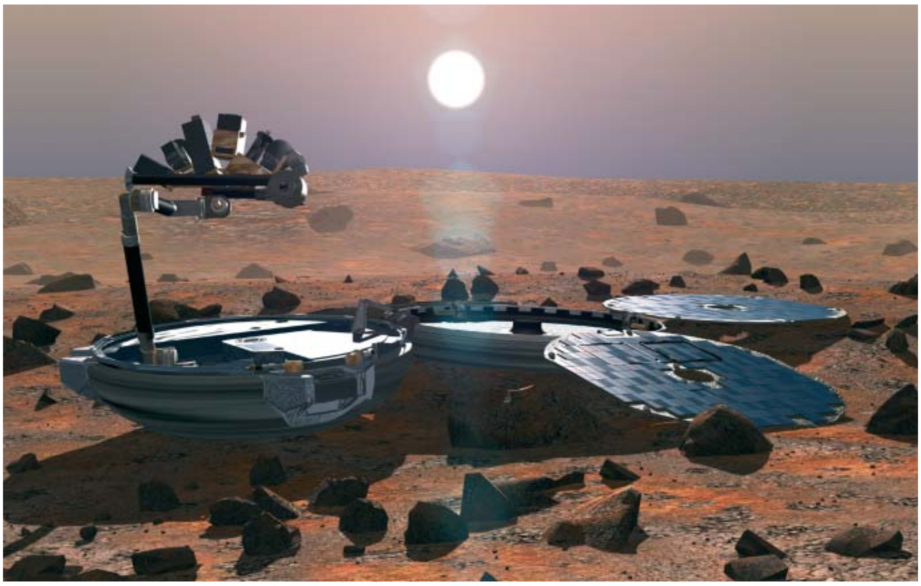
Quite apart from the major and minor constituents of the martian atmosphere (CO_2, N_2, Ar, O_2, CO, H_2O, Ne, Kr and Xe in abundance order) there are also likely to be important trace constituents. So far, only upper limits can be placed on these (Owen, 1992; Owen et al., 1997). It is vital that the minor and trace species on Mars are measured. The abundance and, where possible, isotopic information for trace atmosphere gases could be the best possible indicators of contemporary biological activity on the planet. The equilibrium composition of Earth's atmosphere, for example, is dictated by the delicate balance of biological production on the ground and chemical destruction above it. Sampling Earth's atmosphere anywhere on the planet will lead to the detection of species that could not be there but for biology. The same would probably be true for Mars if life exists; even a remote subterranean lifeform might be recognised from the identification of a gaseous by-product of its metabolism, i.e. a species out of chemical equilibrium. The best chance in this respect would appear to be methane: it is produced on Earth by a great variety of primitive organisms, is chemically short-lived, being destroyed by photolytic oxidation but stable to gas-solid degradation reactions, and detectable at high sensitivities. Since biological processes tend to impart large isotopic fractionations during methane production from its precursors, this parameter may be useful in the preliminary hunt for extant life on Mars.

1.2 The Beagle 2 investigation

The main focus of the Beagle 2 scientific payload is to establish whether there is convincing evidence for past life on Mars or to assess if the conditions were ever suitable. Beagle 2 also plans a globally responsive test to see if there is any present-day biological activity on Mars.

Fig. 1. A fully deployed model of the Beagle 2 lander showing the arrangement of solar arrays (four petals plus the lid). The base unit (diameter ~66 cm) accommodates GAP and the lander systems, including batteries and transceiver. The PAW is shown deployed and making contact with a sample under investigation. ***All Rights Reserved, Beagle 2***





In 1996/97, ESA's Directorate of Manned Spaceflight and Microgravity commissioned a study into the search for life in the Solar System. The final report (ESA Exobiology Team, 1999) concluded that, despite Viking results, Mars represented the best immediate opportunity for searching for life beyond the Earth. The presence, or recognition, of any, or all, of the following were considered to be important indicators of biology:

— water;
— appropriate inorganic minerals (e.g. carbonates);
— carbonaceous debris;
— organic matter of complex structure;
— chirality;
— isotopic fractionation between reservoirs (e.g. organics and carbonate).

No other Mars mission yet plans such a comprehensive and complete investigation. Furthermore, martian sample-return missions, once the preserve of NASA, but increasingly seen as likely to be driven by a European-led effort, are unlikely to yield results before 2015. However, none of the above tests provides an unambiguous answer alone. It is therefore the key objective of Beagle 2 to perform a programme of experiments using compatible and synergistic instrumentation capable of addressing five of the above six indicators.

At the centre of the Beagle 2 scientific payload is a miniaturised chemical laboratory, the Gas Analysis Package (GAP), designed to make quantitative and stable isotopic measurements of gases such as H_2, N_2, O_2 and CO_2. GAP includes a 6 cm-radius magnetic sector mass spectrometer, which can be operated in either static or dynamic modes, and the supporting equipment to analyse atmospheric, rock and soil samples from the surface of Mars. The system can process and determine some of the noble gases (Ne, Ar and Xe; including some isotopic measurements) as well as anticipated trace constituents such as CH_4. The search for chirality was omitted from the Beagle 2 programme on the grounds that the most interesting molecules require the complex step of derivatisation; it would seem prudent to confirm their existence before including the necessary processing steps that would complicate the instrumentation.

To assist in the primary mission objective and provide essential context, the Beagle 2 payload incorporates a set of deployable *in situ* instrumentation. The payload therefore incorporates an arrangement of imaging devices, field spectrometers, sampling tools and environmental sensors in order to characterise fully the landing site in terms of geology and environment. By definition, this array of diverse yet complementary instrumentation provides a degree of scientific redundancy to a mission with minimal or zero engineering redundancy. Furthermore, even if the main exobiological objective of the mission proves inconclusive or the negative results of Viking are confirmed, a wealth of novel science will be conducted with the Beagle 2 payload.

The individual experiments on Beagle 2 are described in detail in later sections; here, the payload is considered in a general sense. The lander configuration is shown in Fig. 1; its mass breakdown is given in Table 1. Together, the GAP and the lander service systems (electronics, batteries, transceiver etc) occupy two-thirds of the lander base. The *in situ* instruments and sampling tools are located on the Position Adjustable Workbench (PAW), effectively the ‘hand’ at the end of a robotic manipulator that unstows when the lander is unfolded on the surface. During transit to Mars, these items occupy the remaining recessed third of the lander base. Finally, the majority of environmental sensors are strategically located about the lander.

Other novel elements of the *in situ* payload include a ‘torch’: a cluster of LEDs for white-light illumination of surface materials to determine the true colour of the martian surface; and a ‘spoon’: a simple soil acquisition-device to act as a backup for the Mole.

As with any lander-based mission, the camera system on Beagle 2 plays a crucial role in both the engineering and the science. Shortly after the lander is deployed on the surface, a panoramic view of the site will be provided by one of the cameras with the aid of the Wide Angle Mirror (WAM), a device attached to the PAW. This will allow the mission planners to unstow the PAW safely subsequently and avoid any obstacles that may be present. The complete scientific investigation of the landing site with the stereo cameras using the spectral filters will be accumulated systematically over the primary mission period because of the data volumes involved, communications constraints and other experiment requirements. However, an early priority for the cameras is to image the area within reach of the PAW and allow a Digital Elevation Model (DEM) of the surface to be constructed. Such a model is vital for planning the *in situ* analysis and sampling activities of candidate rocks and soils. In addition to assessing their morphologies and spatial distribution, rocks within reach of the PAW and the sampling Mole will be imaged through various filters to determine their composition remotely. A set of candidate sites for detailed

Table 1. Beagle 2 mass budget (kg).

Scientific Payload	
GAP and local electronics	5.74
PAW	2.75
BEEST	0.250
ESS	0.156
Subtotal	*8.896*
Lander Engineering	
Structure (base and lid) including main hinge, etc	11.972
Solar panels including hinges	3.21
ARM	2.11
Transceiver	0.65
Battery	2.63
Electronics and memory	3.02
Miscellaneous (cabling, bracketry, MLI etc)	0.692
Subtotal	*24.284*
Lander total (landed mass)	*33.18*
Probe Engineering	
Structure (heatshield and back cover)	17.81
Parachutes	3.26
Airbags and gas generator	14.59
Subtotal	*35.66*
Probe total	68.84

investigation will be selected based on the remote-sensing data and engineering parameters. The cameras also play an important role in understanding the absorption properties of the atmosphere, in particular with respect to dust and water vapour.

Close-up imaging of rocks and soils will be done initially using one of the stereo cameras, configured to emulate a hand-lens by selecting the appropriate 'secondary optic' filter. Observations at higher magnification are achieved by the self-illuminating microscope, which requires contact to be made with the surface to establish a fixed stand-off distance. Both activities will provide important data on the texture of the rock/soil and nature of the particulates on the surface of the sample under investigation. Any remnant microstructures, if present (and visible) and not destroyed by erosion or the sample preparation process, should be resolvable. The microscope will also provide spectral information on individual grains and identify any fluorescing minerals or materials.

The *in situ* spectrometers will analyse specified areas of each candidate rock or soil patch, previously imaged with the cameras, to determine elemental chemistry and iron mineralogy. A range of major and trace element abundances will be determined by the X-ray spectrometer (XRS) and the iron-bearing minerals in the sample will be identified by the Mössbauer spectrometer. Because the penetration depths of the analysing fluxes for both these techniques are low, the true chemical and mineralogical nature of the fresh material can be determined only by removing any weathering/alteration rind and adhering soil/dust veneers. Mechanical sample preparation is therefore necessary by the PAW Rock Corer Grinder tool. The other function of this tool is to acquire solid samples from rocks in the form of chippings for analysis by GAP.

There is much synergy between experiments in the payload. For example, GAP in conjunction with XRS will be the first to attempt to date rocks on the surface of another planet by radiometric means. To perform a crude radiometric age estimate requires a precise measurement of potassium content in a sample made by XRS and a precise measurement of argon made by GAP from the same sample. GAP will also attempt to derive an exposure age of the surface material by analysing neon isotopic compositions (^{20}Ne, ^{21}Ne, ^{22}Ne).

In the search for organics, the philosophy adopted by Beagle 2 is that unoxidised soil material is most likely to be either at depth, below the superoxidised horizon, or alternatively located under relatively large (~1 m) boulders, which may have lain undisturbed for aeons. The strategy for retrieving such specimens uses the Mole, the primary soil sampling tool deployed from the PAW. The device has the ability to propagate itself directly into the soil to depths up to 1.5 m or crawl across the surface and be deverted under boulders to acquire material from these protected regimes. Elemental chemical analysis performed by GAP (light elements) and XRS (major and trace elements), together with Mössbauer analysis, of such material will provide a route to testing the oxidation hypothesis and developing meaningful models of martian surface environmental conditions.

The quantity of organic matter in acquired samples, if present at all, could be small or highly cross-linked, approximating to elemental carbon (as in some of Earth's most ancient rocks) because of chemical processing. The search for organics will, therefore, be conducted by stepped combustion, a technique that distinguishes carbon species by the temperature at which they burn or degrade in oxygen. Similar experiments have been performed on Earth using many hundreds of meteorite samples and terrestrial rocks, all of which show some trace of organic matter either indigenous to the specimen or from terrestrial biogenic sources. This sort of contamination, which causes difficulties for some research on Earth, could be invaluable on Mars. The stepped combustion method when applied to martian soils and rocks will confirm whether there are any indigenous forms of carbon with the appropriate combustion temperatures for them to be organic. Combustion, of course, converts all carbon entities into CO_2, each with 100% efficiency, unlike pyrolysis which represents only a partial conversion of some components.

The stepped combustion technique that converts organic carbon to CO_2 also allows the measurement of the isotopic composition. Indigenous organic matter on Mars might have a diagnostic $\delta^{13}C$; indeed, the $\delta^{13}C$ values of organic matter in martian meteorites hint that it might be slightly different from that on Earth, but all experiments are confused by terrestrial contamination. If bulk organic matter and carbonates are found adjacent in rocks on Mars, then measurement of the isotopic difference between them will be essential. On Earth, at least, a 30‰ fractionation between inorganic and organic carbon is the most general signature of biosynthesis and has been observed in 10 000 examples all the way back in history, from present day until 3.8 Ga (Schidlowski, 1997); only biology is able to impose such an effect. Such is the ubiquity of terrestrial biology that there is no such thing on Earth as a rock without organic material. Even rocks carefully collected on the Moon, protected and preserved on Earth, show that Earth's biological activity is impossible to exclude. Rocks collected and returned to Earth from Mars would almost certainly be susceptible to such effects. Therefore it is imperative that stepped combustion, with attendant isotopic measurements, be performed *in situ* on Mars to establish a true positive or negative for the presence of organic matter.

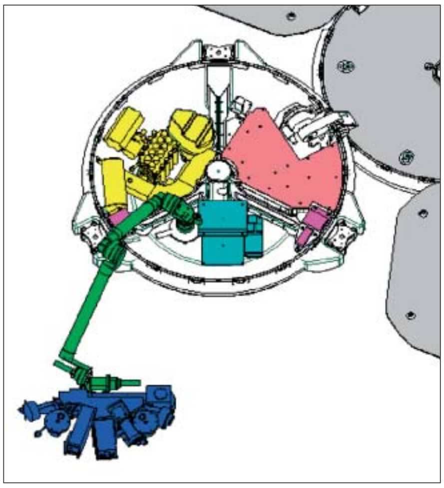


Fig. 2. Location of key elements of the Beagle 2 lander. Thermal insulating foam is removed for clarity. The GAP (yellow) and lander support systems (pink) occupy complete 120° sectors of the base. The PAW (dark blue) houses all the *in situ* instrumentation and is manoeuvred by the ARM (green). Some instruments on the PAW have associated electronics housed in the lander base (light blue). A few environmental sensors are also visible (purple).
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Unlike organic matter, carbonates should be totally immune from degradation by oxidants. Given that soils are the weathering products of rocks, thoroughly mixed by aeolian processes, then fine particles represent the best route to locating martian carbonates and measuring their geochemical parameters, e.g. isotopic compositions. GAP is able to measure the abundance of carbonate in soil and rocks at levels well beyond the capability of spectrometric methods.

Since the separation schemes needed for studying the constituents of rocks are the same as those needed for the characterisation of the martian atmosphere, the gas analysis package on Beagle 2 is admirably suited for direct analysis of the major martian atmosphere component CO_2 and for minor constituents, particularly CO, H_2O, N_2, the noble gases and minute amounts of hydrocarbons. Beagle 2 could thus be expected to provide a detailed and comprehensive study of the constitution of the atmosphere with precise isotopic data for major, minor and trace components. It would follow some constituents during diurnal cycling and as a function of the mission duration to investigate daily and longer-term climatic processes on Mars.

In respect of methods for separating trace components, procedures to extract and purify methane, originally developed to provide isotopic information about the sources of this harmful greenhouse component in Earth's atmosphere, are included as part of GAP. A confident detection of methane on Mars, a species that would be out of chemical equilibrium, would have enormous repercussions for deciding if there is still an active biology on the planet.

2. The Beagle 2 Scientific Payload

The payload (Fig. 2) on Beagle 2 can be divided into three categories:

- the Gas Analysis Package occupies about 33% of the lander base section and requires samples, including atmospheric gases, to be delivered via an inlet system. GAP is the primary science experiment on Beagle 2; its lead institute is the Open University;
- a collection of *in situ* investigation instruments and tools located on the PAW, an integrated structure attached to the end of the Anthropomorphic Robotic Manipulator (ARM). The tools are used to prepare the surfaces of samples for study by the *in situ* instruments and to extract cores from these samples for analysis by GAP. The Mole ground penetration tool is deployed from the PAW. The lead institute for the PAW is the University of Leicester; individual instruments are supplied by various institutions (see later);
- a suite of sensors for dynamically monitoring the martian environment. These are located both on the PAW and about the lander. The lead institute for the environmental sensors is the Open University.

2.1 Gas Analysis Package

GAP (Fig. 3) has three modes of operation: quantitative analysis, qualitative analysis and precise isotopic measurement. Instrument modes will be decided according to the type of investigation required. There will be three main types of study:

- search for organic matter;
- stepped combustion for total light element content and speciation;
- atmospheric analysis.

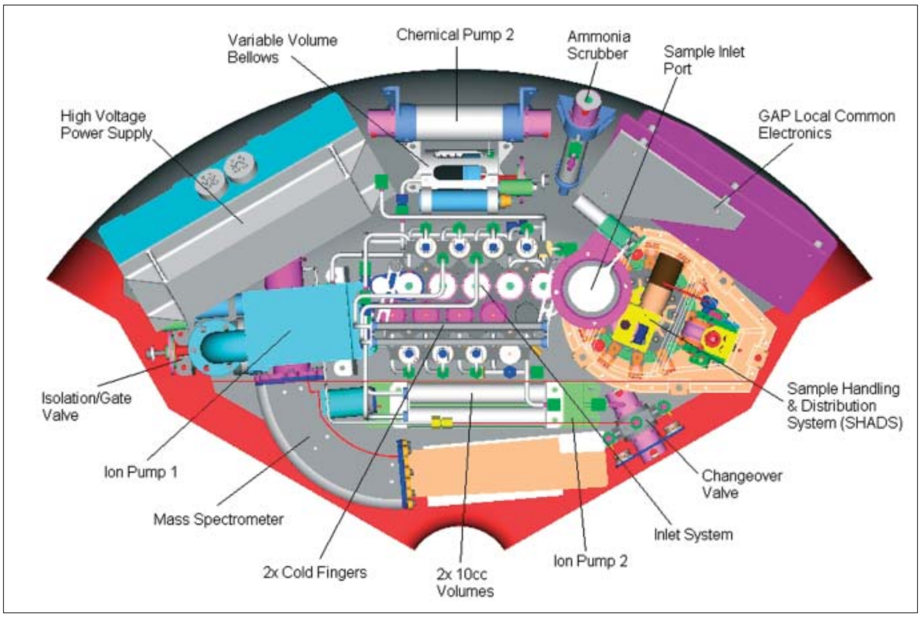
In all cases of isotope ratio measurements, the principles of GAP are derived from MODULUS (Methods of Determining and Understanding Light elements from Unequivocal Stable isotopic compositions), a concept developed for the Rosetta mission (Wright & Pillinger, 1998a) and expanded to include Mars (Wright & Pillinger, 1998b). Specific chemical reactions appropriate to martian species, e.g. CO_2, CO, H_2O have been worked out to afford full C, O and H isotopic characterisation without the necessity of having to resolve isobaric interferences. This philosophy incorporates real-time calibration of the instrument using a variety of reference gases, e.g. a reference CO_2 used during $^{13}C/^{12}C$ measurements, etc. In consequence, stable isotope ratio measurements will be quoted to high precision relative to internationally accepted standards.

GAP is fed either by direct atmospheric sampling, or via one of 12 ovens mounted on a carousel. Material acquired by the sampling tools, in the form of soil or rock chippings, is deposited via an inlet system into one of the ovens, which is then rotated to a tapping station to connect the oven to GAP. The ovens withstand temperatures up to 1000°C, although in practice 700°C will be adequate for most analyses. Only the sample container will be heated. This consists of a platinum liner heated by a Pt-Rh filament directly wound on to the container. Electrical insulation between the liner and the filament is secured by a thin layer of aluminium oxide deposited on the outer surface. Thermal losses in the oven are reduced by means of an internal radiation shield, and conductive heat losses are cut down by using ceramic support structures with low heat conductivity.

GAP is designed to make quantitative and stable isotopic measurements of gases such as H_2, N_2, O_2 and CO_2. The system can also process and determine some of the noble gases (Ne, Ar and Xe) as well as anticipated trace constituents such as CH_4. It operates in one of two ways, either analysing gases directly (such as those present in the atmosphere, or which can be liberated from samples by heating), or producing appropriate analyte gases (e.g. CO_2) by chemical processing (e.g. conversion of organic compounds to CO_2 by oxidation). In this way, GAP is tremendously flexible, being able to investigate processes of atmospheric evolution, circulation and cycling, the nature of gases trapped in rocks and soils, low-temperature geochemistry, fluid processes, organic chemistry, formation temperatures, surface exposure ages, assist in isotopic rock dating, etc.

At the heart of the GAP system is a 6 cm-radius magnetic sector mass spectrometer, which operates in both dynamic and static modes, i.e. continuously pumped and isolated, respectively. The mass spectrometer includes six ion beam detectors. The main unit is a triple-collector array for the determination of N_2 (m/z 28, 29, 30), O_2 (m/z 32, 33, 34), and CO_2 (m/z 44, 45, 46). A spur in the flight tube of the instrument includes a double-collector for measurement of D/H ratios (H_2^+ and HD^+ at m/z 2 and 3, respectively). A further detector mounted on the high-mass side of the triple-collector comprises a pulse-counting electron multiplier for measurements of trace gases. When operated dynamically, the mass spectrometer should be able to measure stable isotope ratios to high degrees of precision and accuracy (±0.1‰ when expressed as a δ-value). In contrast, static operation will allow high levels of sensitivity albeit with some reduction in precision of the isotopic measurements.

As an illustration of instrument performance, note that when Viking test equipment analysed two different Antarctic soils, each containing 300 ppm carbon, they were



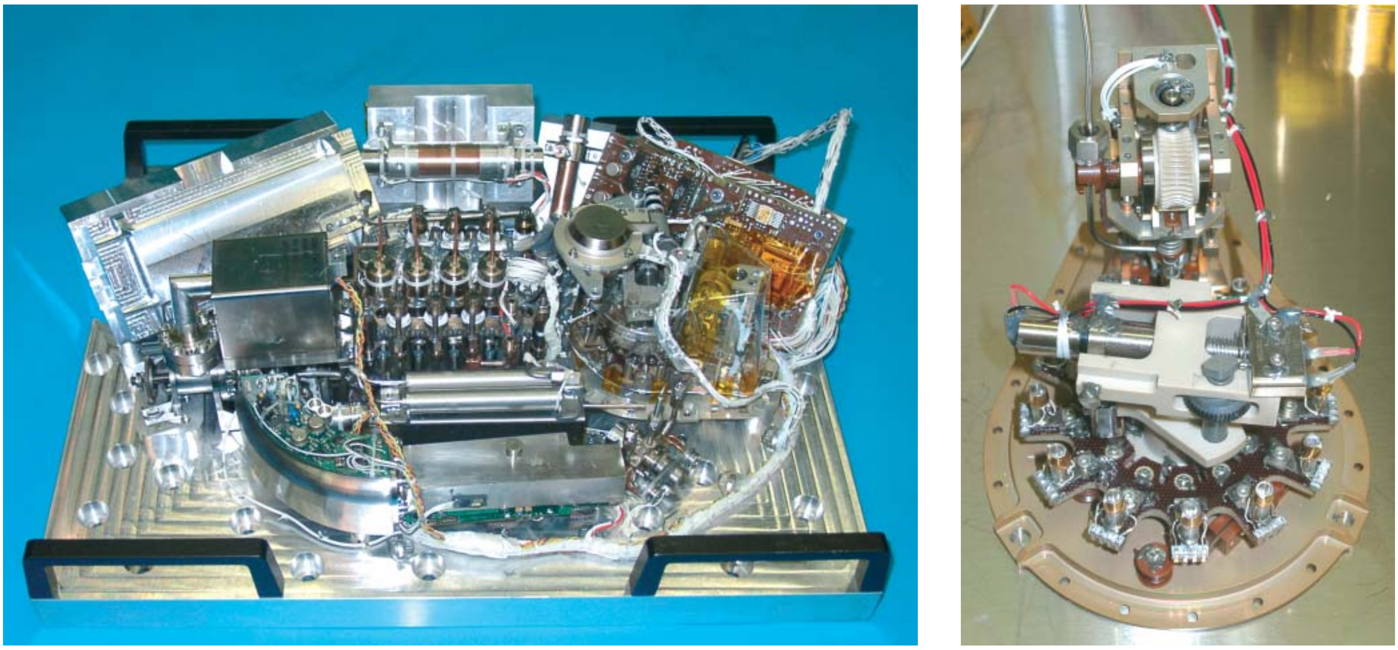


Fig. 3. The Gas Analysis Package, the primary experiment that occupies a complete 120° sector of the lander base. All the key components are annotated. Below left: the Flight Model GAP in transportation case before final sterilisation. Below right: the Sample Handing and Distribution System (SHADS), showing the carousel of ovens (lower part of assembly) and tapping station (to rear). ***All Rights Reserved, Beagle 2***

determined to have about 5 ppm and 0.01 ppm C as organic carbon. This probably reflects the low yield of pyrolytic reactions from highly cross-linked carbonaceous materials. Had materials of equivalent character been analysed on Mars by Viking, the latter of these would not have yielded any carbon above background, even though a significant fraction of the 300 ppm total carbon may have been non-pyrolytically degradable organic matter. Laboratory analyses of carbon in SNC meteorites by a system similar to GAP is regularly used to measure carbon contents of 250 ppm, or less, from a few milligrams of sample. Thus GAP should provide meaningful data from samples where Viking would have detected nothing. The mass spectrometer on GAP has been designed to measure, quantitatively and isotopically, nanogram quantities of carbon in any form. For a 50-100 mg sample (the target for Beagle 2 operations on Mars), this translates to a detection limit for carbon of 0.02-0.01 ppm.

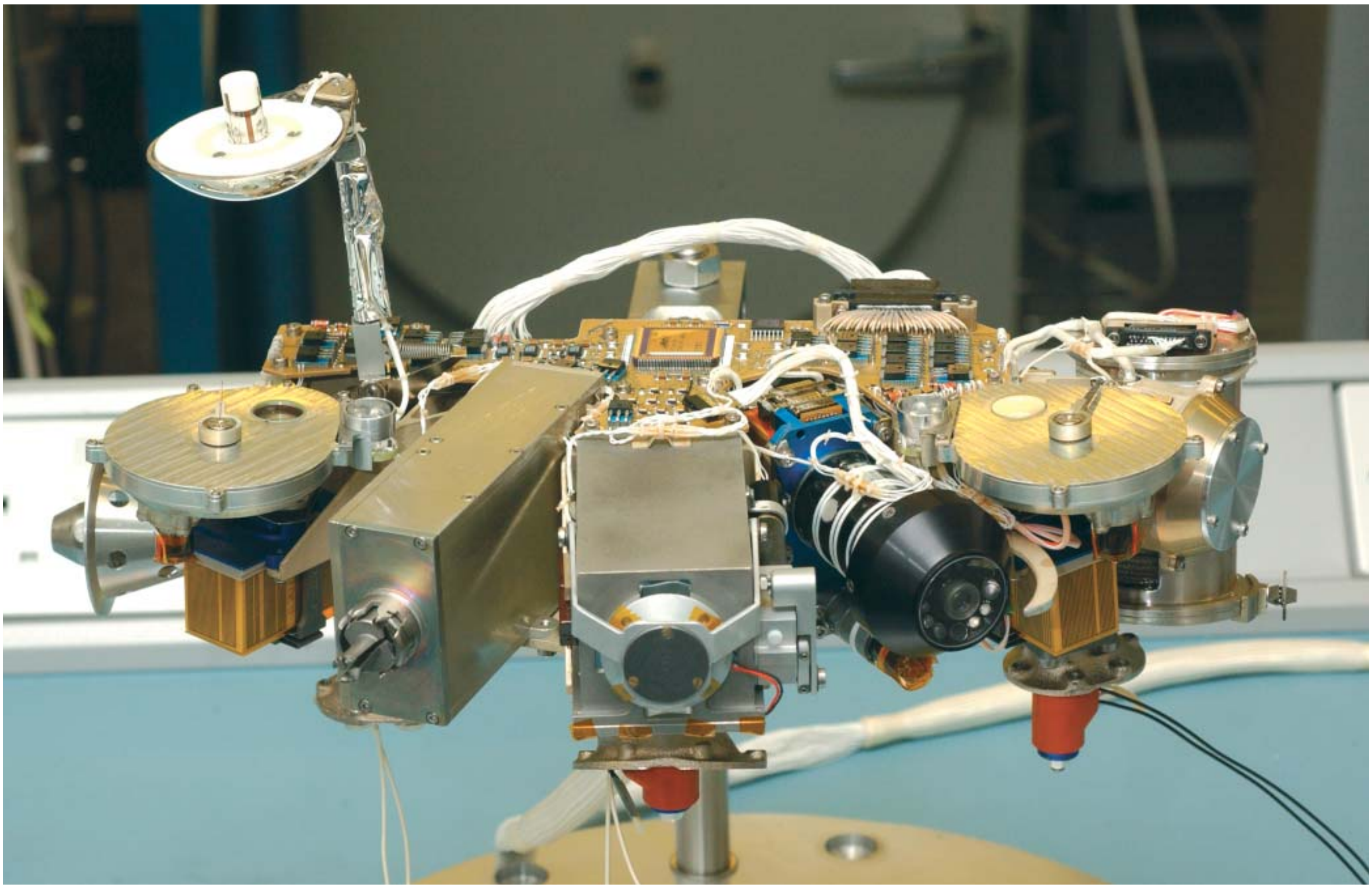


Fig. 4. The PAW FM, fully assembled and ready for sterilisation, November 2002. Two of the three Frangibolt actuators are visible under the mounting feet.
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This represents a very significant advance on previous *in situ* investigations of Mars, and opens up the possibility of a serious reappraisal of the presence of organic materials on the planet.

2.2 PAW subsystem

The PAW (Figs. 4 & 5) is a highly optimised and compact integrated suite of scientific instruments, sample acquisition and preparation tools, deployed by the ARM for *in situ* investigation of the surface. All the lander imaging systems and field spectrometers are housed on the PAW and rely on the versatility of the ARM for essential categorisation of the landing site. In addition, GAP, as Beagle 2's primary scientific experiment, relies on the PAW-ARM to deliver solid samples for isotopic analysis.

The majority of instruments and tools on the PAW are serviced by the PAW electronics. Complex ARM harnessing between the PAW instruments and the lander support systems is kept to a minimum by the inclusion of an FPGA within the PAW electronics. The fully equipped PAW is 38 cm at its widest point and has a mass of only 2.75 kg.

During cruise and coast to Mars, the PAW-ARM is stowed within a recess in the lander base. The PAW is attached to the ARM via a right-angle bracket and is held down to the lander base by three feet that secure the system during launch and other extreme environmental conditions. The baseline release mechanism is to have one Frangibolt actuator per foot; these are operated prior to initial deployment of the PAW and the beginning of surface operations. Once deployed, the PAW does not return to the stowed configuration.

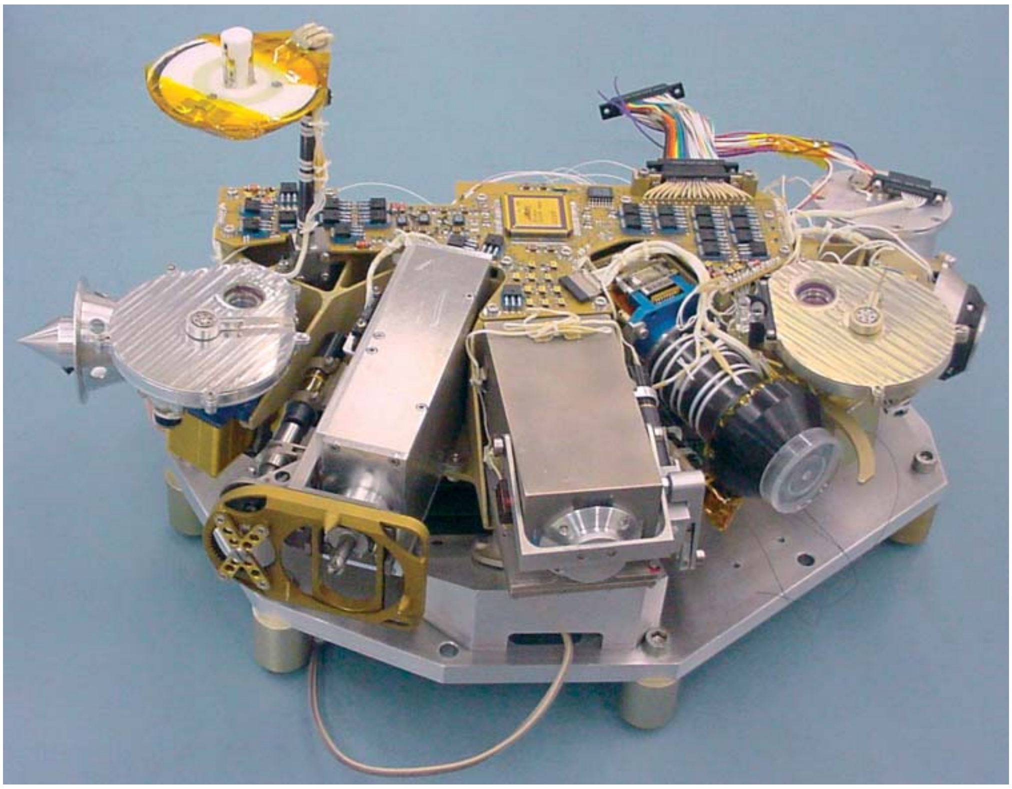
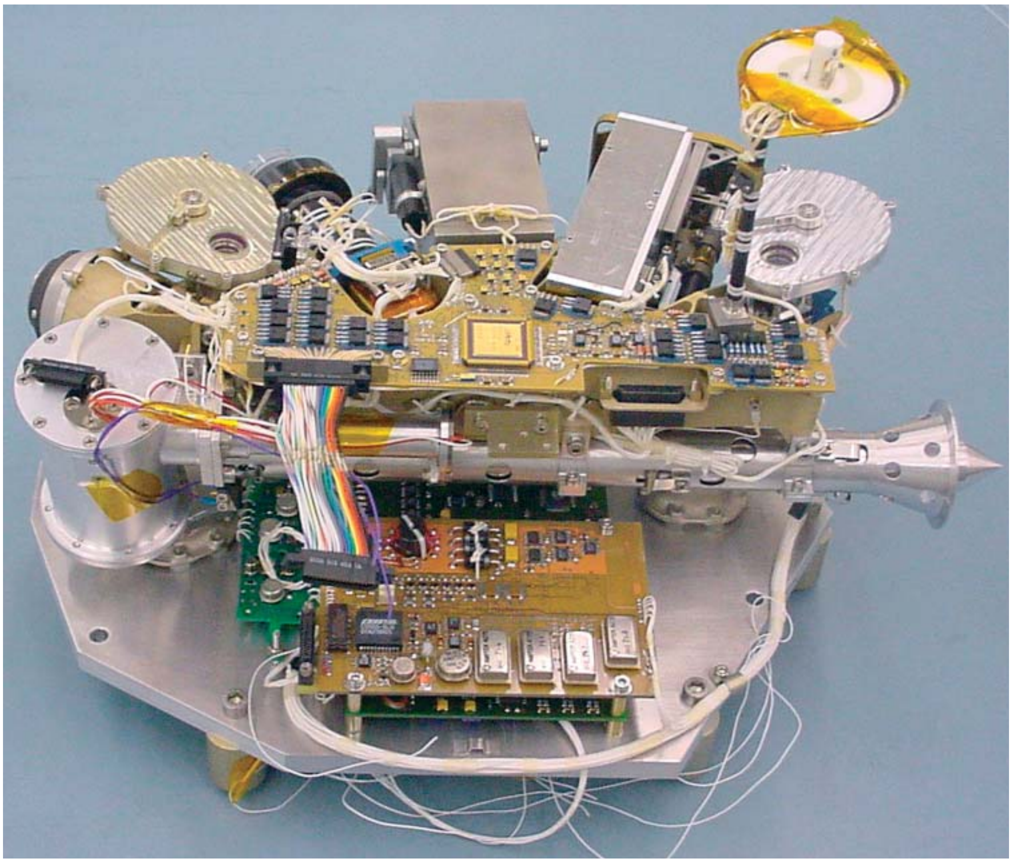


Fig. 5: The PAW Qualification Model (QM) and Back End Electronics Stack (BEEST) mounted on the combined assembly plate. Note that the Rock Corer Grinder QM is equipped with a translation table, an assembly subsequently deleted from the Flight Model (see Section 2.2.6). ***All Rights Reserved, Beagle 2***



The principal objectives of the PAW-ARM subsystem are:

- multispectral stereo imaging of the immediate area around the lander;
- Digital Elevation Model (DEM) construction of the landing site (especially the 1 m^2 PAW-ARM working zone);
- multi-instrument *in situ* rock/soil analysis;
- wind measurements at various heights about the martian surface;
- acquisition of core samples from rocks;
- acquisition of soil samples (Mole or spoon) from the subsurface;
- delivery of solid (core or soil) samples to GAP via the inlet port;
- dust-removal from lander surfaces, if possible;
- pre-PAW-ARM deployment hazard mitigation via the WAM

In addition, the following are worthy of inclusion in extended operations:

- analysis of soil samples with *in situ* instruments, being considered for the primary mission because it provides for complete assessment of samples acquried from the subsurface. This applies to samples acquired by the Mole and spoon and deposited on a suitable surface on the lander. Possible determination of super-oxidation depth if this is present within the top 2 m of the regolith;
- analysis of uncovered soil surfaces with spectrometers. This requires the top layer of soil to be scraped off by the PAW; this may also apply to semi-consolidated blocks if there are any at the landing site. Measurements made in contact with the soil surface (contamination issues);
- imaging of the Mole-hole. Examination of the hole left by the Mole after penetration will provide information on various geotechnical properties of the surface and near-surface materials. The hole, if it remains intact, will also be useful for imaging diurnal frost deposition and particle-settling processes.

Several lead institutes were involved in supplying hardware to the PAW:

- X-ray Spectrometer (XRS): University of Leicester, UK;
- Mössbauer Spectrometer (MBS): University of Mainz, D;
- Stereo Camera System (SCS): Mullard Space Science Laboratory, UK;
- Microscope (MIC): Space Research and Planetary Sciences Div., Physikalisches Institut, Bern, CH (PI formally at Max Planck Institute for Aeronomy, Lindau, D);
- camera heads for SCS/MIC and primary optics and close-up lens for SCS: Space-X (formerly a division of CSEM), CH;
- Planetary Underground Tool (PLUTO) and the Sampling Mole: DLR, Cologne, D;
- Rock Corer Grinder (RCG): Hong Kong Polytechnic University, China;
- Wind Sensor: Oxford University, UK;
- Wide Angle Mirror (WAM), torch, spoon: University of Leicester, UK.

All the other elements of the PAW, including the control electronics, mechanical structure and harnessing, were designed and supplied by the University of Leicester as part of the PAW lead activity.

2.2.1 X-ray Spectrometer

The X-ray Spectrometer (XRS; Fig. 6, Table 2) is loosely based on the successful APXS experiment flown on Pathfinder Sojourner but favouring the excitation method used by the Viking spectrometers. Like the APXS, the primary goal of XRS is to determine, *in situ*, the elemental composition, and, by inference, the geochemical composition and petrological classification, of the surface material at the landing site. Major elements (Mg, Al, Si, S, Ca, Ti, Cr, Mn, Fe) and trace elements up to Nb are detectable with XRS. The exclusion of a proton mode offered by APXS is offset by the greater sensitivity of GAP in determining light-element abundance. However, a

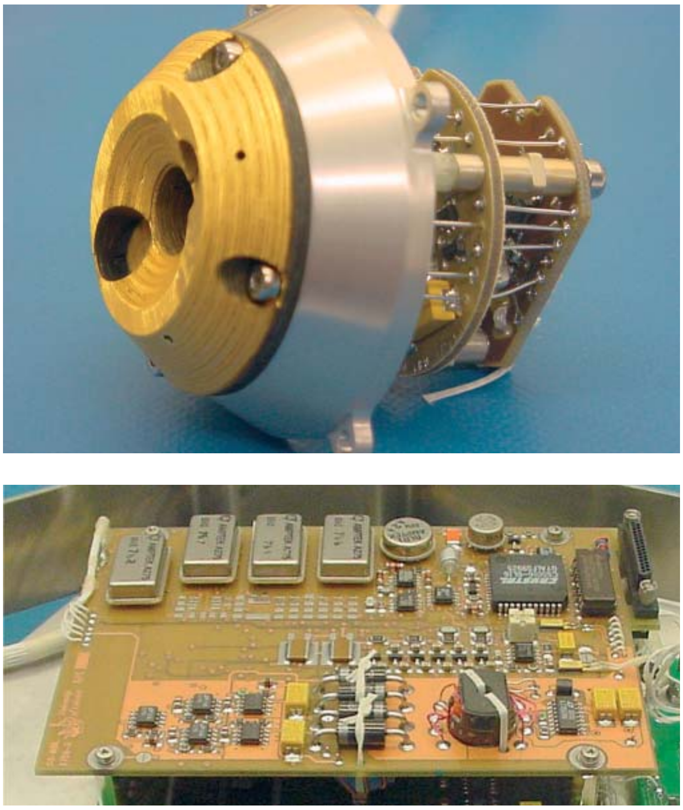


Table 2. XRS engineering parameters.

Mass*	154 g (DHA 56 g; BEE 98 g)
Dimensions	DHA 47 mm diam. x 47 mm; BEE 120 x 81 x 15 mm
Power	PPS +6 V (BEE); TCS (BEE heaters). Nominal current 450 mA; current limit after switch-on for 5 s followed by 660-625 mA for ~12 s. BEE provides all power directly to DHA
Data volume	32 kb (MCA mode (default); histogram fixed size); <<1Mb (diagnostic mode; count rate and integration time dependent)

*excluding DHA housing, which is part of the PAW structure

PPS: Payload Power Supply. TCS: Thermal Control System.

Fig. 6. QM of the X-ray spectrometer. Above left: the Detector Head Assembly is carried on the PAW. The conical carbon-fibre reinforced plastic stand-off cone is gold-flashed and contains the excitation sources and the detector element. Left: the Back End Electronics is located at the base of the ARM in the relatively warmer environment of the lander base.

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more ambitious and unique application of XRS is to use the precise measurement of elemental abundance in conjunction with measurements made by GAP to attempt a crude radiometric age determination.

XRS employs X-ray fluorescence spectrometry to determine the elemental constituents of rocks (Rieder et al., 1997). The principal components of the instrument are a set of four radioisotope sources, two ^{55}Fe and two ^{109}Cd, to excite the sample via primary X-rays at 5.90, 6.49, 22.16 and 24.94 keV, arranged around a Si PIN diode X-ray detector. A 7.5 mm-thick Be window over the diode permits detection of fluorescent X-rays down to 1 keV. The energy resolution of the detector (~300 eV) is sufficient to resolve all lines of interest. The lower energy cut-off of the Be window transmission is well matched to the X-ray opacity of a 6 mbar CO_2 martian atmosphere. The instrumental resolution requirement is ~25 eV across a 24 keV range (1-25 keV detector bandpass). Data are digitised using a 16-bit analogue-to-digital converter for good differential non-linearity performance and binned to 12 bits for onboard storage. Further binning to 10 bits on the ground will provide ~23 eV resolution.

Crude radiometric dating of martian rocks *in situ* will be by the $^{40}K \rightarrow ^{40}Ar$ method. For this, XRS needs to make a precise measurement of K on a fresh sample of rock. Preparation of the surface for XRS is performed by the Rock Corer Grinder housed on the PAW. It is essential that the surface for XRS is both flat and free from weathered rind because both factors will compromise the performance and results. The Ar component is determined by GAP as part of a suite of experiments performed on a core sample extracted later from the same specimen. The target performance of XRS is to provide a determination of K with a relative precision of better than ~5% in silicate rocks with K_2O levels of 0.2% by weight or greater.

2.2.2 Mössbauer Spectrometer

Mössbauer spectroscopy is an extremely useful tool for quantitative analysis of Fe-bearing materials and is therefore particularly suited for *in situ* studies on the surface

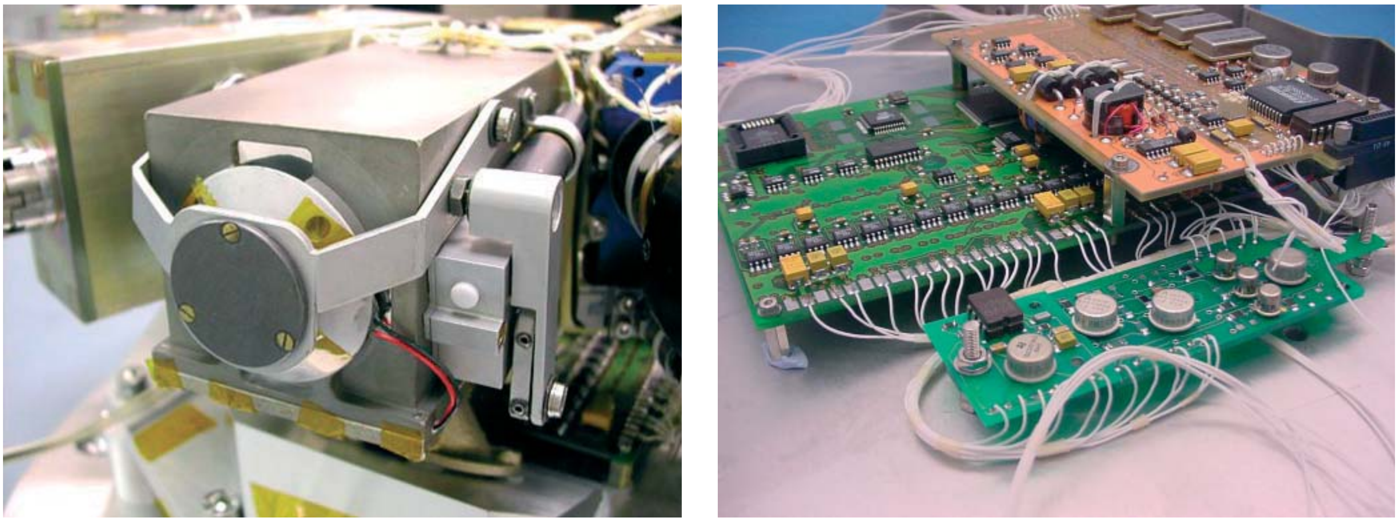

Fig. 7. The Mössbauer spectrometer. Left: the Detector Head Assembly (DHA) is located on the PAW and contains the radioactive sources and detectors. A mechanical shutter blocks the primary beam when the instrument is not in use. Right: the Back End Electronics (BEE; the larger circuit board to the left) is located at the base of the ARM in the relatively warmer environment of the lander base. The image also shows the XRS BEE (top right) and Wind BEE (foreground). ***All Rights Reserved, Beagle 2***

of Mars. The Fe-rich nature of martian deposits enables relative proportions of Fe in olivine and pyroxene to be determined using the Mössbauer technique, together with magnetite in basalts. In conjunction with the X-ray Spectrometer, the Mössbauer complements the *in situ* geochemical and petrological work, and provides support for the measurements made by GAP. For example, a pure carbonate (other than siderite) gives almost no Mössbauer signal because the technique is specific to Fe mineralogy; such a signal may favour a candidate rock over another worthy of isotopic analysis.

The Mössbauer effect provides information about the iron content of mineral samples by measurement of the Doppler shift in the velocity (or energy spectrum) of gamma-rays emitted by a stationary target bombarded by an isotopically equivalent gamma-ray source (Klingelhöfer et al., 1996; Klingelhöfer, 1998). Thus the instrument uses gamma rays from the decay of ^{57}Co to ^{57}Fe. The electronic environment of atoms in a sample dictates the absorption characteristics and thus they give spectra dependent on their valence state and bonding. The strength of the signals is quantifiable, so the instrument can characterise the mineralogical makeup of the rocks and soils, and hence help to identify the petrological classification. Its ability to measure valence states provides important information about oxidation, and therefore relative changes in the rocks and soils can provide a detailed understanding of the weathering environment.

The principal scientific objectives of the Mössbauer Spectrometer (MBS; Fig. 7, Table 3) are:

- identification of Fe-bearing phases with low detection limits;
- determination of the oxidation state of iron-bearing minerals;
- identification of Fe carbonates, sulphates, nitrates etc. that may provide information on early martian environmental conditions;
- determination of Fe oxides and the magnetic phase in martian soil;
- detection of nanophase and amorphous hydrothermal Fe minerals that could preserve biological materials.

The footprint of the instrument is circular, with a diameter of about 1.5 cm. The average information depth is of the order 100-200 mm. The extent of dust layering found on rocks during the Viking and Pathfinder missions may exceed these values, and the thickness of weathering rinds may be even greater.

The Mössbauer parameters are temperature-dependent and under certain circumstances the Mössbauer spectra may change drastically with temperature. This

Table 3. MBS engineering parameters.

Mass	DHA 438 g; BEE 102 g
Dimensions	DHA: 45 x 50 x 90 mm; BEE: 100 x 160 x 30 mm
Power	PPS +6 V; 3 W
Data volume	130 kbit

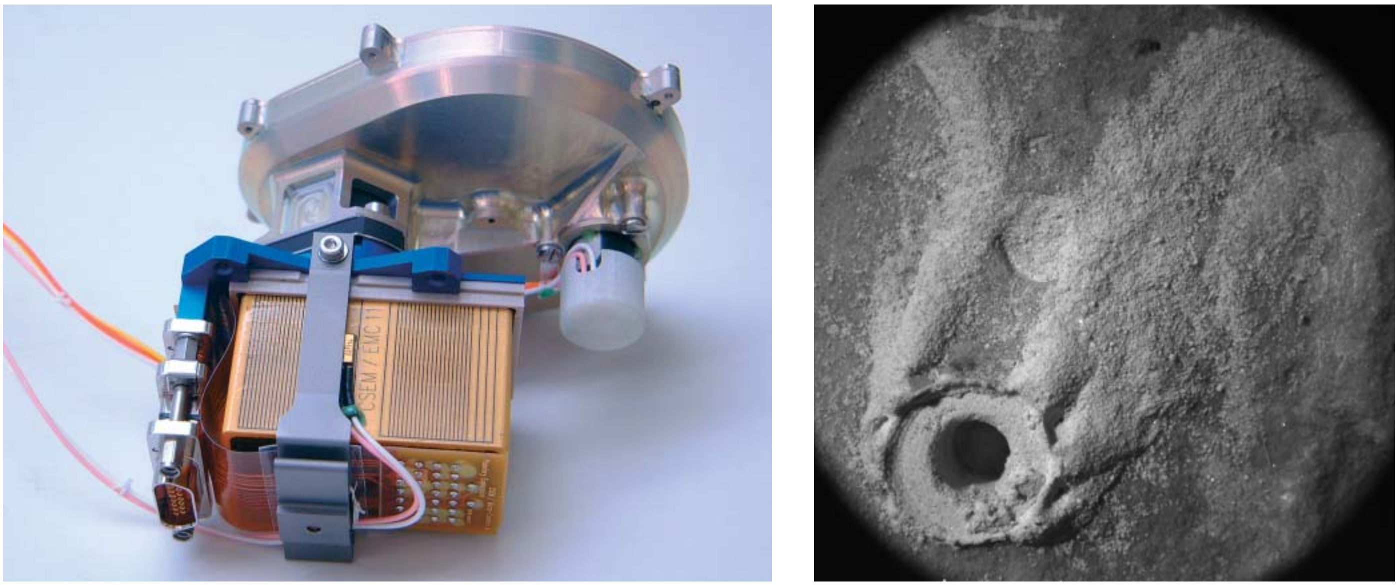

Fig. 8: Left: FM stereo camera, showing the camera head and Filter Wheel Assembly (FWA). The filter wheel itself is driven via a stepper motor shown protruding from the back of the FWA. Right: laboratory image acquired with the Development Model camera and filter R1 (close-up lens; see text and Table 4). The sample is a quartzose sandstone previously prepared with the QM Rock Corer Grinder (see Fig. 12).
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is particularly relevant for small particles exhibiting superparamagnetic behaviour (e.g. nanophase Fe oxides). The observation of such changes will help in determining the nature of the iron-bearing phases. Therefore, Mössbauer measurements will be performed at different temperatures. Ideally, these should span both the highest temperatures (during the day) and lowest temperatures (during the night).

2.2.3 Stereo Camera System

The Beagle 2 Stereo Camera System (SCS) is designed to perform a similar function to the Imager for Mars Pathfinder (IMP). Indeed, IMP was the baseline for many of the SCS design features, including the spectral coverage, and operating procedures. The major design difference is that, while IMP created stereo images by using mirrors to fold the light from two windows onto different halves of a single detector chip, SCS consists of two identical CCD cameras and integrated filter wheels (Table 4). Another important difference is that IMP was mounted on a deployable mast 1.75 m above the surface, while SCS is mounted on the PAW on the end of the ARM. The stereo baseline is 195 mm and each camera is mounted to provide a toe-in angle of 4.65° for the required stereo coverage.

A primary engineering objective of SCS is the construction of a DEM of the landing site, in particular the area within reach of the ARM, from a series of overlapping monochromatic (670 nm) stereo pair images. The DEM is reconstructed on Earth and used to position the PAW against target rocks and soils. In addition, a wide range of other imaging studies of the landing site and atmospheric/astronomical observations is possible. The following studies are baselined:

- 360° panoramic imaging to characterise the landing site and, depending on the topography, allow the location of the landing site to be determined with respect to orbital images;
- multi-spectral imaging of rocks and soils to determine mineralogy (if not completely obscured by aeolian dust);
- close-up imaging of rocks and soils using the right-hand camera (equipped with appropriate secondary optics as part of the filter set). This feature emulates the field geologist's hand-lens (Table 4);
- observations of the Sun to measure absorption of specific solar wavelengths by water vapour;
- observations of the Sun and general sky brightness at several times during the day

Table 4. The Stereo Camera System filter set.*

		λ (nm)**	Shape	Application
R 1	CLOSE-UP LENS; x6.4 magnification	Wide	curved	Geology
R 2	Ferric oxyhydroxide (local maximum)	600	flat	Geology
R 3	Maghemite (local maximum)	800	flat	Geology
R 4	Goethite, enstatite & hypersthene	900	flat	Geology
R 5	Ferrous silicates	965	flat	Geology
R 6	Diopside & fosterite	1000	flat	Geology
R 7	NEAR STEREO; Ferric oxides/oxyhydrides & Fe Silicates	670	flat	DEM/Geology
R 8	FAR STEREO; Ferric oxides/oxyhydrides & Fe Silicates	670	curved	Stereo/Geology
R 9	BLUE; Ferric oxides/oxyhydrides	440	curved	Colour/Geology
R 10	GREEN; haematite, d-FeOOH, goethite & lepidocrocite	530	curved	Colour/Geology
R 11	Dust Opacity	450	flat	Dust
R 12	HOME; Dust Opacity	670	flat	Dust
L 1	Discriminate crystalline hematite, crystaline goethite & nanophase ferric oxide	480	flat	Geology
L 2	BLUE; Ferric oxides/oxyhydrides	440	flat	Colour/Geology
L 3	GREEN; haematite, d-FeOOH, goethite & lepidocrocite	530	flat	Colour/Geology
L 4	Ferric oxides (local maximum) oxyhydroxide minerals	750	flat	Geology
L 5	Haematite, Pyroxenes & Olivines	860	flat	Geology
L 6	Low-Ca clinopyroxenes	930	flat	Geology
L 7	NEAR STEREO; Ferric oxides/oxyhydrides & Fe Silicates	670	flat	DEM/Geology
L 8	FAR STEREO; Ferric oxides/oxyhydrides & Fe Silicates	670	curved	Stereo/Geology
L 9	Continuum Band	925	flat	Water
L 10	Water Absorption	935	flat	Water
L 11	Continuum Band; Dust Opacity	990	flat	Water/Dust
L 12	HOME; Continuum Band; Dust Opacity	880	flat	Water/Dust

*the majority of filters used on Pathfinder appear here, albeit shared between two cameras. A secondary optic for close-up work (R1) is included. The long-wavelength solar filters are selected during periods of non-use to minimise exposure of the CCDs to UV during the day.

**centre wavelength. Passbands vary per filter ranging from 17 nm to 42 nm for geology, 4nm to 6 nm for dust/water, and 560 nm for the close-up lens.

to allow the determination of atmospheric optical density and aerosol (dust and water ice) properties;

— astronomical observations of Phobos and Deimos (spectral characteristics) and bright stars to allow night-time optical density to be determined. There are also 'public awareness' opportunities to image the Earth-Moon pair (maximum 3-pixel separation, at beginning of mission) from the martian surface;

— observations of lander surfaces and, if possible, air bags and landing scuff marks in soil to determine dust properties;

— if sufficient bandwidth is available, to return full-frame solar images (IMP solar images were 31 x 31-pixel sub-frames), unique 'Sun dogs' and other halo effects arising from CO_2 ice crystals may be observable.

Additional possible observations include looking for transitory or seasonal changes (dune migration, surface frosts) at the landing site or in the sky (clouds, haloes, dust devils?).

Table 5. SCS engineering parameters.

Mass	174.5 g (SCS-L); 175.5 g (SCS-R)
Dimensions (per camera)	79 x 63 x 75 mm
Power (per camera)	PPS +15 V (CCH); PPS +5 V (CCH); PPS +15 V (FWA). Nominal currents: 70mA (CCH); 40mA (FW moving)
Data volume	10 Mb (uncompressed) or 1 Mb (compressed) per image

The camera system must focus over a wide range of distances to achieve the scientific objectives. To keep the design simple, a fixed objective lens is used. This was designed to produce an optimum focus between 0.6 m and 1.2 m to support stereo pair imaging/DEM generation for the surface within reach of the ARM. To focus out to greater distances, curved filters provide optimum focus at distances between 1.2 m and infinity. Each camera is equipped with 48° optics allowing for 100% overlap at 1.2 m distance. The inclusion of a secondary optic in the filter set for the right-hand camera allows for inspection of materials at approximately 100 mm distance with this camera. The CCDs allow for an exposure range of 1 ms to 65 000 ms.

The imager on Pathfinder had a sufficiently large depth-of-focus to perform all the landing site imaging at a single fixed focus The fact that the SCS has two working distances complicates filter selection for Beagle 2 somewhat. Potentially the size of the filter set would need to be doubled if it were required to do all science at each working distance. Given these constraints, two assumptions are made:

— imaging of the area within reach of the PAW is critical for DEM generation but stereo imaging of the rest of landing site is less important;
— best-resolution images are required of potential targets of interest for the *in situ* instruments. However, spectral properties of rocks and soils more than 1.2 m from the cameras can be retrieved from slightly out-of-focus images, albeit at reduced resolution.

All of the imaging systems used on the PAW (both stereo cameras and the microscope) use common camera head (CCH) technology consisting of a micro-integrated electronics cube and a CCD detector (1k x 1k frame transfer device). These camera heads were produced by Micro-cameras and Space Exploration SA (Space-X), formerly a division of Centre Suisse d'Electronique et de Microtechnique SA (CSEM) under a Technology Research Programme (TRP) contract to ESA (11233/94/NL/FM(SC). For the SCS, this company also provided the primary optics and the close-up lens.

2.2.4 Microscope

The microscopic imager (Fig. 9, Table 6) on Beagle 2 will investigate the nature of martian rocks, soils and fines at the particulate scale. Such studies will provide important data in support of the exobiological objective in the form of direct evidence of fossils, microtextures and mineralisation of biogenic origin if these are present. In addition, the physical nature and extent of weathering rinds/coatings on rocks and soils will benefit the *in situ* geological investigations. Atmospheric and global planetary studies will also benefit from detailed knowledge of dust morphology.

Given that the discovery of martian biota will be of major scientific, if not philosophical, importance, minimisation of ambiguity is vital. Thus, several methods of investigation of a sample are needed to corroborate that a martian deposit is indeed biogenic. Therefore, in support of the exobiological objective, the microscope will seek evidential data in the form of preserved fossils in whatever form. Sedimentary pyrite and, in particular, framboidal textures are frequently observed in recent and ancient sediments on Earth. Although examples exist for a purely inorganic origin, the

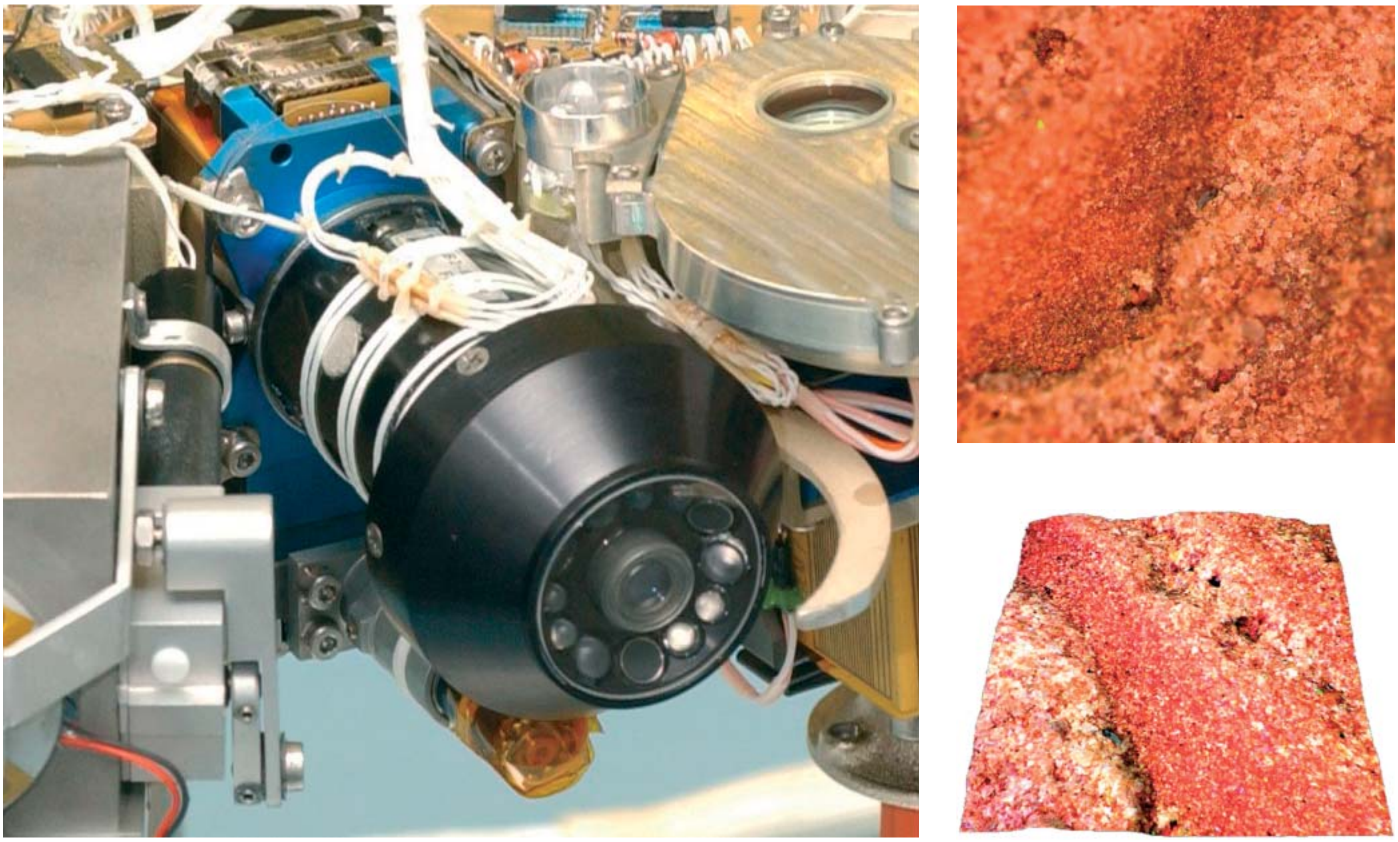


Fig. 9. The FM microscope, showing the camera head (detector and electronics), optical tube and LED illumination system. The standoff 'thumb', part of the PAW structure, is at the right of the image; it provides a fixed stand-off distance of 12 mm. The point of contact of the thumb and the PAW orientation are optimised after SCS imaging. Upper right: a colour composite image acquired with the microscope. The sample is a layered limestone from Piz Alv, Switzerland. A 3D reconstruction of the sample's surface is shown below. Entropy analysis determined the depth of the scene from 60 images at different focus positions. The layering is clearly evident in this isometric view. ***All Rights Reserved, Beagle 2***

Table 6. MIC engineering parameters.

Mass	151 g excluding focusing mechanism (53.7 g), which is part of the PAW assembly
Dimensions	111.58 mm x 45.24 mm (max. dia. of optical head)
Power	PPS +15 V (CCH); PPS +5 V (CCH); PPS +15 V (LEDs); PPS +15 V (Focusing mechanism)
Data volume	10 Mb (uncompressed) or 1 Mb (compressed) per image. Default mode is single best focused image plus depth map derived via onboard algorithm in LSW.

presence of framboidal pyrite in sedimentary systems is overall considered as evidence for a biological origin. In that respect, microscopic examination of the martian surface and, in particular subsurface material, for pyrite as a potential biogenic mineral might provide important evidence in the search for extinct life.

One of the major drawbacks of the Pathfinder mission was the uncertainty concerning the extent to which the APXS experiment was affected by a possible silicate-bearing weathering rind on the surface of sampled rocks. There is now no evidence that the APXS ever sampled unweathered material. The surfaces of many rocks facing north-east at the Pathfinder landing site appeared less red in the initial panorama. However, it has been recently shown that the remarkable brightness of the sky produced by airborne dust affects the illumination of the surface in such a way that rocks appear redder when in shadow or oblique sunlight. The initial interpretation of the less red faces of rocks as dust-scoured (and hence unweathered) surfaces must therefore be questioned and cannot be justified without a more sophisticated treatment of the illumination. Argument about contamination of sampled materials will always occur unless the sampling strategy provides a method of exposing fresh (unaltered and unweathered) material. Detailed microscopic study of rock and soil surfaces will be an important factor in the *in situ* investigations.

Apart from being a potential barrier for *in situ* geological study, martian dust plays a key role in the atmospheric energy budget. Material in suspension in turn controls the global circulation and the present climate. It is also suspected that the martian dust has had a major influence on the evolution of the surface and the long-term evolution of the planet's climate. To date, properties of the dust particles have been inferred from remote sensing from Earth, Mars orbit and landed craft. A major contributor to the overall dynamic, thermal and radiative properties of the martian atmospheric dust is particle morphology. A thorough understanding of the physical nature of this material has wide-reaching consequences for planetary scientists. The Beagle 2 microscope will be the first attempt to image and assess individual particles directly of sizes close to the wavelength of scattered light.

The microscope consists of a camera head identical to that used by the stereo cameras and a 10-fold magnifying lens system of 20 mm focal length. The depth of field is 40 mm and the image size is 4.1 x 4.1 mm; thus the scale is 4 µm/pixel (at 12 mm distance. Focusing is achieved by moving the whole assembly in and out (total travel 6 mm) with a stepper motor-driven translation table secured to the PAW structure. Spectral information can be gathered by using an illumination system consisting of a concentric set of super-bright LEDs around the lens system, uniformly illuminating the field of view. Four wavebands, each with a bandwidth of 30 nm, are accommodated (642, 523, 466, 373 nm).

Materials exposed on the surface of Mars, including rocks, soils and drifts, are known to be highly irregular at all scales. The microscope has a small depth of field so the acquisition of focused images of irregular surfaces ideally requires many individual images to be taken at various delta stand-off distances from the target. Single 'snapshot' images obtained with the microscope are likely to have little scientific value. Arrays of images at coarse stand-off distances are undesirable because subtle morphological and textural features, which may be significant, would not be resolvable. A complete set of individual images obtained at each stand-off position is achieved via the focusing mechanism on the PAW.

Generally, individual images compress well because they are usually dominated by out-of-focus areas (although scene-dependent, estimated compression on Beagle 2 is about 10:1). Unfortunately, the number of these 'image layers' can be as large as 60-100 per illumination configuration. By applying a focusing algorithm to a set, a single in-focus image derived from all stepper motor positions plus a depth map for 3D reconstruction map can be compiled. This process can either be done *in situ* or back on Earth. However, a single in-focus image plus map (i.e. two images) is much more efficient in terms of data volume. For this reason, the onboard software includes a focusing algorithm.

2.2.5 PLUTO and the Sampling Mole

It is of prime importance to supply GAP with material from rocks and soils to realise the mission's primary objective. The Planetary Underground Tool (PLUTO; Fig 10, Table 7) subsurface soil sampling device provides samples of soil from depths down to 1.5 m and, depending on the terrain, from under a large boulder. Both activities have never been attempted on Mars. The Viking missions had access to depths of only 20 cm in the surface soil, which proved to be still within a layer of presumably highly oxidised material with no measured concentrations of organic matter. It is expected that the top metre of bulk soil on Mars has in the past been exposed by aeolian mixing processes to the atmosphere and UV flux, and thus subjected to oxidation and irradiation processes that destroyed any organic matter over a scale of decades. If biological activity ever existed on Mars, then decomposition products in the form of biomarkers would best be preserved at depth in the bulk soil or within rocks.

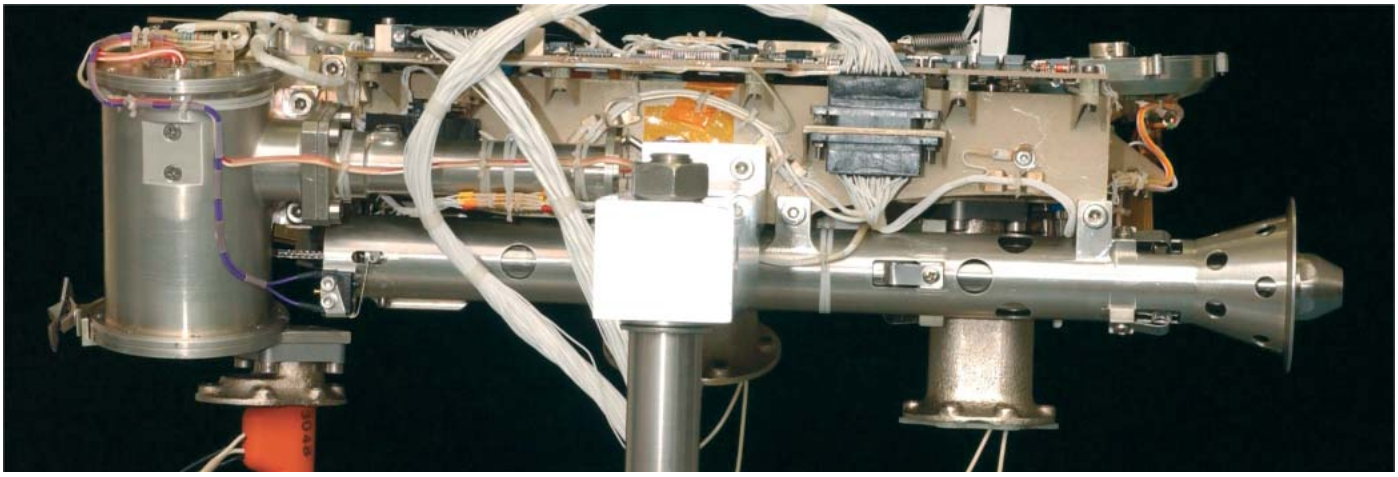


Fig. 10. The PLUTO FM mounted on the PAW FM. The Mole is just visible at the right, protruding from the launch tube (minus the sampling head, which is fitted as late as possible to avoid biological contamination). The winch housing is the cylindrical object on the left. ***All Rights Reserved, Beagle 2***

Table 7. PLUTO engineering parameters.

Mass	340 g (Mole); 550 g (deployment unit); total 890 g
Dimensions	approx. envelope ~380 x ~90 x ~80 mm (Mole = 280 mm long)
Power	3 W (17 W for pin-puller release after landing)
Data volume	~ kb (HK only)

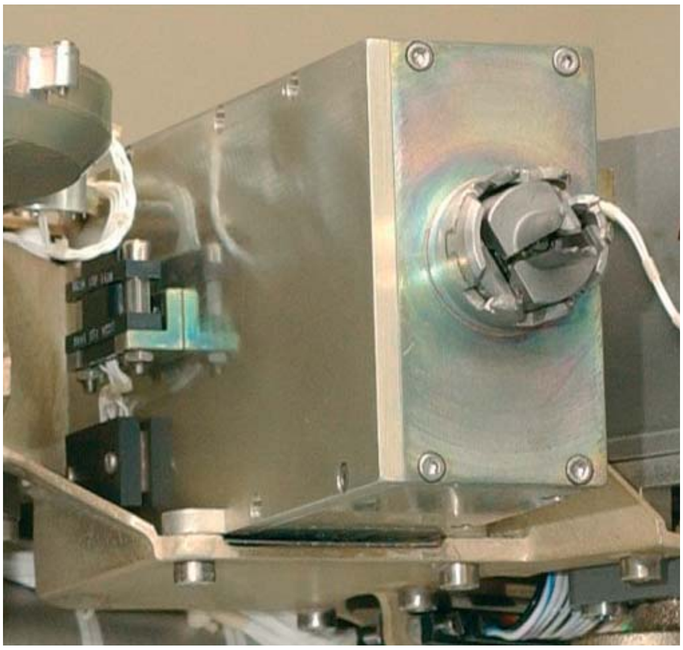
PLUTO employs a self-penetrating sampling Mole tethered to a support mechanism attached to the PAW. The Mole is the primary soil-sampling device. It is based on a Russian self-burying penetrometer; a scaled-down version of the original device was developed within an ESA TRP activity specifically for space applications (Re et al., 1997). It requires no reaction force from the lander once a small initial penetration is achieved: the Mole proceeds into the subsurface, connected by a tether for power (for the inertial hammering mechanism) and can reach depths several times the length of its casing.

At the tip of the Mole is a sampling mechanism that can be commanded to open at the appropriate sampling depth to acquire some 0.20 cm^3 of soil. Once secured by closing the mechanism, the sample is delivered to GAP by retrieving the Mole, retracting the tool into the 'launch tube' and moving the ARM back to the GAP inlet port on the lander. Samples are released by opening the mechanism again once in position, docked to the inlet. With one shock occurring every 5 s, it may take 30 min to 1 h to reach a vertical depth of 1 m under Mars gravity and the estimated soil resistance.

In addition to serving as a soil sample-acquisition device, the Mole provides a platform for *in situ* temperature measurements as a function of time and depth while embedded in the subsurface. Moreover, soil mechanical properties and layering will be estimated from the ground intrusion behaviour.

For retrieval from the subsurface, the cable reel operates in reverse, pulling the device back into the launch tube on the PAW, the latter remaining in position throughout the entire operation. The Mole retraction manoeuvre has been extensively tested on a variety of analogous materials. Retraction can also be aided by operating the hammering mechanism while rewinding the cable, an activity more likely to be considered for deep sampling. Once back inside its tube housing, the Mole is ready to discharge its cargo into the GAP sampling inlet.

The Mole can also be deployed laterally across the surface, away from the lander and towards a suitably sized boulder beyond the reach of the PAW, using the shocks



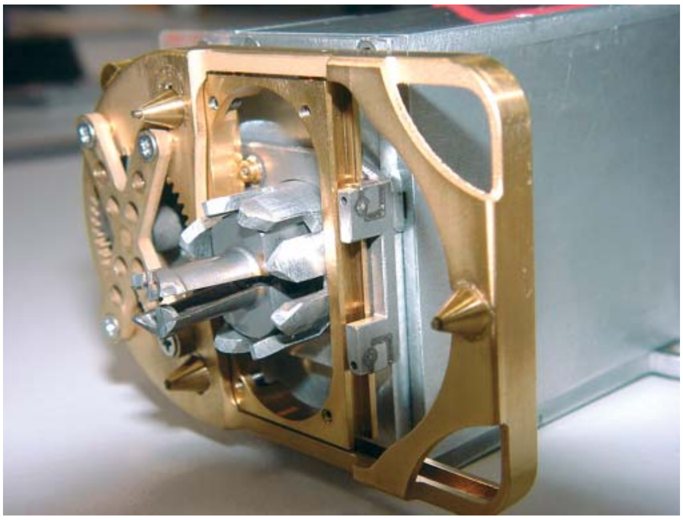


Fig 11. Upper left: the Rock Corer Grinder FM. Note the dual functionality and shape of the sampling tip. Right: results of coring into a field sample of quartzose sandstone with a case-hardened thin (~1 mm) weathering rind (Planetary Science Sample Library 146/274). Lower left: the RCG QM equipped with the Translation Table (TT) for transcribing the tool-head during grinding. The TT was not fitted to the FM following an engineering and scientific assessment on the effectiveness of the device. ***All Rights Reserved, Beagle 2***

Table 8. RCG engineering parameters.

Mass	348 g (FM without Translation Table)
Dimensions	approx. envelope ~30 x ~60 x ~100 mm
Power	6 W
Data volume	~ kb (HK only)

from its hammering mechanism for forward motion, at a rate of about 10 mm travel for each percussive stroke. Such hammering perpendicular to the local gravity vector had already been verified during an early ESA TRP activity. Once the Mole encounters a large rock with an overhang, it will be diverted downward to initiate soil penetration under the rock, thereby allowing access to protected samples.

2.2.6 Rock Corer Grinder

It is a scientific requisite that all the PAW instruments have access to fresh, unweathered/unaltered material in order to avoid the effects of surface weathering rinds thought to be prevalent on all exposed material on Mars. In addition, the spectrometers require a prepared flat area of optimum size to counter geometric effects that can seriously compromise instrument performance. To address these requirements, the PAW is equipped with a combined Rock Corer Grinder (Fig. 11, Table 8) tool.

The grinding action of the RCG removes as much weathering rind material as possible, up to 6 mm, by producing individual or an array of flat, 10 mm-diameter

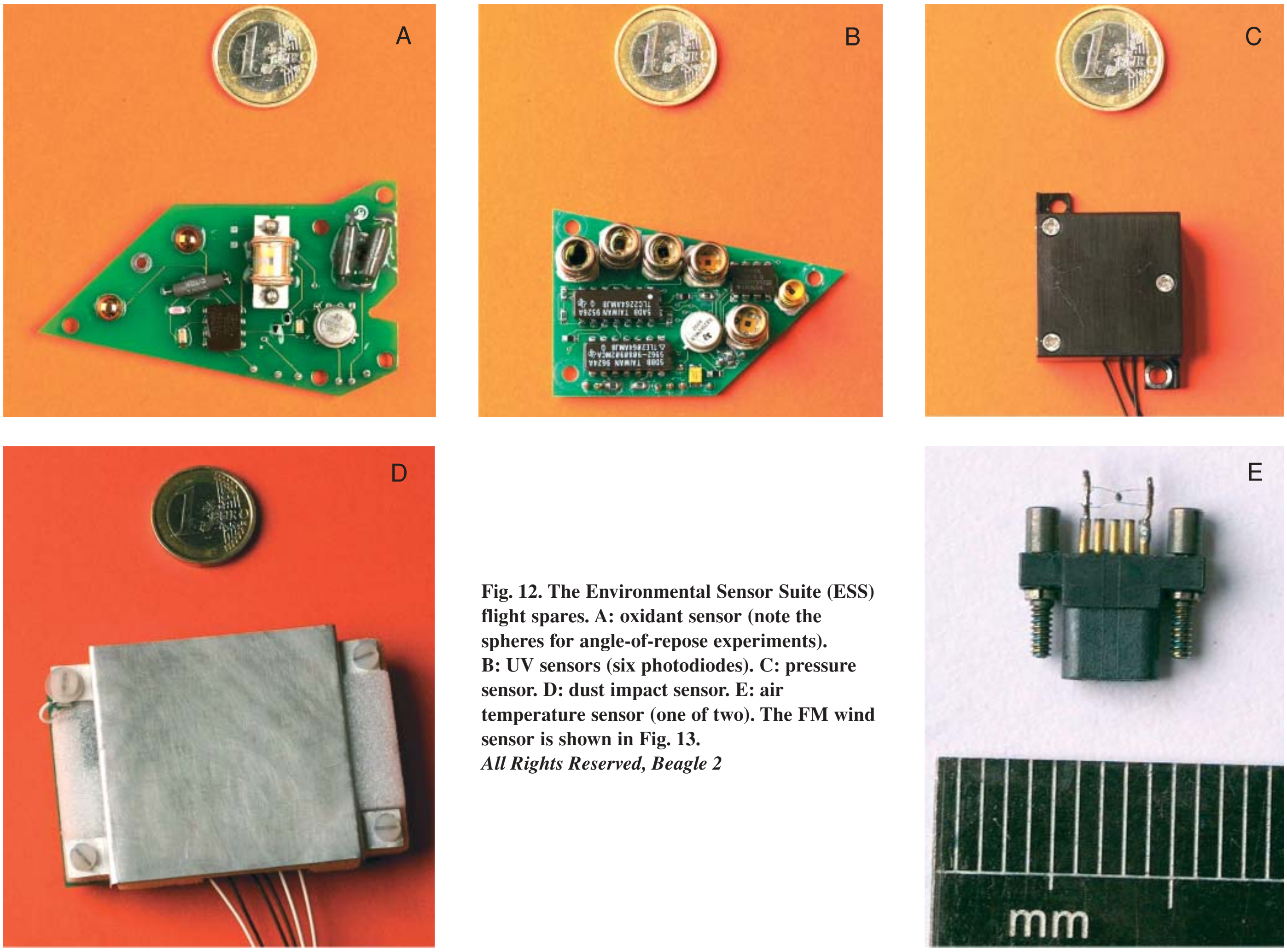


Fig. 12. The Environmental Sensor Suite (ESS) flight spares. A: oxidant sensor (note the spheres for angle-of-repose experiments). B: UV sensors (six photodiodes). C: pressure sensor. D: dust impact sensor. E: air temperature sensor (one of two). The FM wind sensor is shown in Fig. 13.
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fresh surfaces suitable for the spectrometer instruments. A translation table mechanism was developed for the RCG QM to transcribe the tool-head over the surface of a sample to produce a flat area of ~30 mm diameter. However, for mass and other reasons, this facility was not adopted for flight. After all *in situ* analyses have been completed, a sample from the ground patch is extracted by using the coring action of the device and delivered to GAP via an inlet port on the upper part of the lander. Coring is achieved by a hammering/rotating action of the main drive where material is retained within the Micro End Effector (MEE) jaw-type device. Cores, or more precisely a collection of rock chippings, obtained by this tool are of reproducible volume suitable for the GAP ovens.

2.3 Environmental Sensor Suite

Beagle 2 is equipped with a complementary set of environmental sensors (Fig. 12) to assist in both the prime objective, characterisation of the landing site and meteorological studies. Measurement of the UV and radiation flux (a RadFET within the lander electronics measures total dosage) at the surface together with the oxidising capability of the soil and air provides direct input into the astrobiological investigations. In addition, measurement of atmospheric temperature, pressure, wind speed/direction, dust saltation and angle-of-repose will complement the *in situ* experiments. Dynamic studies such as dust devil profiling will also benefit assessments of aeolian erosion rates, as will an understanding of the boundary layer wind regime using the wind sensor on the PAW.

The mass of the complete suite of sensors is 156 g. Each sensor is powered via the lander Auxiliary Power Supply (APS) and typically has a 0-5 V analogue output. Depending on the sampling rate adopted during operations, the environmental sensors can generate between kilobytes of data (low rate typically one reading from each sensor every 10 min) through to megabytes (high rate typically 4 Hz).

2.3.1 Oxidant sensor

One controversial issue arising from the Viking results is the postulated presence of hydrogen peroxide or other oxidising compounds in the soil, used in several cases to explain the results of the experiments designed to detect martian life. The Beagle 2 oxidant sensor is a one-shot measurement, in which a sensitive titanium film is exposed to the atmosphere and its resistance is monitored as it oxidises. It is not, however, H_2O_2-specific but will also detect other oxidising species, such as O_3. By simultaneously monitoring the UV and dust sensor, it is hoped to shed some light on the processes generating any oxidants. At the end of the mission, the PAW will be used to deposit quantities of soil onto the film, and to monitor the response. The sensor is located near the rim of the lander base.

2.3.2 Ultraviolet sensor

Short-wavelength UV, such as UVB and UVC, are harmful to life and can directly damage DNA. The UV environment on Mars is known to be harsh, and it is unlikely that life can survive on the surface, but subsurface life may still be possible. This sensor will produce a 5-point spectrum in the range of 200-400 nm, covering UVA (320-400 nm) and UVB (280-320 nm) over seasonal and daily time-scales. At wavelengths below 204 nm, the CO_2 atmosphere is strongly absorbing, partially blocking the UVC band (100-280 nm). The sensor is located near the rim of the lander base.

The unit uses six photodiode sensors, each with a particular bandpass filter:.

- 210 nm: main TiO_2 dust absorption band;
- 230 nm: biologically damaging and rapidly time-varying regime;
- 250 nm: secondary TiO_2 band;
- 300 nm: mid-UVB;
- 350 nm: mid-UVA;
- 200-400 nm (no filter): calibration channel.

2.3.3 Wind sensor

A hot-film wind sensor (Fig. 13) was supplied by Oxford University (UK). It is mounted with an associated air-temperature sensor on the PAW. The difference in heat transfer coefficients between the three films can be used to calculate a 2D wind vector perpendicular to the axis of the wind sensor. In its normal orientation, the sensor measures a horizontal wind vector. The sensor is calibrated for the range 0.3-30 m s^{-1} though wind speeds above this range can also be measured. There are several sensor-specific goals and activities:

- obtain a long-term meteorological record of wind speed and direction, and air temperature at the landing site;
- obtain higher frequency data (~1 Hz) at various times of the day to enable characterisation of boundary-layer turbulence and fluxes;
- detect and observe dust devils;
- characterise the vertical profile of air temperature and wind speed at different times of the day, by taking measurements with the sensor head at different heights above the surface.

At times, the top surface of the lander can be up to 80°C hotter than the surround-

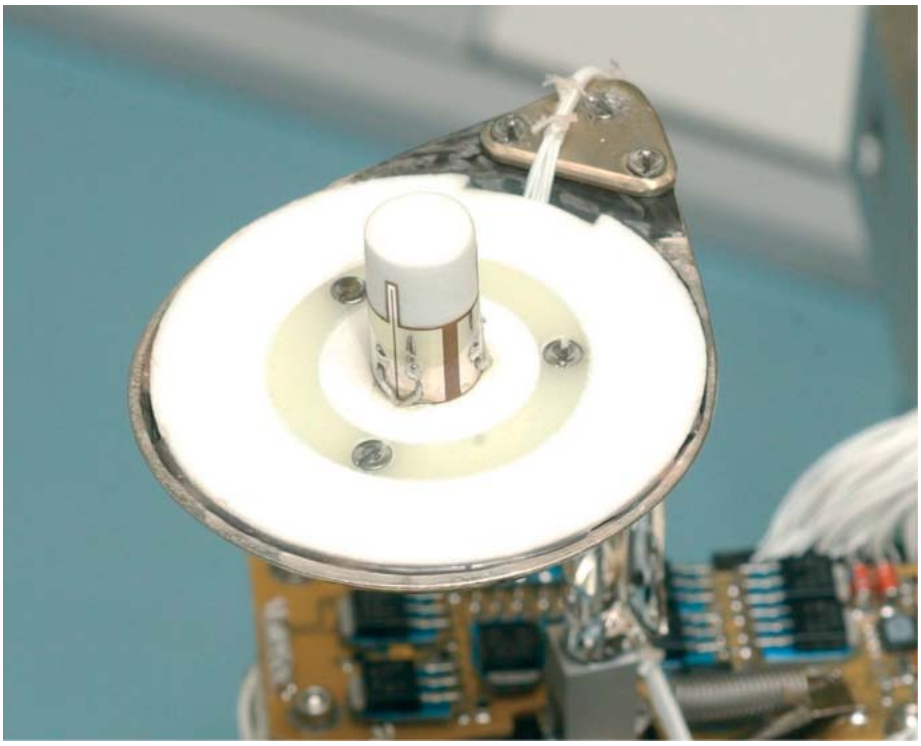

Fig. 13. Wind Sensor FM integrated with the Wide Angle Mirror during final assembly of the PAW FM. For an alternative view, see Fig. 4. ***All Rights Reserved, Beagle 2***

ing surface, giving rise to a convective plume. This plume, which affects meteorological measurements made directly above it, will be studied by moving the temperature and wind sensors into different positions above the lander. Such a plume was seen by the Viking landers (Ryan & Lucich, 1983), and the effect should be stronger on Beagle 2 because of its geometry.

2.3.4 Air pressure

The Barobit pressure sensor was supplied to Beagle 2 by the Finnish Meteorological Institute. It uses the same Barocap sensing element as in the Meteorology Instrument System aboard the Mars-96 small stations and penetrators (Harri et al., 1998) and within the MVACS package on the Mars Polar Lander. Barocap is a capacitive absolute pressure sensor based on a thin silicon diaphragm. The Barobit design is based on the EGA-P experiment flown aboard Mars Polar Lander. Barobit electronics and Beagle 2 data-handling capability limit the measurement accuracy down to about 0.006 hPa and resolution to 0.003 hPa. The sensor is located in the lander base.

2.3.5 Air temperature

Air temperature will be monitored at two locations using commercial 0.3 mm-diameter bead platinum resistors. The sensor is optimised to give the highest sensitivity and accuracy of better than 0.01K over the range –10°C to –60°C. At the extremes of the operating temperatures (less than –100°C and greater than 10°C), the accuracy is reduced to about 0.1K. One sensor is mounted at a fixed height of around 0.05 m above the ground, on the edge of one of the solar panel sheets, in an attempt to isolate it thermally from the effects of the hot lander body. An identical sensor is mounted as part of the wind sensor assembly on the PAW, allowing air temperature measurements at heights of up to 0.6 m.

2.3.6 Dust impact monitor

A dust impact monitor, located near the rim of the lander base, will measure the

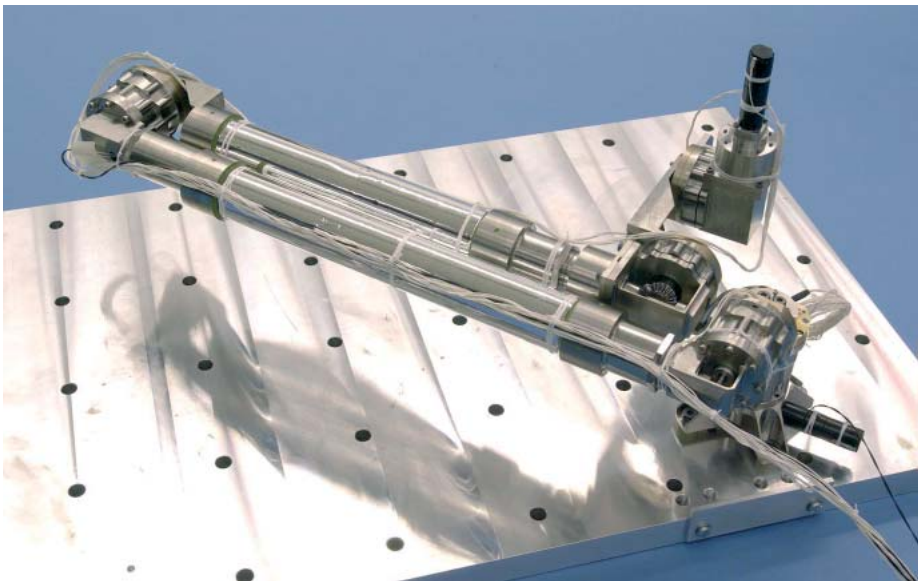

Fig. 14: The ARM Development Model.
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impact rate and magnitude of wind-blown dust, providing information about the regolith transport and mixing mechanisms on the surface. The sensor is mounted horizontally, near the rim of the probe, and will listen continuously for dust impacts. It consists of a simple aluminium sheet, 0.25 mm thick, with a polyvinylidene fluoride (PVDF) piezoelectric film on the rear face. PVDF films such as this have been used on several missions, most recently on the high-rate detector within the CDA instrument aboard Cassini (Tuzzolino, 1995). Maximum sensitivity of the device is 1×10^{-10} kg m s^{-1} (equivalent to a 0.2 mm glass bead dropped from 10 mm height on Earth); the sensor records the magnitude and time of an impact.

3. Surface Operations

3.1 Anthropomorphic Robotic Manipulator (ARM)

The Beagle 2 ARM (Fig. 14) is a 5-degree-of-freedom manipulator, with the PAW permanently attached to the wrist. The fully extended ARM is 109 cm long, measured from the centre of the body joint to the centre of the PAW wrist joint. Each joint comprises a DC brushed motor driving through a 100:1 harmonic gearbox. Joint position is detected by a potentiometer mounted directly onto the output shaft. A typical joint speed is 0.6° s^{-1} (axes 1-3 only).

The ARM's primary purpose is to position and orientate the PAW so that the instruments and tools can perform their tasks. Requirements imposed on the ARM by the PAW include:

- working zone DEM (0.6 m to 1.2 m near-stereo) requires PAW/ARM to view the scene from as many perspectives as possible – at least two or three – while maintaining targets of interest in focus;
- 360º multi-spectral panorama (including > 1.2 m far-stereo) requires PAW/ARM pointing straight up for maximum height advantage and rotation about this axis. The relative position of the Sun with respect to the viewing scene needs to be considered for optimal illumination and direct solar avoidance during geological imaging;
- close-up lens for imaging rocks, coarse detritus and large clasts at a working distance of ~80 mm requires optimum PAW orientation to avoid navigational hazards, including contamination from the surface.

It is proposed that a number of positions be selected within the sphere of PAW/

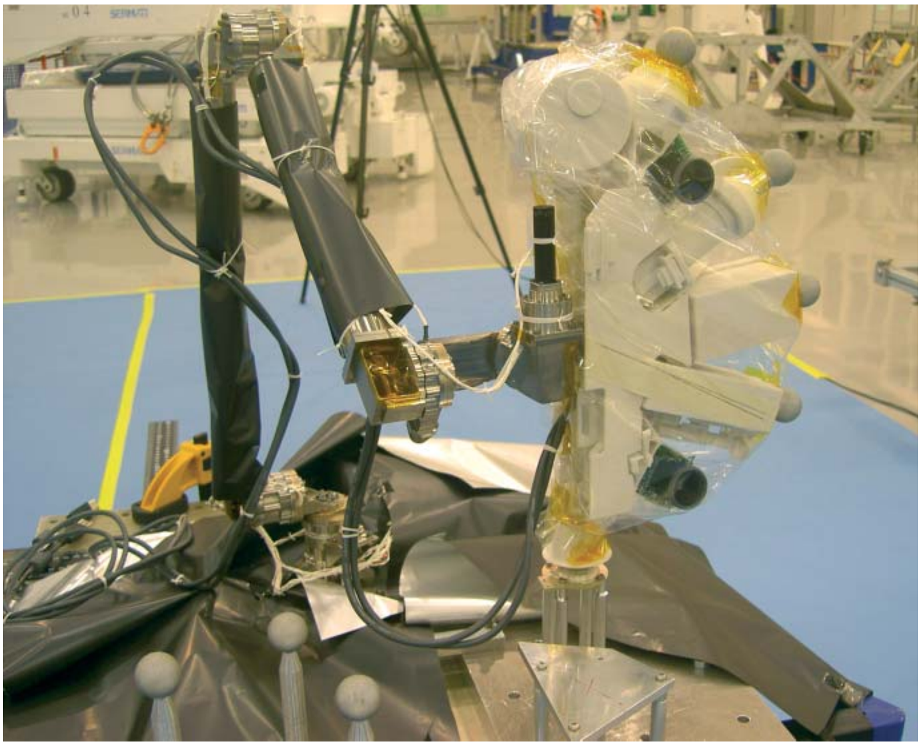

Fig. 15. The ARM FM equipped with a one-third mass PAW during calibration work. The configuration shows the sampling Mole docked to a representative (in terms of mechanical interface and location) GAP inlet.
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ARM operations that are deemed to be ‘safe points’. These are configurations that can be returned to at any time without risk of collision and from which a series of pre-set manoeuvres can be initiated.

Those operations requiring actual contact to be made with a sampling surface or activities with the Mole need special attention and are discussed in the following sections. Most imaging tasks do not require contact with the sample under investigation but some scenarios involving close-up work will require careful navigation to avoid local collisions with objects on the surface. A complete and accurate DEM of the area reachable by the PAW/ARM and PLUTO sampling Mole, and an initial characterisation of potential sampling targets contained within the zone, is an early priority. Only when this has been done can the majority of PAW/ARM operations commence.

3.2 Positioning

During initial positioning, the location of the spot where the PAW comes into contact with the candidate sample is not expected to be very precise. A suitable goal is to achieve initial contact within ±5 mm of a nominated position, based on the working zone DEM and the capabilities of the ARM. Angular contact should be within 5° of the average normal to the chosen spot. Once initial contact has been made, then this point becomes the reference datum and subsequent positioning will be relative, and therefore more accurate, albeit subject to surface roughness constraints.

The requirement for lateral positioning of the RCG for coring and the instruments is ±2 mm from the centre of ground patch. This is primarily to ensure that the instruments view the same spot within the prepared area. Along with this tighter positional alignment, it is required that the ARM can position a tool or instrument within 1º of a nominal perpendicular to a face. This is required in particular for spectrometer positioning, because any angular misalignment alters the distance between the detectors and surface. It is expected that if this angle is achieved then the action of applying a longitudinal force coupled with the compliance of the ARM would remove any angular error anyway.

Fig. 16. Sampling operations at the Lander Operations Control Centre, Univ. Leicester (UK) during early December 2003. The lander Ground Test Model, equipped with the DM ARM, is deploying the QM PAW and performing a sampling operation with the Rock Corer Grinder. The sample itself, in this case a fissile shale, is seated in a bed of coarse sand and within the working zone of the PAW/ARM defined by the raised area.
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The only instrument that requires more precise positioning is the microscope, which needs to be positioned longitudinally to an accuracy of 40 µm for focusing. This means that some device is required to move the microscope over a range of ±3 mm to within an accuracy of 40 µm. A separate actuator on the PAW provides this.

There is no precise positioning requirement for the PLUTO sampling Mole. It is expected that positioning within ±3 mm in any axis and within 5° of a nominal ‘launch’ angle will be acceptable.

For the wind sensor to be maintained horizontally with respect to the martian surface requires the PAW/ARM subsystem to account for relative lander orientation. The latter will be determined via the onboard accelerometers if they survive the landing shock. Alternatively, some estimate may be achieved via the stereo cameras.

3.3 Approach technique

Once a sampling spot has been identified on the candidate rock, the ARM will orientate the PAW to align the RCG as orthogonal to the sampling surface as possible and advance the PAW along the RCG axis towards the surface (Fig. 16). The RCG is proposed for all initial contacts with candidate samples, because it is more robust than other instruments, to establish a reference point from which all subsequent positioning can be performed with more accuracy. Furthermore, the first operation in the analysis cycle involves imaging the weathered surface with the close-up lens. This requires a PAW reorientation anyway, so nothing is gained by placing one of the longitudinal instruments against the sample first. Advancement in this way proceeds until contact has been detected or a predetermined timeout has expired. In the latter case, some sort of corrective action will have to be applied that may involve aborting the sequence and moving to a safe/default position, branching to another activity.

The final approach prior to making contact may be achievable by operating a single joint other than the wrist. For example, if the elbow joint is considered, and the forearm/PAW length is 400 mm, then the PAW needs to sweep forward up to 5 mm in the worst case, to prepare the surface with the RCG. This equates to an angle of about 0.7° swept by the RCG during operation, compatible with the accuracy of surface preparation achievable by the RCG.

On the approach to the rock, if not during the whole of the movement, the ARM movement will be stopped as soon as a sufficient contact force has been reached. This is sensed by a piezoelectric force load washer (sensitivity 3 pC N^{-1}) that generates an electrical signal upon contact with a resistive surface: a rock, instrument calibration target on the Calibration Target, GAP inlet or sample dish. Forces required by the various instruments and tools are determined from this point as a function of ARM velocity, direction and time. Suitable choice of sampling site can utilise the weight of the PAW or vertical component thereof. A different contact strategy will be required for investigations of rocks and unconsolidated materials.

The piezoelectric sensor will not normally give any charge output while the PAW is being moved around gently during normal ARM movements. The primary mode of operation is to use the sensor to detect the moment when the PAW comes into contact with the rock. The ARM is then allowed to continue to drive for a given time after contact has been detected, determined by the stiffness of the arm joints. The ARM will stop advancing shortly (~102 ms) after contact has been detected. The exact length of time depends on the instrument or tool being positioned and the anticipated orientation of the PAW with respect to the contact surface.

The ARM must operate with a degree of autonomy owing to the limited communication periods available with Earth. However, it is not intelligent but follows predetermined manoeuvres or strategies, which then allow it and the associated PAW to survey the martian surface and analyse the rocks.

3.4 Nominal rock analysis cycle

Given the constraints of the surface operations timeline and scientific requirements, only a small number of rocks (~3) are expected to be fully investigated *in situ*. Assuming that a number of appropriately sized rocks lie within reach of the PAW/ARM, each potential candidate for detailed analysis will have to be assessed based on bulk spectral properties, morphology and PAW/ARM accessibility. Once a candidate has been chosen, the full suite of analysis will be performed *in situ* by the PAW instruments and by GAP on the same material. Of course, this modus operandi may change on arrival at Mars, especially if the landing site yields unexpected or scientifically interesting diversity.

The list below describes a typical analytical sequence after a candidate rock has been selected for detailed study:

Assessment
Image the candidate rock from various angles using geology and stereo filters.
Select an area of rock for investigation (constrained by ARM, PAW access, surface morphology and spectra).

Analysis (weathered surface)
Obtain close-up images of the selected surface using hand-lens and microscope.
Perform detailed measurements with the spectrometers.

Surface preparation
Grind away the surface weathering rind and create a flat working surface.

Analysis (fresh surface)
Obtain close-up images of the prepared surface using hand-lens and microscope.
Perform detailed measurements with the spectrometers.

Sample acquisition and disposition
Extract a core from the centre of the sampling area.
Obtain close-up images of sampling area using hand-lens and microscope.
Deliver core (chippings) to GAP via the inlet port.

This sequence is based on fundamental field practice but may have to be modified as a result of surface operations and constraints.

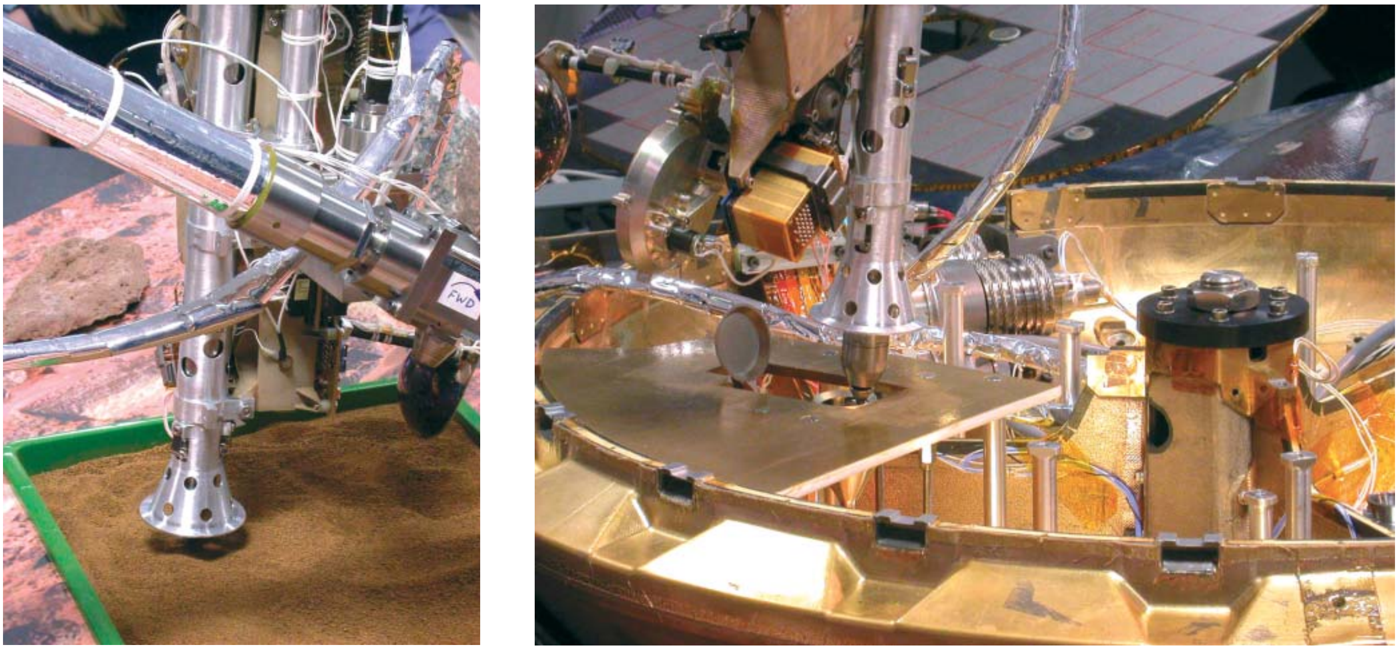

Fig. 17: PLUTO sampling operations at the Lander Operations Control Centre, Univ. Leicester (UK) during early December 2003. The lander Ground Test Model, equipped with the DM ARM is being used to deploy the QM PAW and perform shallow soil sampling operations with the Mole. Left: the sample being acquired from unconsolidated coarse sand (JSCMars1). Right: the sample being deposited into the GAP inlet port; note the inlet cover and funnel in the representative section of the lander deck.
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3.5 PLUTO (Mole) and spoon operations

The Mole (Fig. 17) is deployed in one of two ways. In the vertical mode, the sampling Mole penetrates the regolith to a specified depth (maximum 1.5 m baselined), from where a sample is retrieved. Temperature measurements are obtained at various depths (maximum 1.25 m). In the horizontal mode, the Mole crawls across the surface towards a candidate rock and is potentially deverted to retrieve a sample from a sheltered zone under a boulder. The number of samples acquired by the Mole during the primary mission will be restricted to about three.

The uppermost zone of the martian regolith is probably heterogeneous and chaotic. Suspended rocks and pebbles may deviate (or impede) the Mole, thereby contributing to an error in the depth measurement. Mole operations will be progressively more ambitious during the course of surface activities in order to minimise the risk to the scientific objectives of all instrumentation dependent on the device.

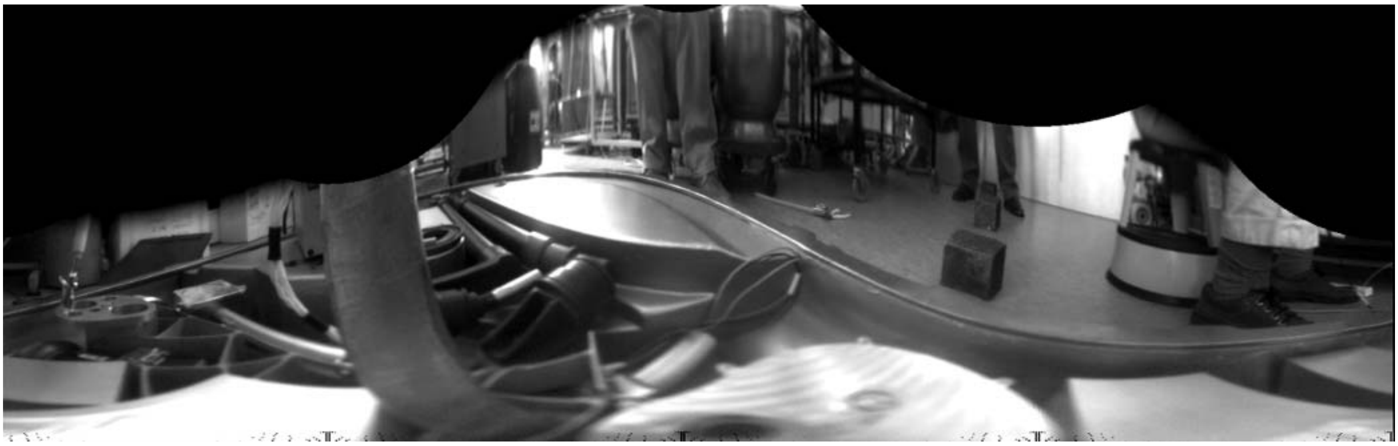
The PAW is also equipped with a ‘spoon’ as a backup method of sampling unconsolidated soil. The design ensures that no more than 20 mm^3 of material is collected, thereby avoiding the risk of overfilling the sample ovens.

3.6 *In situ* calibration and validation

Once Beagle 2 has finally come to rest on the surface of Mars and fully deployed itself, the PAW is ready to obtain the first image of the landing site. This is achieved via the Wide Angle Mirror, which moves into the FOV of the right-hand stereo camera when the pre-tensioned spring holding it down is released by the opening of the lid and solar panels. The figure of the WAM is designed to provide a 360º view of the landing site that includes the horizon. Fig. 18 shows simulated and actual views using the WAM.

Immediately after PAW/ARM release and deployment, a programme of calibration and verification will be initiated. Each instrument will undergo a predefined checkout and *in situ* calibration sequence as soon as possible. This will avoid possible erroneous effects caused by degradation of the data from the targets owing to dust accumulation etc. Recalibration will also occur throughout the surface mission to monitor any changes and, if necessary, for instrument diagnostic reasons.

The lander is equipped with a Calibration Target (CT) consisting of individual targets specific to or shared by the deployable instruments. Each instrument’s CT will



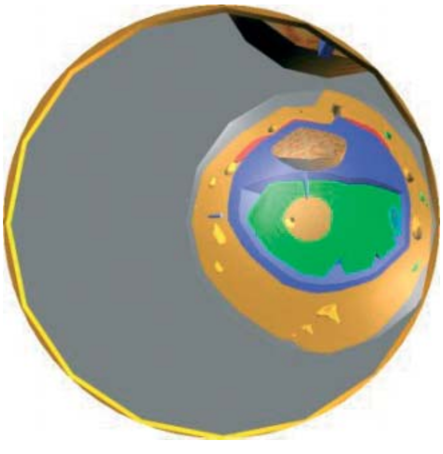


Fig. 18. Imaging with the Wide Angle Mirror. Right: early simulated view of a rock-strewn landing site prior to PAW/ARM deployment via the WAM and right-hand stereo camera. The scene is made up of sky (grey), lander structure (blue/green) and a martian surface (brown). Far right: image taken with the DM Stereo Camera and a spherically figured WAM. Camera is visible in centre of image together with the structural & thermal model PAW and lander model. The WAM mast is clearly visible in the lower half of the image. Above: processed version of the far-right image courtesy of Joanneum Research, Austria.
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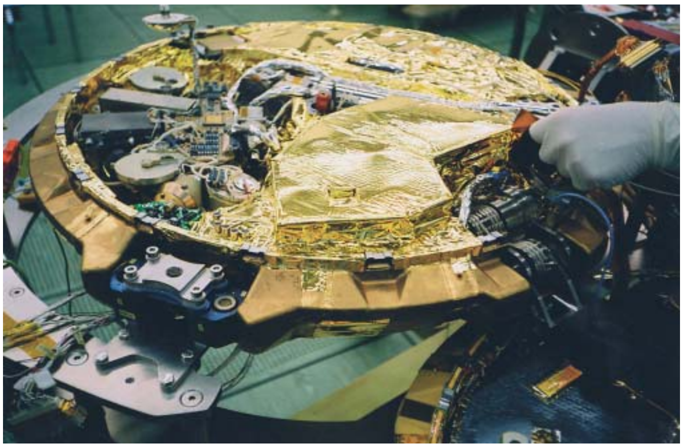
be 'known' by the onboard software and flagged as a designated point. The position of the CT has been chosen to allow PAW optimal viewing of the imaging targets and provide access for physical contact to be made by the spectrometers and the microscope. The latter case requires some structural support beneath the CT to accommodate the weight of the PAW.

4. Spacecraft Engineering

The 69 kg Beagle 2 is a highly sophisticated spacecraft (Figs. 19 & 20), which uses advanced technologies and very limited redundancy in order to meet the tight mass restrictions dictated by the Mars Express spacecraft requirements. Beagle 2 will be ejected from the orbiter before the Mars orbit insertion, and enter the planet's atmosphere on 25 December 2003 after a coast phase of about 6 days. The entry, descent and landing system will deliver it to the martian surface, where the nominal science operations phase will begin after an initial commissioning phase. The nominal lifetime of Beagle 2 is 6 months. The following sections provide an overview of the technical aspects of the Beagle 2 lander.

In addition to the Beagle 2 Flight Model, a number of system and subsystem models were built to support the lander test activities. The Beagle 2 programme delivered the following models to Mars Express:

- the protoflight model (PFM) to be integrated to the orbiter on the launch site;
- the electrical test model (ETM) for software and interface tests;
- two mass/stiffness models (MSM#1 and #2) for mechanical testing, one equipped with a QM Spin-Up and Eject Mechanism (SUEM).



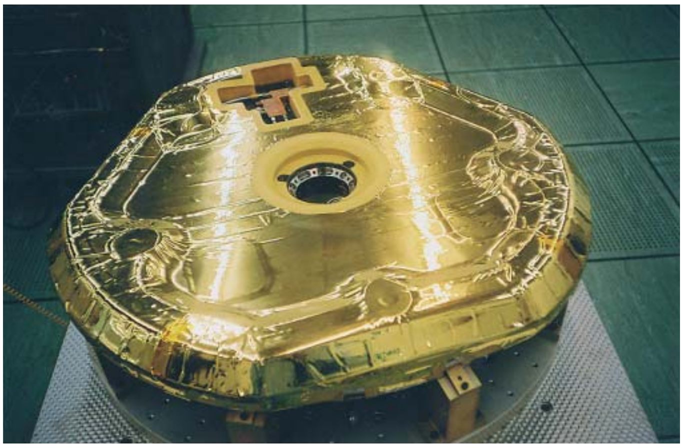


Fig. 19. The Beagle 2 Flight Model during final assembly in the aseptic clean room at the Open University, Milton Keynes, UK. Note that the Wide Angle Mirror on the PAW is held down under spring tension when the lander lid is closed. Above is the the closed lander, ready for integration into the descent capsule. *All Rights Reserved, Beagle 2*

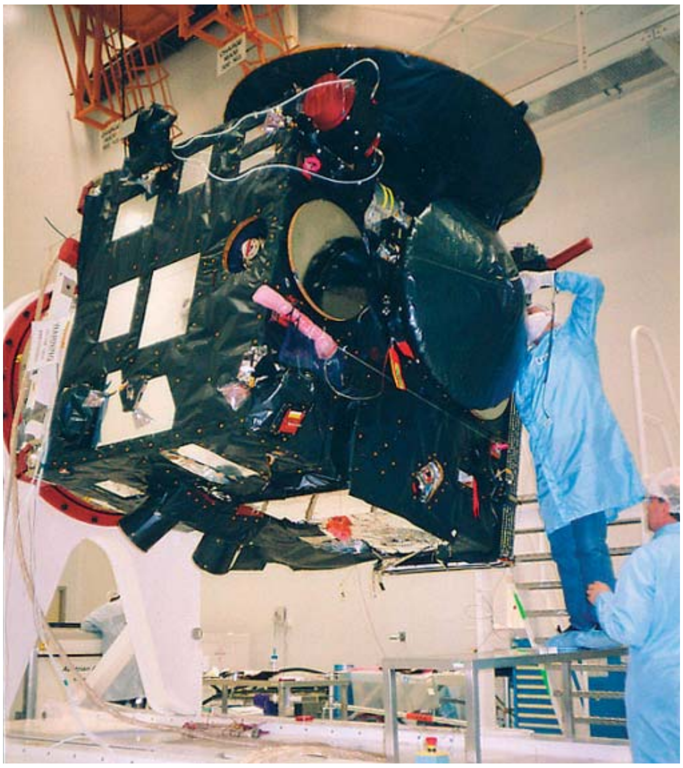


Fig. 20. Below: the fully assembled and encapsulated Beagle 2 probe, ready for delivery. Left: enshrouded in thermal insulation and integrated on Mars Express. *All Rights Reserved, Beagle 2*

— the volume interface model for mechanical integration tests;
— two pyro and frangibolt units (1 FM and 1 EQM).

A number of additional models (aeroshell assembly model, Development Model, SUEM QM #2, common electronics development model) were built for test purposes but not delivered to Mars Express.

The Beagle 2 lander comprises a number of subsystems on the landing module, and some support systems that remain on the Mars Express orbiter. The Beagle 2 system components are described briefly below.

The Entry, Descent and Landing System (EDLS) will decelerate Beagle 2 during atmospheric entry and deliver the lander to the surface of Mars. The entry sequence is controlled by onboard accelerometers and fixed time offsets and delays derived from modelling of the entry phase. The aeroshell, comprising a thermal protection system, an ablative front shield and a back cover, will decelerate the lander and protect it during the initial atmospheric entry. It will reduce the probe's speed from Mach 31.5 to Mach 1.5. Before entering the transonic region, the pilot parachute is deployed. After reaching subsonic speed, pyrotechnic bolts release the back cover and the front shield. The parachute system consists of a pilot 'chute and a main 'chute. The pilot 'chute decelerates the lander to subsonic speed. After the release of the back cover and front shield, the main 'chute is deployed, which is released on impact on the ground. The main parachute's deceleration of the lander also automatically releases the front aeroshell, which is held in place by aerodynamic pressure following release of the bolts. Once the probe is 200 m above the surface, detected by a radar altimeter, the airbag system is activated. It absorbs the remaining speed of ~17 m s^{-1} in a series of 10-20 bounces. When the probe finally comes to rest, the lacing that holds the airbags together is released, forcing the segments apart via their internal gas pressure and allowing the 33 kg lander to drop to the ground, where it finally deploys itself (Fig. 1).

At the end of the cruise phase, the capsule is released from Mars Express using the spring-powered spin-up and eject mechanism. This provides the probe with the correct axial velocity and spin rate for stability during the coast phase until entry. The capsule aeroshell is made of carbon fibre with a surface layer of powdered cork (Norcoat) tiles impregnated with phenolic resin for thermal protection during entry. The back cover is made of carbon fibre with titanium stringers again covered with Norcoat tiles. These structures act as a bioshield, enveloping and protecting the lander, airbag system and parachute from all the environments the probe encounters en route to Mars and pre-launch following sealing of the probe.

The lander structure consists of an upper (lid) and lower (base) shell, which are held closed by a clamp band until after landing. The shells are made of Kevlar, providing both energy absorption during impact with the ground and thermal protection during surface activities. The inner structure of the lander comprises carbon fibre skins on an aluminium honeycomb core. The lander outer structure contains a crushable honeycomb designed to deform around small rocks while still protecting the integrity of the payload and systems.

A main hinge mechanism allows the shells to open and provides self-righting by shifting the centre of gravity (dominated by the base) if the lander lands the wrong way up. The lander lid houses the solar panels, which are deployed via electrically-powered hinges. The base shell accommodates the robotic arm, which allows the PAW instruments to be deployed.

Beagle 2 is powered via a 42-cell lithium ion battery that is kept warm by the thermal insulation and by heater power during the martian night. When Beagle 2 is deployed on the surface, power to charge the battery and/or supply daytime experiments is provided by four deployable solar panels of total effective area of about 1 m^2. The panels employ high-performance triple-junction gallium arsenide cells mounted on germanium substrates. The electronics module of the lander provides power distribution, conditioning and management.

The lander common electronics consists of a number of circuit boards, forming the electronics module (ELM). A local common electronics module (LCE) that supports GAP is accommodated separately. The lander electronics provide the following functions:

- onboard processor (ERC32) and data handling;
- power conditioning, distribution and management;
- interfaces to instruments and equipment.

An interface to the lander electronics is provided via the probe umbilical. The ERC32 processor is controlled by the onboard software, which consists of four basic modules:

- the Bootstrap Loader (BL), which resides in a PROM. It contains the programs run initially after power-on (mission phase detection, execution of application software image);
- the Common Software (CSW), which provides low-level hardware drivers and utilities;
- the Probe Software (PSW), which provides the functionality required for entry, descent and landing, as well as for handover to Lander Software functionality;
- the Lander Software (LSW), which provides the lander subsystem control and instrument and experiment functionality for the surface operations.

The CSW, PSW and LSW are stored in EEPROM and loaded into and executed from RAM memory.

The Beagle 2 communication system provides the means for bi-directional UHF radio communication with the Mars Express orbiter and NASA's Mars Odyssey. It consists of the following:

- transceiver (transponder and interface digital baseband circuits);
- diplexer, power divider and radio-frequency cables;
- receive and transmit antenna integrated into the lander lid structure.

The data rates provided on the forward link (Mars Express to Beagle 2) are 2 kbit s^{-1} and 8 kbit s^{-1}. The return link data rates are 2-128 kbit s^{-1}.

Under the UN COSPAR regulations for planetary protection, planetary landers carrying life-detection instrumentation (designated as category 4B) are subject to sterilisation procedures, which have a major impact on probe design and assembly, integration and verification. In order to meet these requirements, the Beagle 2 Planetary Protection Plan was implemented, ensuring that both the protection of the martian environment and the life-detection capabilities of Beagle 2 were not compromised. The FM lander/capsule was assembled in an Aseptic Assembly Facility (Fig. 19). All components were sterilised and cleaned before integration. After lander integration was completed, measures were taken to prevent any contamination during tests and on the way to the launch pad.

5. Flight Operations

The Beagle 2 mission can be divided into five phases:

- cruise and coast following deployment from Mars Express;
- descent;
- initial lander operations (status and integrity checkout);
- primary (baseline) mission (landing to +180 sols);
- extended mission, subject to additional funding becoming available (+180 to +669 sols, i.e. martian year).

An operations team with varying levels of involvement will support all phases of the mission. Most operations will be conducted remotely from the UK via data links, with only a small team at ESOC for critical operations. Data will be released at intervals to the public via project-controlled web sites and the media centre, consistent with the ESA mission publicity and information plan.

Surface operations will be dictated by the ability to communicate with either Mars Express or Mars Odyssey. The telecommunications system is designed to relay at least 10 Mbits per day. Communication sessions are dictated by the landing site, Mars Express orbit, availability of relays via the NASA Mars Odyssey mission, etc.

Beagle 2 remained passive for long periods of the cruise phase. At two intervals during cruise, the probe was checked out and the battery charged. The data and command interface with Mars Express allowed reprogramming of the onboard common electronics in Beagle 2, which will control the descent sequence, had it proved necessary to redefine the landing sequence time delays. Temperature and heater power for the Beagle 2 probe were monitored throughout the cruise phase.

The descent will be fully controlled by the processor within the common electronics. This will be powered up via a hardware timer ~60 min before atmosphere entry in order to avoid depleting the battery. The onboard processor will continue to control Beagle 2 until the first communication session is held via either Mars Express or a relay via Mars Odyssey.

The following operations, which will be initiated following release of the gas-filled landing bags and impact with the surface, will be performed automatically:

- deploy solar panels;
- start battery charging (for the remainder of the day);
- obtain monochromatic image with right-hand stereo camera and WAM. WAM will automatically be positioned in the field of view;
- initiate overnight low-power mode if no contact occurs on sol 1;
- continue low-power mode and daytime battery charging until communication possible.

Following first contact and evaluation of the lander status, including analysis of the first image, the following operations will be commanded:

- deploy the PAW-ARM subsystem to a safe/default configuration;
- begin the initial imaging phase. An early priority is to provide sufficient stereo coverage of the PAW-ARM working zone for DEM construction.

Once the area within reach of the PAW-ARM has been modelled, the following activities dominate the rest of the primary phase of the mission:

- communication sessions;
- accumulation of multispectral images of the landing site and atmosphere;
- PAW-ARM activities, including target assessment, selection, *in situ* analysis, surface preparation and sample acquisition;
- extended sampling activities with the Mole;
- gas analysis of samples acquired by the PAW or directly from the atmosphere;
- battery charging.

To conserve power, ARM positioning and GAP processes will be performed during the day, whereas low-resource activities such as spectrometry and microscopy will be done at night. Obviously there is some logical and/or priority order to some of the activities listed above. Furthermore, much is dependent on what Beagle 2 is presented with at the landing site. It is estimated that an ideal (complete) sampling cycle will take tens of sols. Assuming a baseline of 5-6 samples is available for analysis, the primary mission will last ~80-100 sols plus additional time for early operations. Given these factors, a target primary mission lifetime of up to 180 sols is assumed.

The majority of an extended mission, if funded, will be devoted to atmospheric science because it is expected that available solar power will be reduced by dust settling on the solar panels and hence a low-power mode will be implemented. The following operations are expected during the extended mission:

- communication sessions;
- occasional imaging of the landing site and lander targets to monitor for seasonal and other changes;
- repetition of atmospheric analyses, i.e. daily, seasonal and other changes;
- *in situ* analysis of other rocks and soils;
- additional sample analysis by GAP, if resources permit and ovens are available.

6. Landing Site Selection

Three locations on Mars had been visited by landers before 2003. The Viking and Pathfinder sites had in common their rock-strewn landscapes; at the Pathfinder site, coverage by fragments of ~3 cm was ~16% (Golombek et al., 1997). Size-frequency data suggest that there should be three specimens larger than 10 cm m^{-2} of surface, one of which would be ~20 cm. Boulders like Pathfinder's Yogi (> 1 m) occur at a rate of one per 100 m^2, so an individual rock of such proportions might be found 5-6 m from Beagle 2 at any landing locality similar to that of Viking or Pathfinder. The soil consistency on Mars is sandy and the presence of rounded pebbles in the Ares Vallis confirmed that water and wind had probably once modified the terrain (Smith et al., 1997). The Pathfinder location was specifically chosen because it was likely to have been a flood region; the success of this prediction means that similar sites can readily be selected for Beagle 2, especially given the availability of Mars Global Surveyor images to guide decisions.

The Beagle 2 team identified a number of sites that were considered to fit the mission objectives and constraints (within ±35° of the martian equator and below the datum). Candidate sites fell into three categories:

- craters in highland terrain with evidence of runoff channels around their margins, e.g. Gusev (15°S, 185°W), Becquerel (22°N, 8°W);
- regions near the highland/lowland boundary, e.g. Elysium basin (0-20°N, 170-210°W) and the margin of Amazonis (4°N, 150-151°W);
- previous landing sites: Viking-1 in Chryse Planitia (22.4°N, 48°W) and Pathfinder in Ares Vallis (19.5°N, 32.8°W).

While all candidate sites, with the possible exception of the Viking-1 site, show evidence of flooding in the past and hence possible sedimentary deposits, the highland region was discounted because of the incompatibility with the expected size of the landing ellipse (~250 x 30-50 km). Further work on site selection followed analysis of data from Mars Global Surveyor, resulting in the identification of three suitable regions: the Maja Vallis channel area in Chryse, Tritonis Lacus on the margin of the Elysium Plains, and Isidis Planitia.

6.1 Isidis Planitia

The landing site for Beagle 2 was eventually chosen as the area around 265.0°W and 11.6°N within Isidis Planitia (Bridges et al., 2002). The site satisfies the safety requirements for landing (average slope of 0.57° and a low elevation, being more than 3.6 km below the martian datum) and provides an environment with good exobiological potential. The rock abundance is estimated at about 2-17% (mean 11%) and, in addition, Isidis shows evidence for the concentration and remobilisation of volatiles.

In a regional sense, the pattern observed in thermal inertia data suggests that sedimentary materials have been added to the landing site area from the Noachian units around the southern half of the basin. At the same time, a variation in the degree to which tuff cones have been eroded suggests that they formed intermittently over a long period of time (within the Amazonian period, and possibly Hesperian as well). The whole area has also been resurfaced in relatively recent times by aeolian deposition and/or erosion, which is highlighted by a deficit in impact craters larger than 120 m diameter.

In conclusion, Isidis Planitia represents an opportunity for sampling a set of martian materials not previously encountered by other missions. These include Noachian rocks from Libya Montes, rocks from below tuff cones (which might show evidence of geological activity involving CO_2-H_2O fluids) and rocks from some of the local impact craters (Bridges et al., 2002).

7. Scientific Analysis

In addition to the instrument experimenters, the Beagle 2 project has set up a group of adjunct scientists under the Chairmanship of the Associate Science Leader, Dr. A. Brack (Centre de Biophysique Moléculaire, Orleans, F). These investigators, who have no hardware role, work in a great variety of disciplines; their theoretical input and background laboratory experience will greatly enhance the interpretation of the returned data and contribute to the overall success of the mission.

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