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WOBBLE ("Water Observations from a Balloon Borne Light Explorer") is a mission concept study for a small robotic probe to explore Mars and to accomplish a scientific mission compatible with the goals of the NASA Code S enterprise. The detection of past or present water is a crucial goal for Mars exploration, representing a cross-cutting science theme relevant to past or extant life, climate history, sample return missions and eventual human exploration. The WOBBLE mission concept was developed to study evidence of water using in-situ detection methods. The features on Mars most suited to this investigation are the gullies identified by Malin and Edgett[1] as evidence for recent, near-surface runoff of liquid water. These features are typically located on the inside face of crater rims, where the local slope angle is at or near the angle of repose. This makes the terrain difficult or impossible to access with conventional wheeled rover technology. Combined with the small size of the gullies in relation to a standard landing error ellipse, scientific investigation of these features requires a new approach to surface mobility. WOBBLE uses a low-altitude balloon-borne platform to traverse the surface from the landing site, to the investigation site, and then rise up the slope to investigate the regions of interest at close range. Of the mobility technologies available for near-term Mars exploration, only a balloon platform is capable of a well targeted, detailed sampling of the gully regions over periods of days or more. The science approach embodied in WOBBLE is two-pronged, designed to investigate both the historical evidence of liquid water utilizing high-resolution geomorphology and the characterization of mineral deposits, and present subsurface liquid water using radar sounding techniques. The WOBBLE balloon is a high-pressure hydrogen gas design, 24 meters in diameter and lifting a total payload of 130 kg, including a high-resolution camera/IR imager, Raman spectrometer, and a ground penetrating radar (GPR) sounder. The stowed balloon and payload are designed to fit within the current airbag delivery system being built for the Mars Exploration Rovers. Characterization of local meteorological conditions and wind is made over the initial sols following landing and before balloon inflation. Following balloon inflation and launch, a controlled, targeted approach toward the identified regions of interest is made in a series of several low-altitude "hops," with the balloon tethered to the ground between the hop intervals. A "snake" system is used to control the altitude to a few tens of meters above the local ground level. Enroute to the target gully, GPR soundings and Raman spectroscopy measurements study past or present water, while continued camera bearings and meteorological measurements refine the next "hop" trajectory. Once at the gully/outflow region, GPR and Raman soundings continue while the camera obtains detailed, $\approx 0.5cm$ images for geomorphology studies. The WOBBLE concept is applicable to Mars Scout, Mars Surveyor, or Discovery class missions.

Introduction

Exploration of Mars is at its incipient stage. To date three successful landings, four flybys, and five orbiters have investigated the planet. While the role of the orbiters in the characterization of Mars is important, and will provide invaluable data for the foreseeable future, only lander missions are capable of performing the in-situ experiments to satisfy the goals set forth by the Mars Exploration Payload Analysis Group (MEPAG).[2]

Out of the lander missions only the Mars Pathfinder had surface mobility through the Sojourner rover, albeit on the order of 10 meters from the landing site. More lander/rover missions are planned for the future, with the 2003 Mars Exploration Rovers currently under development. The 2003 MERs are designed to have ranges of up to 100 meters per Martian day (sol) for at least 90 sols. Advanced lander/rover combinations are planned for 2007 and beyond. Powered by radioisotope thermoelectric generators (RTGs) the 2007 rovers will have ranges on the order of tens of kilometers. A quantum leap from the Sojourner rover the mobility through 2003 and beyond surface rovers is limited to relatively flat and obstruction free terrain.

It should be noted at this point that NASA JPL scientists and engineers are addressing the issues of land mobility in rough and steep terrain with the development of an all terrain exploration (ATE) rover[3] and of the cliff-hanging rover.[4] Both ATE and cliff-hanging rovers will be able to tackle steep terrain but their mobility is still constrained by the size of the boulders they can drive over and the distribution of boulders larger than those they can drive over.

At this point it seems that air[1] mobility is the key to medium and long range robotic exploration of Mars. Heavier and lighter than air vehicles can carry science instruments over ranges of a few thousands of kilometers on Mars.

From gliders, to propeller and rocket propelled heavier than air explorers have been investigated.[5] Baseline mission scenarios for propeller airplanes have endurance of about three hours and ranges of about 2000 *km*. Flying at altitudes between 1 and 9 *km* the airplanes would take high resolution still and video images of the canyons in Valles Marineris for example,[6] and perform gravitational, magnetic, and electric field measurements.

Lighter than air explorers have been proposed for Mars mission, but their goals are either similar to those of the heavier than air vehicles or are employed to perform controlled landings.[9] In both types of missions the balloons are deployed during the entry thus highly increasing the risk to the mission.

To perform in-situ science experiments in a relatively small target area, such as the debris apron and run-off channels of the gullies present in some crater walls, we propose a mission which employs a balloon to provide the mobility of the science packages. The balloon is deployed after landing, from a heritage entry, descent, and landing system (EDLS,) specifically, the EDLS of the Mars Exploration Rovers. To date, this architecture provides an optimum mobility vs. risk factor. Furthermore, the risk of the mission can be considerably reduced by simulation and prototyping both on Earth, prior to launch.

The following section will present the science objectives of the mission and the instruments selected to achieve the objective. The general mission architecture will then be presented followed by the most important vehicle subsystems. The paper will end with a summary and a brief presentation of technologies which can be used to reduce mission risk.

Science Objectives and Instrumentation

The goal of the WOBBLE mission is to elucidate the origin of the gullies observed in Martian valley and crater walls. Due to their striking similarity to outflow gullies on Earth it was hypothesized that the gullies observed on Mars were generated by a liquid aquifer during geologically recent times. A recently released MOC image of a typical gully region is reproduced in Figure 1. It is proposed that to achieve the goal of the mission the science package will take high resolution visible and images of the gullies, perform infrared (IR) and Raman spectrometry, and laser induced fluorescence analysis. The high resolution visible spectrum images will provide clues of the mechanism behind the formation of the gullies plus rock size and distribution. The IR and Raman spectrometry and fluorescence analysis will determine the composition of the rocks and soil in the debris apron. Of particular interest is the presence of salts which depress the freezing point of water.

Additionally the science package will include a ground penetrating radar (GPR), and electromagnetic (E&B) probes. A secondary science package will include a a meteorology station (metmast.)

The GPR will look for present day underground water, either liquid or frozen, and will also investigate

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[1] Here air is the term used for the mixture of gases that constitutes the Martian atmosphere.

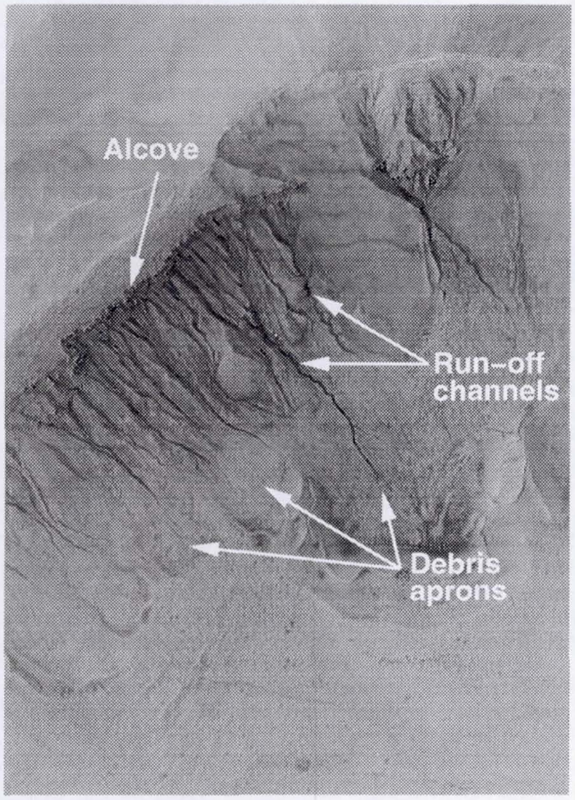


Fig. 1 Recently released (October 7, 2002) image of gullies observed by the MOC instrument. The crater is centered at $39.0^o S$ and $166.1^o W$. The image is one of highest resolution images of the Martian surface, at 1.5m/pixel. The similarity with outflow gullies on Earth suggests that the Martian gullies have been generated by an aquifer. Photo credit: NASA/Jet Propulsion Laboratory and Malin Space Sciences.

the mineralogy to depths between tens and hundreds of meters. The E&B probes will support the GPR sounding by measuring the local electromagnetic environment.

The main role of the metmast is to provide data for the balloon operations and its secondary role is to take measurements of the air temperature, pressure, and wind velocity.

Two low resolution digital cameras will be employed to track pilot balloons launched prior to the main balloon launch, to monitor the inflation of the main balloon, and to track the main balloon departure.

Table 1 lists the science instruments and their characteristics.

Overall Mission Architecture and Design

This section describes the overall mission and its architecture plus the constraints that were identified and which drove the design of the mission.

To accomplish the science objectives the mission will place a balloon in a crater on Mars to make detailed observations of gullies present in the walls of the crater. The possibility of an extended mission to float and observe the surface randomly for an additional month or two is also provided for. The mission will use the assets already in Mars orbit as telecommunications relays.

Landing Site Selection

A landing ellipse with a major axis of $30km$ and a minor axis of $10km$ is achievable by a MER-like carrier and EDLS but in order to achieve it a sixth trajectory correction maneuver (TCM) is required. The sixth TCM is performed within a few hours before touchdown and it has not been attempted yet. This will increase the risk to the mission but within tolerable margins.

A preliminary landing site has been chosen after a study of the images taken by MOC and analysis of topographic data from the Mars Orbiter Laser Altimeter (MOLA) instrument. The constraints for choosing the landing site were:

1. The size of the crater be at least 10% larger than the major axis of the landing ellipse.
2. The crater has a gullies in its walls.
3. The crater is in a zone accessible by the mission, i.e. the declination and azimuth of the reentry corridor shall allow landing inside the crater.
4. The bottom of the crater shall be relatively flat. This constraint is derived from the constraints of the MER EDLS and the exact definition of the "flatness" constraint of the MER EDLS will be used.

The crater selected is the so called Aerobraking crater and it was imaged by MOC during the aerobraking phase of the MGS mission. The images of the Aerobraking crater provided one the first evidence of existence of the gullies. The Aerobraking crater has a diameter of $50km$ and it is centered at $65^o S$ and $15^o W$ in the Southern Noachis Terra. An image of the Aerobraking crater and a notional landing ellipse of the appropriate size is presented in Figure 2. Further studies of the selected landing site are necessary. Of prime importance is the simulation of the winds inside the crater for a period of a few days. The goal of the simulation is to provide estimates of the wind velocities. Since the wind provides the motive force for the balloon it is useful to know if the wind velocity vectors point towards the outflow gullies and if they do so at what time. This simulation will strongly influence the decision to proceed further with the selected landing site.

High fidelity meso and microscale atmospheric models for Mars have been developed[10, 11] and it is envisioned that these models will be used to simulate the

Table 1 Instruments proposed for the WOBBLE mission and their characteristics.

Instrument	Complexity	Mass (kg)	Power (W)		Downlink (kbits/s)	
			Peak	Average	Peak	Average
Pre-launch metmast	simple	1.0	2.0	1.0	0.1	1.2
Low res cameras	simple	0.1	0.2	0.0	10	300.0
High res camera and IR spectrometer	moderate	1.0	1.0	1.0	4000.0	4000.0
3D electric field probe	simple	1.0	0.5	0.1	1.0	1000.0
3D magnetic field probe	simple	1.0	0.5	0.1	1.0	1000.0
GPR receiver	moderate	0.5	10.0	1.0	0.5	0.5
Raman spectrometer	complex	2.5	3.0	2.0	0.1	2.0
Laser induced fluorescence	complex	1.0	4.5	1.0	0.2	2.0

weather conditions at the landing site. The results of the atmospheric simulations will be coupled with a virtual reality model of the crater and its surrounding area to create a simulation environment. Tests of the balloon control system and of the navigation methods will be performed in the simulation environment to reduce the risk of the mission.

Mission Scenario

The mission will use the MER EDLS system. After touchdown and bag deflation the MER-like lander will deploy the metmast and monitor the atmospheric conditions at the landing site. A couple of low resolution cameras will be deployed as well. Their purpose is to monitor the deployment of the main balloon and the flight of pilot balloons which will be launched prior to the launch of the main balloon. During the first phase of the mission the cameras will also be used to take images of general public interest for PR purposes. The main balloon and the science package will remain stowed. The design of the high resolution camera enclosure and pointing mechanisms will allow it to take images of the crater walls and identify the position of the landing site with respect to the gullies.

The metmast will collect atmospheric data for a few days and will communicate the results to Earth. Each day, a pilot balloon will be released, at different times of the day, and the low resolution cameras will track its flight. Based on the data from the metmast and the flight path of the pilot balloons the science team will attempt to validate the results of the atmospheric simulations performed prior to the mission. If the simulation results match the data obtained by the mission the deployment of the main balloon will be given the go-ahead.

If the results obtained with the atmospheric models are too far off from the observed conditions and cannot be validated the models will be rerun with the new data and improved models will be obtained. The first phase of the mission will be extended by a few days in order to validate the new results and possibly reprogram some of the navigational algorithms.

The main balloon will inflate and using an autonomous navigation system will proceed with low altitude flying towards the gullies. Ideally the balloon will perform only one hop from the landing site to the vicinity of the gullies. However, the navigation system will be designed to be able to handle incremental navigation through multiple hops. See Figure 3 for a depiction of the sequence of events.

After each landing the science package will deploy the GPR antenna and other instruments mounted on booms to take data. An idea to mount the GPR antenna on the balloon envelope has been abandoned because the motion of the balloon in the Martian boundary layer would interfere with the collection of data. Deployment of the GPR antenna on the ground, in a manner similar to the Netlander mission is considered at the time of this writing. It has not been determined yet if the GPR antenna will be re-stowed after each landing or if the science package will carry multiple disposable antenna sets. The deployed disposable antenna set will be discarded prior to each hop.

One mission scenario proposed the release of the main balloon from the gondola carrying the science package. The balloon will carry a weather station similar to that mounted on the metmast and will take a vertical profile of the atmosphere. Another scenario under consideration is to release the balloon with the weather station plus the high resolution camera mounted on a stabilized platform. The balloon would be controlled to raise slowly over the gully. While over the gully the camera would take high resolution images and the ground and sent them back to the orbiter acting as a communications relay or to the science package

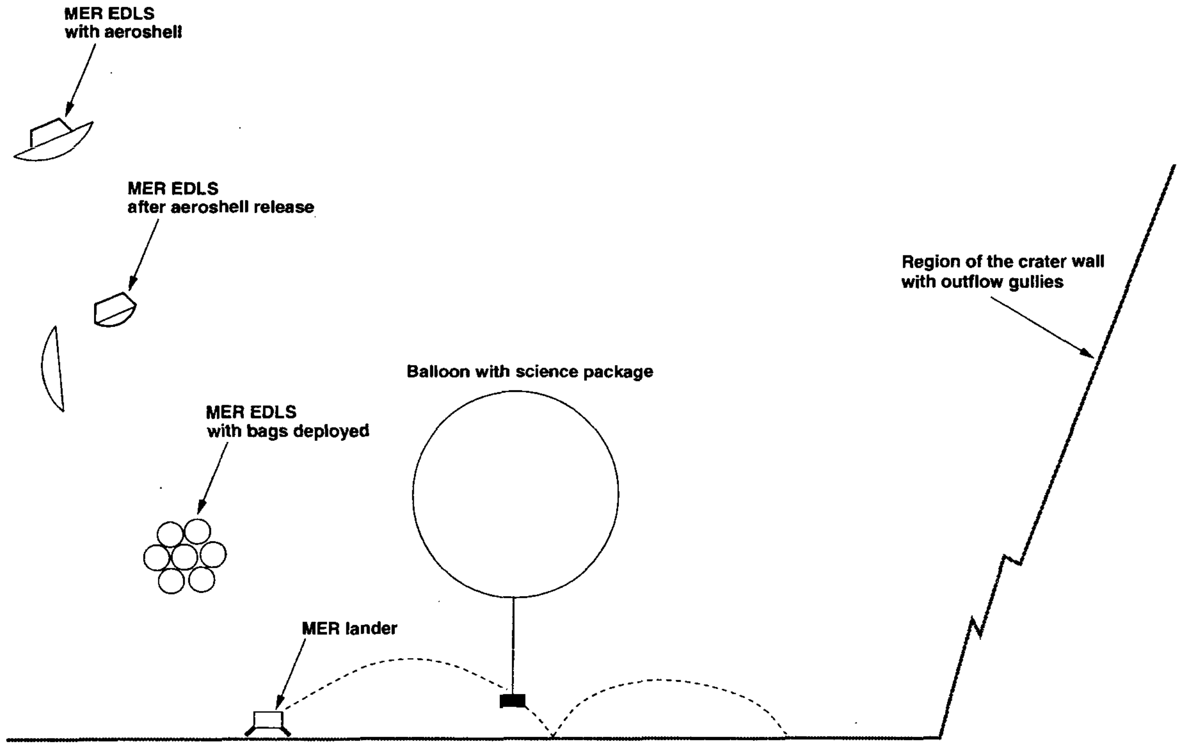


Fig. 3 Illustration of the WOBBLE concepts of operation. The typical EDL sequence of the MER is followed. Note that the parachute is not shown for simplicity. Once the airbags are deflated the lander deploys its metmast and takes measurements of the atmospheric conditions. Once the atmospheric conditions are deemed reasonable the balloon is deployed. The balloon takes a science package housed in a gondola to the region with outflow gullies in a few hops. In one scenario the balloon with a weather station is released from the gondola. In another scenario the balloon carries the high resolution camera along with the weather station.

left behind. A third scenario considers the deployment of a cable between a base in the debris apron and the crater wall. The cable will be deployed and anchored in the crater wall by a hypervelocity penetrator. Another, less energetic, method of deployment is the release of the main balloon with the cable acting as a tether. An anchor or a grapple will be dropped from the main balloon once a suitable anchoring spot is found. Once the cable is deployed and secured the science package will be deployed from a cable-car allowing the in-situ study of the the debris apron material and of the run-off channels. Figure 4 illustrates the cable-car concept of operations.

Of the three scenarios proposed the scenario with the cable-car science package permits detailed science experiments of long duration, possibly weeks and months, compared to a few days of the first two scenarios. At the same time the cable-car scenario has the highest risk of the three.

Main Balloon and Gondola

The initial design of the main balloon proposes a super-pressure envelope inflated with hydrogen. The hydrogen will be stored criogenically during transit. Preliminary mass estimates of the science packages and the structure of the gondola total $125kg$. A balloon inflated with hydrogen with a diameter of $12m$ will provide a lifting capability of $137kg$, enough to lift the science payload and the envelope and ancillary items. For the balloon sizing it has been estimated that the Mars atmospheric density is $20g/m^3$. The material used for the balloon is Mylar C, with a thickness of $6\mu m$. For navigation and control of the landings a multiple inflation and venting system will be provided. The upper and bottom parts of the balloon will be separated by a Mylar membrane. The upper half of the balloon will be inflated once and the lower half will be inflated and deflated to control the flight. A snake will trail behind the gondola to provide an additional means of altitude control. The snake will be segmented so that parts of it can be discarded if they become tangled.

The gondola will be manufactured of lightweight alloys and will house the science instruments, the balloon inflation and venting mechanisms, the power and telecom subsystem. It will be designed to withstand multiple landings.

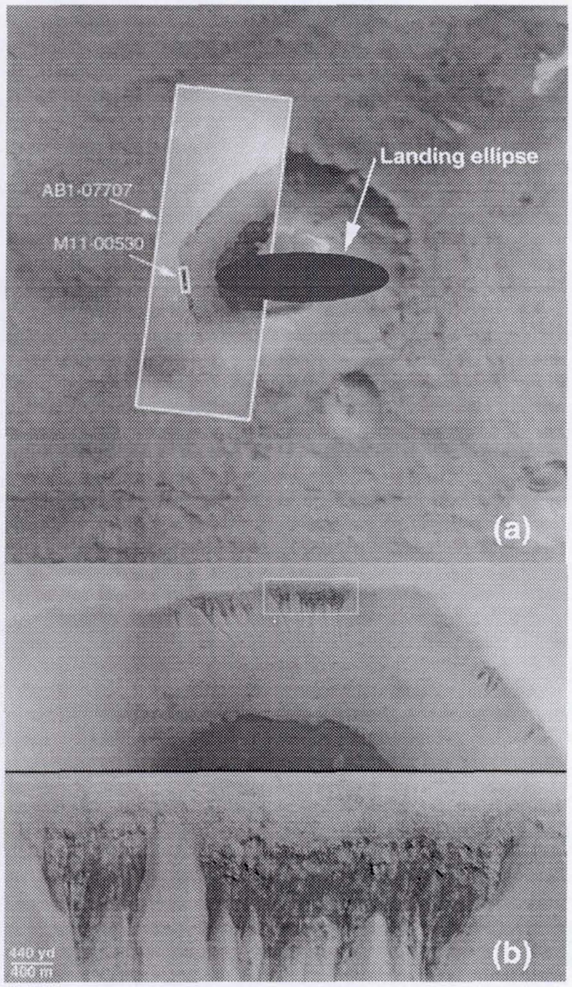


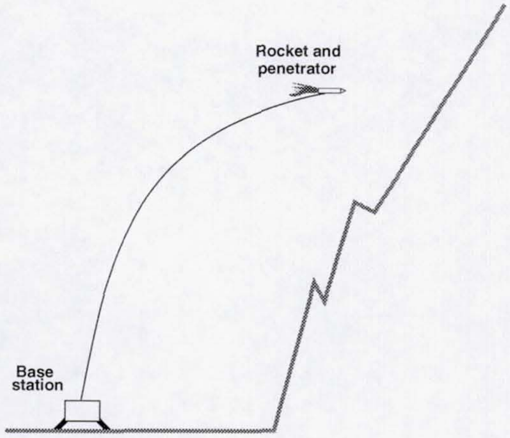
Fig. 2 Image of the Aerobraking crater with a notional landing ellipse (a) and details of the gullies in the crater wall (b). The crater has a diameter of $50km$ and it is centered at 65^oS and 15^oW in the Southern Noachis Terra. Note that the alignment of overlaid landing ellipse does not represent the true direction of the landing ellipse of the mission but it was included for illustration purposes. Photo Credit: NASA/Jet Propulsion Laboratory and Malin Space Sciences.

The breakdown of the balloon and gondola mass is presented in Table 2. It is to be noted that the total mass in Table 2 includes a 15% margin. For the time being no cost estimates can be provided because the technology is at an incipient stage.

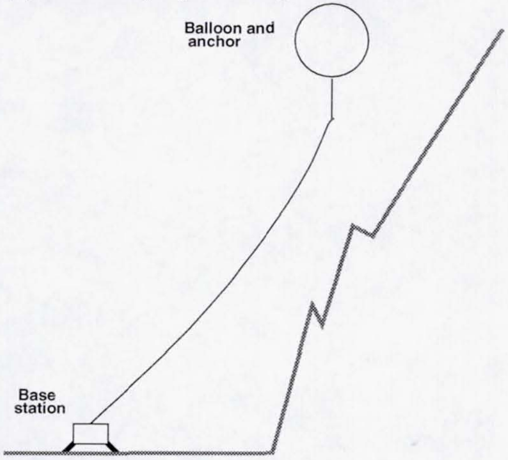
Command and Data Handling Subsystem

The relevant mission parameters used in the design of the command and data handling (C&DH) subsystem are

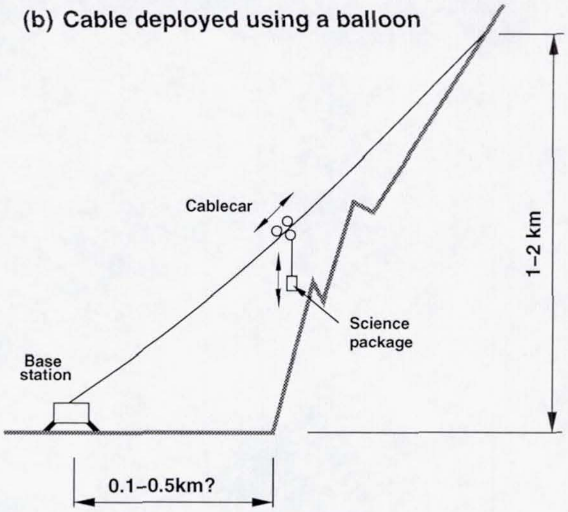
- Primary mission duration of 70 days



(a) Cable deployed using a rocket



(b) Cable deployed using a balloon



(c) Cable and cablecar deployed over gully

Fig. 4 Proposed deployment scenarios. Deployment by a hypervelocity penetrator (a) and by the balloon (b). Figure (c) shows the deployed cable and the cable-car.

Table 2 Balloon and Gondola Mass Breakdown

Component	Mass (kg)
Envelope	48.0
Fill Gas	3.4
Gondola	18.0
Instruments	8.2
Controls, telecom, power	34.0
Total	**129.6**

- Mission class B/C
- Technology cutoff 2004
- Radiation 5 krad, 100 mils AL, RDM=2

The instruments on the lander and balloon. The lander instruments include, a meteorology station, two low-res cameras and pilot balloon launcher. The instruments on the balloon include hi-res camera, 3D electric field sensor, 3D magnetic field sensor, GPR receiver, Raman spectrometer, laser induced fluorescence instrument. Average and peak data rates for the instruments are presented in Table 1. The total data volume from the instruments on the lander was estimated to be 14 Mbits/day and the total data volume from the instruments in the balloon gondola was stated to be 120 Mbits/day.

A RAD6000 computer is proposed for the lander science package. There is an interface board to the cameras which also doubles as NVM. The amount of memory on this board is 256 Mbytes (4 Gbits). This provides sufficient margin and redundancy since single-string. In addition, not accounted for in the storage is the telemetry from the lander. The amount of memory (and power required) may be reduced to fit the memory requirements for this proposed mission. The balloon borne science package assumes an advanced MCM heritage based upon a modified X-2000. The SFC is the RAD-750. The NVM is assumed to be 2 Gbits which also exceeds the requirements. The analysis of the data storage in the telemetry may need to be revisited with an expectation that the required memory will increase.

All C&DH elements are single-string (except memory where data can be stored redundantly) increasing the risk on the system. If the telecom interface board on the lander fails, there is no communication of any data from the balloon for example. The design calls for turning off CDS at night. Typically the SFC would be considered critical hardware and section 1.29 of the JPL Guidelines states, that "in-flight routine power cycling of critical hardware for power margin management purposes shall be avoided, unless cycling is essential to mission viability and the risk is demonstrated to be acceptable." The costs for each of the components are US$8.4 M for the balloon borne C&DH and US$ 16.0M for the lander C&DH subsystem.

Table 3 Power subsystem mass and cost breakdown.

Component	Mass (kg)	Cost (M US$)
Balloon solar array	5.55	1.16
Balloon batteries	1.69	0.73
Balloon power electronics	2.57	1.05
Lander solar array	11.0	2.6
Lander batteries	13.0	1.15
Lander power electronics	7.0	1.27
Total	**40.81**	**7.97**

Power Subsystem

The design requirements for the power subsystem include a launch year of 2007 and 2004 as the technology cutoff year. The power needed by the science instruments is presented in Table 1. The design assumed that the solar array will be deployed after landing. The batteries on board will provide electrical heater power during the night. The solar environment drove the design of the power system and the daily solar flux was assumed to be $3.5kWh/m^2$. The design made the following assumptions

1. There will be $10h/day$ of near complete darkness during which only the survival heaters will run.
2. There will be $5h/day$ of transitional power during which the subsystems will be in power neutral sleep.
3. There will be $10h/day$ of operational power.
4. The ratio of survival heater load to operational load is $1:3$.

The power produced by the solar array on the balloon borne science package is $68W$ and the energy storage of the battery is $144Wh$, $5Ah$ at $28V$. The electronics for the balloon borne package were sized for $68W$. The lander solar array power is $175W$ and the energy storage of the battery is $2700Wh$. The lander electronics were sized for $176W$.

The mass and cost breakdown of the power subsystem is presented in Table 3.

Telecommunications Subsystem

The mission requires telecom elements on the balloon and ground station. The lander station data telecom equipment (DTE) hardware consists of a $15W$ SSPA and a $0.3m$ patch array HGA, which can downlink a minimum rate of 320 bps at 2.5 AU. The lander also accommodates a high power ($10W$) UHF relay to provide a minimum of 100 $Mbits/Sol$ (at least $6dB$

margin depending on terrain) with data rates that vary with ellipticity of the orbit and elevation from the horizon. The balloon will use a low power ($0.5W$) transmitter to provide a minimum $5Mbits/Sol$ during the extended mission. Because of the short proximity of the balloon to the lander, the link can sustain a rate of $1Mbps$ assuming a clear line of sight and flat terrain.

There are two UHF transceiver designs implemented for this mission. The landed ground station has the Electra UHF transceiver which is being developed for the MRO mission. This model does not include the X-band receiver block which is present in the original Electra design. The balloon uses a miniaturized UHF transceiver, a heritage design from DS-2, which has a reduced functionality from the Electra transceiver. The modification to this transceiver from the DS-2 transceiver is the added capability to communicate with the Electra radio. This incorporates an increase in mass and DC power consumed.

EDL communications is supported by the UHF transceiver aboard the ground station module. The assets already in Mars orbit will receive the EDL communications. A primary UHF relay has not been designated yet.

Due to mass and cost constraints, redundancy for the landed ground station is supported by the dual frequency (UHF and X-band) telecom design. The risk of failure for the SDST, or other single string X-band components, is assumed acceptable by the project. Two transceivers are carried for redundancy aboard the balloon.

Estimates of the mass and cost of the DTE are not available at the time of this writing.

Summary

An original mission to study the gullies present in Martian crater walls has been presented. The mission uses a balloon to carry a science package from a landing site inside a crater to the region with gullies. The balloon control system will use the wind for motive force and will fly at low altitude. It is envisaged that incremental navigation in multiple hops might be used to reach the gully region, depending on the atmospheric conditions.

The instruments have been selected to provide complementary experiments which will reveal the formation mechanisms of the gullies and the morphology and composition of the debris in their aprons. The science package has a relatively high readiness level (low risk.)

The balloon and the navigation system are technologies with a low readiness level (high risk.) The risk can be substantially reduced by performing simulations of the winds inside craters and using the results in a virtual reality environment to test various navigation methods and balloon control architectures. Thus the risk of the mission could be reduced with a relatively low budget before building and testing any hardware. Once proven in software the control and navigation methods could be tested on Earth to further increase the readiness level.

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