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Mars 2001 Aerobot/Balloon System Overview

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Abstract

In late 1995, a study was initiated at the Jet Propulsion Laboratory (JPL) of a 2001 Mars Aerobot/Balloon System (MABS) Mission Participants included NASA Goddard Space Flight Center, Wallops Flight Facility (WFF), Lockheed Martin Aeronautics (LMA), the French Space Agency (CNES) Toulouse Space Center, NASA Ames Research Center (ARC), and Space Dynamics Laboratory (SDL) plus numerous industrial partners. The purposes of the study were to 1) determine technical feasibility of a long duration 2001 aerobot mission in the Martian atmosphere, 2) formulate a baseline concept, 3) identify pre-project technology requirements, and 4) develop a preliminary cost, schedule and plan. The study scope included definition and identification of mission concept technical issues including science instruments, gondola, balloon system design, entry vehicle and cruise spacecraft design, and launch vehicle performance considerations.

Key constraints on the mission study were a 2001 Mars launch opportunity (although 2003 and 2005 were also examined), a Delta launch vehicle, maximum use of Mars Surveyor Program (MSP) cruise and entry systems, the use of Mars Global Surveyor and MSP orbiter for relay communications capabilities and a 90 day mission duration. Key assumptions of the study included 1) a gondola mass on the order of 10 kg including science instruments, (plus deployable science packages), 2) "constant" density altitude, superpressure balloon design without landing capability, and 3) cruise altitude of 5-8 km above reference level.

The study effort concluded that the MABS mission is feasible based on conservative assumptions on environmental conditions and technical readiness, provided early and significant NASA investment in balloon system technology is initiated.

Background

In the mid-1980s, the French and the Soviets began studying a Martian Aerostat mission for the 1994 Mars opportunity. The French were to supply the balloon system and the Soviets were to provide the gondola and deliver the system to Mars. The system design concept eventually evolved into a 6-micron thick mylar balloon which would be overpressure during the day, descending to the surface during the night (Ref. 1). At night, the balloon would rest on the surface on a guiderope or "anding snake" suspended from the gondola. The mass of the landing snake on the surface relieved negative buoyancy so that the gondola did not touch the ground. The mission was to last about 10 days before gas leakage reduced lift and kept the balloon from ascending during the day.

As early as 1992 the joint program was experiencing the detrimental effects of the collapse of the Soviet Union. The immediate impact was a slip of the launch to at least 1996. This programmatic uncertainty also resulted in funding and related technical difficulties within the French program. By early 1995 it was clear the mission would need to be delayed again, this time to 1998. The French continued a scaled-back development program which had significant successes but also had some nagging balloon deployment failures. The shift of the mission arrival date to 1998 meant that the mission would be arriving in the Northern hemisphere in winter when high surface winds (>30 m/s) were to be expected. The implications of the high winds meant that a balloon which descended to the surface on a landing snake could be destroyed if the drag on the snake became too high. Eventually, due to a combination of programmatic and related technical problems, the program was canceled.

In 1994 another Mars balloon concept called the Mars Aerial Platform (MAP) mission was proposed under the NASA Discovery Program (Ref. 2). The

MAP design consisted of a 12-micron, biaxial nylon 6, supperpressure balloon envelope and a small, 7 kg gondola. The balloon was designed to float at a "constant" density altitude in nominal Martian environmental conditions. A two-balloon mission was proposed which included small surface meteorology packages on the entry vehicle. The MAP mission included a number of innovative features but was criticized for the lack of technology readiness primarily in the balloon envelope design.

Both the Martian Aerostat and the MAP mission concepts have had a significant influence on the MABS design, the primary points of departure being balloon envelope material and design and the assumption of conservative environmental factors.

A significant advance in material design concepts was achieved during the MABS effort. These advances were due primarily to 1) the realization of the difficulty in finding both fracture resistance and toughness in a single-component envelope, 2) the focus of the NASA long-duration stratospheric superpressure balloon program on similar balloon envelope material concepts, and 3) composite material design prototyping and testing carried out in the study. The resulting material concept has twice the strength-to-weight ratio of previous Mars balloon envelope material candidates.

Contributions of Aerobot/Balloons to Mars Exploration

The science experiment potential of a Mars Aerobot/Balloon includes 1) imaging the surface at a scale and resolution relevant to future lander and rover operations, 2) high resolution visible images and IR spectroscopy, 3) collection of data at hundreds of scientifically interesting sites, 4) detection and mapping of subsurface ice and water, 5) *in situ* measurements of atmospheric properties and winds, and 6) deployment of surface packages at interesting sites for exploration.

The need for ultra-high resolution remote sensing which cannot be easily obtained from orbit is driven primarily by the desire for increasing the probability of successful Mars landings, rover operation and sample return. After the Viking landings, engineers considered themselves lucky that both landers survived without damage due to large boulders found near the landing sites. The MSP landers are smaller and thus susceptible to damage or adverse effects of smaller, more numerous rocks. At this time, the landing hazard of these landers has yet to be quantified, however, it is clear that imaging data of the order of 20 cm resolution would be important to the assessment of landing success probability and site selection. In addition, this class of imaging would be important to rover operations planning and rover site selection. At least part of this issue has been resolved by the inclusion of descent imaging capability for future rover missions. Unfortunately, such imaging only provides after the fact information which can be used for post-landing (if successful) traverse operation planning and only then within a kilometer of the landing site. Aerobot data, on the other hand, could provide both medium resolution (2 m/pixel) wide area and ultra-high resolution sampled coverage which can be used to optimize and select future sites for rover operation.

Currently there are about 80 major geologic units identified from Viking data. It is not practical to expect to be able to collect samples from all of these sites and return them to Earth in the near future. An aerobot, with high resolution imaging and spectral instruments, could assist in the process of selecting optimum landing sites to maximize the variety of terrains sampled. In addition, such data enables calibration of global maps and data sets taken from orbital platforms.

Design Philosophy

The MABS design philosophy consisted of several key elements. Mission and "worst case" environmental requirements were identified. Environmental conditions and parameters were researched and analyzed as they relate to balloon system design. Previous Mars balloon proposals and programs made optimistic assumptions on range of environmental parameters expected. For short-duration missions, which fly over a limited amount of Martian terrain, some of this optimism is well placed. However, for missions which are expected to last several months, large parts of the planet are traversed and thus a wide range of environmental conditions are experienced. Here worst case means the worst expected environmental condition during a mission. Worst case does not mean to sum all of the adverse conditions ever seen on a global scale because these conditions are never experienced at the same time at the same place. In addition, in order to develop a system which is robust to changing launch opportunities it is important to consider the seasonal variations in atmospheric pressure in the design so that the basic design can be used for all conceivable arrival conditions.

A very important characteristic of a Mars balloon system design process is the tight design interplay between various elements. To optimize the total system design, all system elements must be considered and the requirements analyzed. As an example, the driving design requirement on the strength of the balloon envelope material may not be the level of supperpressure but instead may be deployment and inflation (D&I) forces depending on D&I method chosen. Another example related to material choice is how sterilization, packing or storage methods can drive envelope design. The balloon is a system with a capital "S" and all the factors influencing its performance must be considered to insure a successful design.

System and subsystem alternatives were identified and the more attractive options were developed and compared in order to select a baseline design. Table 1 illustrates a few of the subsystem design alternatives considered in the study.

Table 1: Subsystem Design Options

Cruise and Entry Systems:
Cruise Stage: MSP-Based, VCP-Based, Adv. Tech.
Entry Vehicle: MSP '98, Pathfinder
Parachutes: MSP '98 Adv. Tech

Balloon Systems:
Envelope Material : Mylar C, Nylon 6, Composites
Scrim Material: Kevlar, Dynema, PBO
Thermo Optical Surface: Transparent, White, & Al
Balloon Geometry: Cylindrical (AR = 3-5), Sphere
Buoyant Gas: Helium, Hydrogen
Deployment & Inflation : Top and Bottom Tanks w/Top Bubble, Bottom Tanks with Bottom Bubble
Reefing : Collar Straps, Sleeve
Envelope Storage: Folded, Wound, Rolled
Payload: 10-20 Kg

Gondola Systems:
System Arch.: Dedicated Prcsr, Shared Computer
Computer : COTS, MCM
Thermal Stability: RHU, Resistive Heaters, Cold Electronics
Structure/Thermal : Mars Rover - Based, New
Communications: New Millennium - Based UHF, MSP '98, Martian Aerostat, New UHF
Sun Sensing: APS Camera, Digital Sun Sensor
Altitude Sensing: Radar, Laser
Velocity Sensing: Imaging (Day), VLBI, Doppler Radar, LIDAR

After selecting a reference system design which meet the mission and science requirements, the advanced technology development needs were established. An overall program was constructed which factored in both the pre-project activities, such as balloon technology development and demonstrations, and the project implementation tasks such as detailed design, fabrication system integration and testing. Two cost estimates were developed. The first estimated was performed by the study team members which was called a "grass roots" estimate. The second was done by the JPL Independent Cost Models Estimation (ICME) based on historical cost performance of similar systems with new ways of doing business factored into the result.

Environmental Models

The environment has a first-order impact on balloon design and flight dynamics. Obvious examples of the effect of environment are (a) the global atmospheric circulation which dictates the balloon ground track and (b) the atmospheric density which determines the required balloon size. Less obvious is atmospheric radiation (both solar and infrared) which helps determine balloon envelope strength requirements. Because there is considerable temporal and spatial variability in the Martian environment, an essential aspect of the feasibility study was to determine the range of environmental parameters and the worst-case conditions for balloon design. Figure 1 describes the basic behavior of a superpressure balloon at Mars given different atmospheric temperatures and pressures. Later a similar chart will be shown which relates specific environmental parameters and conditions to balloon behavior.

Several environmental factors were evaluated for their impact on balloon design: dust, surface thermal inertia, surface albedo, topography, atmospheric surface pressure, and the time of year of the flight. Each of these factors and their interactions are discussed below.

Dust

Mars is famous for its dust storms which vary in extent from localized events to planet-encircling storms. High levels of atmospheric dust increase the opacity of the atmosphere in both solar and thermal radiation wavelengths. Dust moderates the impact of environmental radiation by increasing the optical depth of the atmosphere. From the point of view of balloon design, high dust optical depth is favorable because it reduces the magnitude of the diurnal variation in atmospheric radiation. With moderated radiation, the temperature of the balloon gas undergoes less diurnal variation thereby reducing the balloon material strength requirements. The highest balloon skin strength requirements come from an optically clear atmosphere with no dust. Thus, the worst case for balloon design is an optical depth of zero. The dust storms at Mars are unpredictable but follow a general, seasonal pattern, and near-zero optical depths are possible.

Thermal inertia

The surface of Mars undergoes large diurnal temperature swings which are governed, in part, by the thermal inertia of the surface at a particular location. In the absence of atmospheric participation in the thermal radiation (optical depth of zero), the surface temperature determines the magnitude of the upwelling IR radiation in the atmosphere. Locations with high thermal inertia undergo less-severe diurnal surface temperature swings and provide less diurnal variation in the upwelling thermal radiation. High thermal inertia is favorable for balloon design because it decreases the diurnal temperature variation of the balloon gas.

The SI units for thermal inertia are J m^{-2} s$^{-1/2}$ K^{-1}.

Albedo

The albedo of the Martian surface affects the amount of daytime solar radiation that is reflected onto the balloon from below. Locations with high albedo provide additional daytime solar loading on the balloon and magnify the diurnal temperature variation for the balloon gas. Thus, low albedo is favorable for the balloon design.

Given the typical ranges of albedo and thermal inertia that exist at Mars, the thermal inertia of the surface is usually the most significant of the two parameters for driving the balloon design. Unfortunately, high albedo and low thermal inertia tend to correlate at Mars.

Ratio of albedo to thermal inertia, K

A parameter K was defined to be the ratio of albedo to thermal inertia at a given location. Because low albedo and high thermal inertia are both favorable for balloon design, a low value of K is desirable. Although K is a simple figure of merit, locations with high values of K should be closely evaluated for their potential detrimental impact on balloon performance.

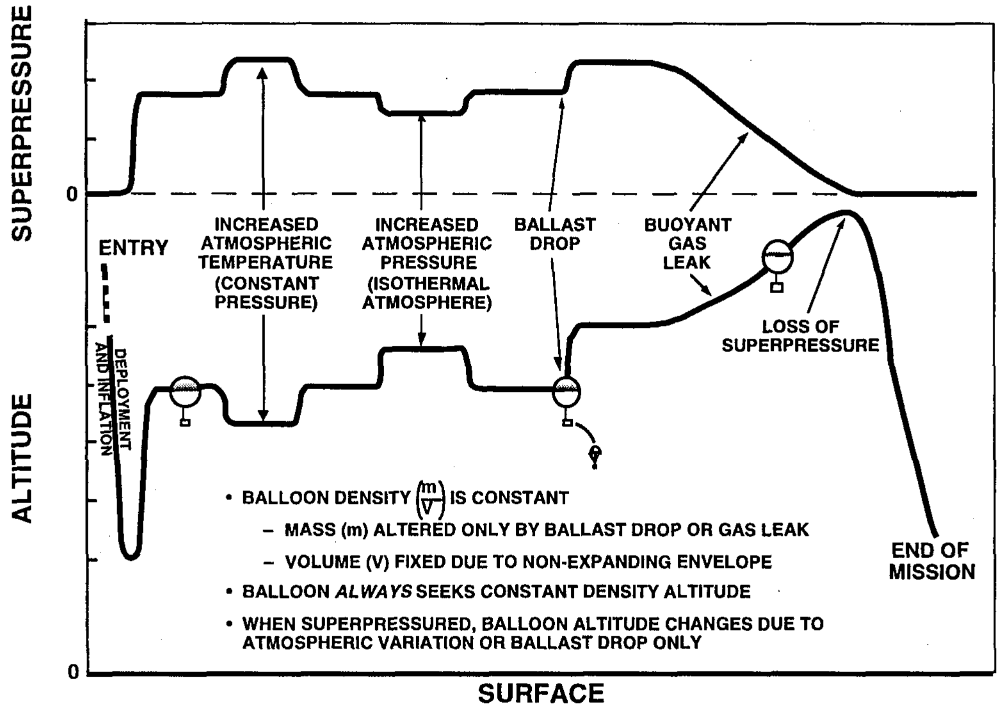

Figure 1. Superpressure Balloon Behavior

Topography

Traditionally, the 6.1 mbar pressure surface derived from radio occultation data is defined to be the 0 km point on the planet. The deepest plains are 5 km below the reference altitude (Hellas Planitia), and the highest mountains are as much as 25 km above the 0 km plane (Olympus Mons). Thus, a 30 km topographic variation exists at Mars.

Topography is important for balloon design for three reasons. First, very large balloons are required to fly over the highest mountains. Second, the thin Martian atmosphere makes entry difficult. Atmospheric entry at a low location is desired.

Third, balloons flying at reasonable altitudes (say, 6 km) may fly above high plateaus (at, say, 5 km) and be very close to the surface of the planet. The balloon will see the full diurnal variation of the surface temperature because the thin layer of atmosphere between the surface and the balloon does little to attenuate the thermal radiative environment. A problem may occur when flying over areas of high topography and low thermal inertia, such as Alba Patera (5 km, 40 deg N, 110 deg. W). The close proximity to the surface accentuates the diurnal variations in balloon gas temperature.

Solar Flux

The eccentricity of the Martian orbit means that the solar energy received by the planet is more intense during the southern hemisphere spring and summer. Thus, the southern summer provides the most severe diurnal radiation variations, a first-order effect for balloon design. A secondary effect of the variation of solar flux is atmospheric surface pressure.

Surface Pressure

During the southern hemisphere summer ($270° \leq L_s < 360°$), Mars is closer to the sun than during the northern hemisphere summer ($90° \leq L_s < 180°$). The higher solar heat flux associated with the shorter Sun-Mars range during southern hemisphere summer results in additional sublimation of the southern polar ice cap and more gas in the atmosphere. Thus, the planet-wide surface pressure is higher during southern summer than northern summer.

The seasonal atmospheric pressure variation affects balloon and mission design. Higher atmospheric pressure leads to higher float altitudes, all other factors being equal. The result can be up to 2 km of seasonal float altitude variation for a given superpressure balloon due to seasonal atmospheric pressure variations alone. A long duration mission must consider the effect of variable surface pressure on float altitude. In terms of balloon design for a long-duration mission, low surface pressure seasons require the largest balloons and represent the worst case for balloon design.

There are both seasonal and diurnal time scales to atmospheric pressure variation. On diurnal time scales, Mars' pressure profile varies only slightly but significantly, less than ±10% per day. The diurnal pressure variations result from the passage of weather systems.

Atmospheric Models

There are two atmospheric models that were used to assist the balloon and mission design efforts during the MABS study, a Boundary Layer Model (BLM), and a General Circulation Model (GCM). Both models and their uses are described in the sections that follow.

Mars Boundary Layer Model (BLM). The Mars BLM estimates environmental conditions at one latitude, for one Martian day on a variable, closely-spaced altitude grid (5 m/division near the surface, 250 m/division at 10 km). Inputs and outputs are summarized in Table 2. The BLM outputs are given on time grid that has 24 points per Martian day.

Table 2 BLM Inputs and Outputs

Inputs	Outputs (24/day)
Optical Depth, τ	T, P
Solar Longitude, L_s	Solar Direct Radiation
Surface Albedo	Solar Diffuse Radiation
Surface TI	IR Diffuse Radiation
Surface Pressure, P_0	Solar Zenith Angle
Solar Flux	

As stated above, the MABS effort was a feasibility assessment for a Mars balloon mission. Worst-case environmental conditions were selected for the design atmospheres. The BLM affords the opportunity to evaluate several sets of input parameters, and, in the process, to determine the set of atmospheric parameters that provides the most difficult environment for balloon flight.

Selection of BLM Inputs. Selection of the input parameters to the BLM was a major aspect of the environmental work during this study. We were guided by experience with balloon design, previous studies, and engineering judgment. Because the balloon was expected to have planetwide coverage, we examined all areas of the planet. Because our design goal was a 90-day mission, a large portion of the Martian year was considered, starting with the earliest possible arrival date and ending with the 90 days beyond the latest possible arrival date.

We generated design environments for each region of the planet: Northern Design Case (NDC), Equatorial Design Case (EDC), Southern Design Case (SDC), and Global Design Case (GDC). The NDC, EDC, and SDC were taken to be more specific in longitude, topography, and time of year than the GDC. Table 3 summarizes some of the parameters for each design case. The latitude range corresponds to the region of the planet, the solar longitude L_s corresponds to the expected arrival and flight windows, and the topography indicates the range of topography to be evaluated.

For each design case, the lowest thermal inertia, highest albedo, and highest K locations were identified. From these parameters, BLM inputs were selected that reflect the worst-case conditions for the region. Table 4 shows the details of the thermal inertia and albedo evaluations for the NDC environment. The thermal inertia and albedo chosen for the BLM inputs are somewhat lower and higher, respectively, than the worst cases for the region to account for measurement uncertainties.

Tables 5, 6, and 7 show similar data for the EDC, SDC, and GDC respectively.

For each BLM design case, the selected altitudes were converted into surface pressures. Previous work done for the MAP proposal provided charts of balloon diurnal superpressure variation as a function of L_s at given latitude using latitude-averaged albedo and thermal inertia (Ref. 2). For this study, we selected the worst-case L_s for each design case based on the MAP charts. The corresponding lowest surface pressure P_0 was selected by taking the surface pressure corresponding to the worst-case L_s and reducing it by 10 %, the maximum diurnal variation expected for surface pressure. Table 8 shows the results of this analysis for each of the design cases. Note that the suffix "h" on the design cases refers to a plateau that would be unfavorable for balloon design as discussed above.

Table 9 shows the BLM inputs selected for the balloon design activity. These eight atmospheres were deemed the worst case environments for balloon flight.

<u>Mars General Circulation Model (GCM).</u> The Mars General Circulation Model (Mars GCM) grew from an Earth weather model in the late 1960s. It simulates the dynamics of the Martian atmosphere on a global scale, much like weather models for the Earth. Atmospheric parameters available from the GCM include winds, solar radiation (direct, upward diffuse, and downward diffuse), infrared radiation (upward and downward), temperature, pressure, and topography. Initially, the Mars GCM modeled only two vertical layers in the atmosphere. As the cost of computational power decreased, improved vertical and horizontal resolution was added to the GCM. Topographic effects have been included. The Mars GCM now models the effect of dust on radiation, dust-wind interactions, and the seasonal sublimation patterns of the polar ice caps (Ref. 3).

The GCM was used to develop balloon flight trajectories based on winds that are representative of the conditions expected upon arrival (Ref. 4) Forecasting the weather at Earth is a difficult endeavor, and predicting the environmental conditions at Mars is a daunting task. The GCM provides representative weather that could be expected at Mars at the arrival times under consideration. Thus, the GCM is appropriate for development of mission strategies and profiles.

The Mars GCM requires several inputs including (a) the initial solar longitude L_s, (b) the initial mass of the atmosphere, (c) the total atmospheric dust load, (d) the global distribution of surface thermal inertia, (e) the global distribution of planetary albedo, and (f) the assumed ratio of the atmospheric optical depth in the IR wavelengths to the atmospheric optical depth in the solar wavelengths, τ_{IR}/τ_{sol}. Viking data guided the selection of inputs for the GCM runs employed in the MGA simulations developed for this study. For example, the total mass of the atmosphere was selected such that the predicted seasonal surface pressure variations match the Viking measurements (Ref. 2).

<u>GCM Output.</u> The GCM output used for predicting MGA trajectories is arranged in a planetary grid upon which atmospheric parameters are reported. The following parameters are given at each grid point:

- atmospheric temperature,
- surface pressure,
- the solar zenith angle,
- direct solar flux,
- downward diffuse solar flux,
- upward diffuse solar flux,
- downward IR flux,
- upward IR flux,
- the east-west wind (zonal) component, and
- the north-south (meridonal) wind component

Table 3 BLM Design case parameters.

	Latitude	L_s	Topography
NDC	30° < N Lat < 60°	225° < L_s < 360°	z < 5 km
EDC	-30° < N Lat < 30°	225° < L_s < 360°	z < 5 km
SDC	-60° < N Lat < -30°	225° < L_s < 360°	z < 5 km
GDC	-60° < N Lat < 60°	0° < L_s < 360°	z < 8 km

Table 4. Northern Design Case (NDC)

	Location W Longitude	N Latitude	TI [SI units]	albedo [-]	K = a/TI [1000/SI]	Topo [km]
Lowest TI	113	41	92	0.298	3.23	4.5
Highest albedo	109	43	117	0.315	2.69	4.5
Highest K	115	39	92	0.303	3.28	5.0
BLM Inputs			80	0.32		0.0, 5.0

Thermal Inertia and Albedo BLM inputs: 30° < N Lat < 60°, Alba Patera.

Table 5. Equatorial Design Case (EDC)

	Location W Longitude	N Latitude	TI [SI units]	albedo [-]	K = a/TI [1000/SI]	Topo [km]
Lowest TI	99	-3	84	0.288	3.44	7.0
Highest albedo	99	3	109	0.355	3.26	6.5
Highest K	97	1	92	0.345	3.75	6.5
BLM Inputs			70	0.36		0.0, 5.0

Thermal Inertia and Albedo BLM inputs: -30° < N Lat < 30°, Topography < 8 km, Just east of Olympus, Arsia, Pavonis, and Ascratus Mons

Table 6. Southern Design Case (SDC)

	Location W Longitude	N Latitude	TI [SI units]	albedo [-]	K = a/TI [1000/SI]	Topo [km]
Lowest TI	93 221	-39 -45	176 176	0.213 0.268	1.21 1.52	5.0 4.6
Highest albedo	295	-59	234	0.333	1.42	-0.5
Highest K	221	-45	176	0.267	1.53	4.6
BLM Inputs			160	0.28		0.0, 5.0

Thermal Inertia and Albedo BLM inputs., - 60° < N Lat < -30°, Cimmeria

Table 7. Global Design Case (GDC)

	Location W Longitude	N Latitude	TI [SI units]	albedo [-]	K = a/TI [1000/SI]	Topo [km]
Lowest TI	99	-3	84	0.288	3.44	7.0
Highest albedo	99	3	109	0.355	3.26	6.5
Highest K	97	1	92	0.345	3.75	6.5
BLM Inputs			70	0.36		0.0, 8.0

Thermal Inertia and Albedo BLM inputs:, -60° < N Lat < 60°, Topography < 8 km, Cimmeria - Just east of Olympus, Arsia, Pavonis, and Ascratus Mons

Table 8. BLM input surface pressures.

	Worst-case L_s from MAP chart	Corresponding P_0 [mbar]	BLM P_0 [mbar]	Corresponding Solar Flux [W/m^2]
NDC (0 km) NDCh (5 km)	225°	6.75	6.0 3.8	718
EDC (0 km) EDCh (5 km)	240°	7.25	6.5 4.2	728
SDC (0 km) SDCh (5 km)	275°	7.40	6.7 4.3	718
GDC (0 km) GDCh (8 km)	240°	7.25	6.5 3.2	728

Table 9. BLM Inputs.

	τ [-]	N Latitude [°]	TI [SI units]	albedo [-]	L_s [°]	P_0 [mbar]	Solar Constant [W/m^2]
NDC (0 km) NDCh (5 km)	0.0	30°	80	0.32	225°	6.0 3.8	718
EDC (0 km) EDCh (5 km)	0.0	-20°	70	0.36	240°	6.5 4.2	728
SDC (0 km) SDCh (5 km)	0.0	-30°	160	0.28	275°	6.7 4.3	718
GDC (0 km) GDCh (8 km)	0.0	-20°	70	0.36	240°	6.5 3.2	728

The pressure at any altitude z can be calculated by

$$P(z) = P_{surf} e^{-(z-z_{surf})/H}$$

where H is the atmospheric scale height, taken to be 11.18 km, and z_{surf} is the surface altitude.

The GCM spatial grid contains 7 vertical divisions (up to about 10 km above the planet's surface), 40 longitude divisions, and 25 latitude divisions. The parameter grid is updated sixteen times per Martian day.

The Mars GCM run that was used for the trajectory predictions for MABS begins at L_s = 220° and has $\tau_{IR} = \tau_{sol}$.

Figure 2 illustrates the relationship between these various environmental factors and conditions and the behavior of a superpressure balloon at Mars.

Balloon Systems

The Balloon System is defined as the Balloon Flight System (BFS) and the Deployment and Inflation System (D&IS). The BFS consists of the Balloon and the Gondola (which will be addressed separately in this paper). The balloon included the envelope, seams, end fittings, load core, inflation tube, diffusers, payload tether/shock attenuator, and separation hardware. The D&IS included the balloon container, deployment hardware/sequencer, tanks, gas and control hardware.

As stated previously, the approach was to heavily leverage ongoing aerobot/balloon activities, take advantage of previous development studies and testing, and to design for the worst case environmental conditions. It was identified very early in the study that two technologies--the envelope material and the D&I of the balloon vehicle, would be critical to the success of a Mars Aerobot/Balloon mission. Furthermore, both of these systems had to be integrated as a system and a systems design approach was imperative. The design of the balloon and the design of the D&IS, heavily influenced the other. Neither could be designed without assessing the impact on the other.

A balloon design tool (Ref. 6) was developed which resulted in iterative equilibrium solutions. It allowed for solutions for cylindrical and spherical balloon shapes based on meeting steady state day/night extremes. The principle unknown was required material strength. Inputs included material areal density, radiative properties, atmospheric and thermal environment, performance requirements, and design constraints. Outputs consisted of system masses, physical properties, and balloon temperatures.

Balloon Flight System

The performance of superpressure (SP) balloons have been well documented. Balloons of the size required for a Mars mission have been successfully flown in excess of 90 days. However, the material used in these balloons, primarily mylar, had very high areal densities, problems with pin-holing and fracture, and were not designed for atmospheric entry deployment and inflation. Experience with scaling up of these balloons to larger designs highlighted many inherent material and fabrication problems. Application of other materials such as Nylon-6, while alleviating some of the problems but not all, had very limited successful demonstration. In addition, neither of the two materials could meet the design strength requirements, limitations on areal density and still be successfully deployed and inflated. It was decided to take advantage of some of the recent composite film work that was currently being pursued by NASA.

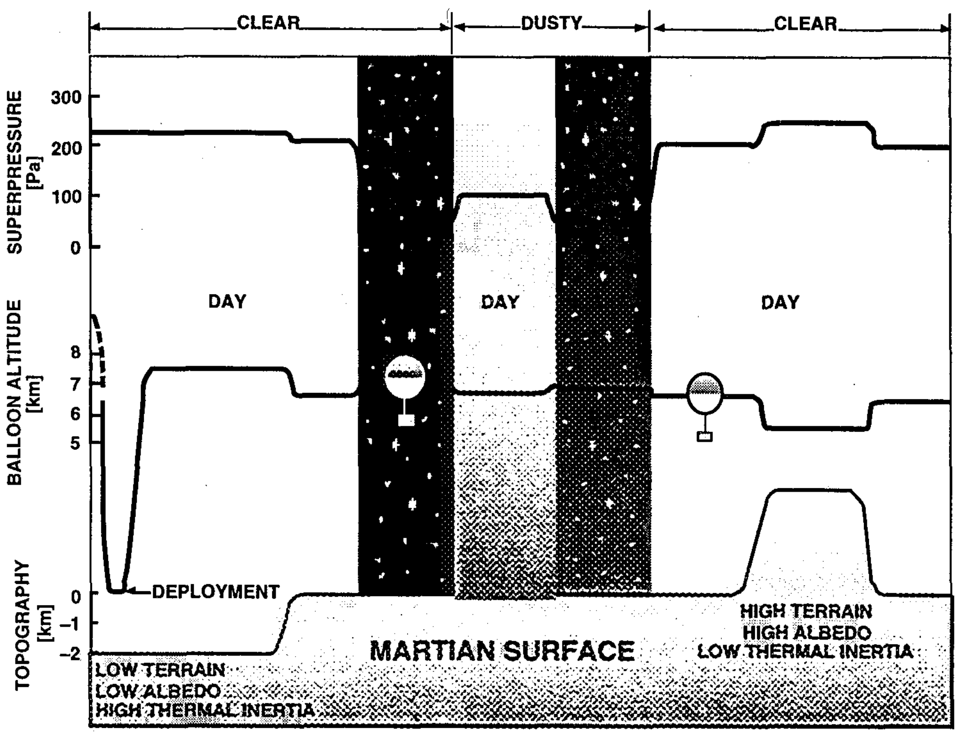

Figure 2. Mars superpressure balloon response to its environment

Structure. There are many structural design considerations which must be accounted for in the design of a balloon structure. The shape, whether spherical, cylindrical or "natural shape" each have advantages and disadvantages. Factors included: 1) macro and localized stress distributions such as load introduction, 2) the total mass of components and their distribution, 3) seam design for strength, gas integrity, and geometry, 4) accessories such as fittings, reinforcements, inflation, etc., 5) fabrication such as tolerances, reliability, packaging, sterilization and 6) load introduction such as payload attachment and shock attenuation during the D&I process. While the spherical shape is the best from a mass/unit area and macro stress state, it presents increased difficulties during the deployment and inflation process. The cylindrical balloon, offers advantages for ease of reefing, load introduction during the D&I, and improved fabricationsuch as ease of maintaining tolerances. However, it results in a larger and heavier balloon and stability problems during inflation of the balloon during descent from altitude. A spherical design was chosen because of mass limitations and stability concerns during the deployment and inflation process which will be described later.

Envelope Material. The identification of an adequate material is probably the most critical factor in the design of a balloon. This has been demonstrated many times over the years in ballooning. One cannot consider only a material's strength or optical properties, although both are very important parameters. Often these can be negated by poor performance in other parameters such as lack of elongation or very poor or no fracture toughness, thereby very intolerant of defects which all balloons have. Research into monolayered films, whether in the form of blends or homopolymers such as current balloon films of polyethylene (PE), mylar or nylon-6, identified the modification of one parameter to improve its performance comes at the expense of other parameters. Often the gain in a desirable parameter with a material selection is offset by a loss in performance in another parameter.

Many different types of materials were considered for the Mars application. Leveraging work currently being pursued by the NASA Balloon Program, it was decided to pursue the development of a "composite" "film" or material. The approach was to take the best properties of different materials and combine them in a manner which would offer the desired overall set of mechanical properties as well as alleviating the individual component deficiencies. Several material combinations were investigated and a prototype material was made and tested. The material (Ref. 6) consisted of a 3.5 micron Mylar base film, adhesively bonded to 55 denier Kevlar scrim in an orthogonal pattern, which was then laminated to 6 micron SF-372® PE. The Kevlar scrim reinforcement provided the requisite strength with very little weight penalty. The adhesive layers provided the bonding between the different components as well as adding pinholing resistance. The mylar provided the substrate stiffness while the SF-372® provided pinholing resistance and fracture toughness.

The resulting material was successfully tested and had the following properties:

Areal Density : 19.66 g/m^2
Tear Toughness: 12 N @ +23°C to 43 N @ -140°C
Strength : ≥ 2500 N/m from +23°C to -140°C
Seam Strength : ≥ 2500 N/m from +23°C to -140°C

The material was subjected to a range of radiation dose levels to determine if the material would survive the requisite sterilization procedures before going to Mars. It was determined through testing that no degradation of strength occurred for required radiation levels of 2 Mrad. Limited testing also revealed that there were no observed component or adhesive delaminations or embrittlement at -198°C.

Although the prototype material met the requirements established for a Mars material, much work and testing would still be required to optimize and develop it for full scale production. However, it did successfully demonstrate the feasibility that an adequate Mars material could be made with sufficient advanced development.

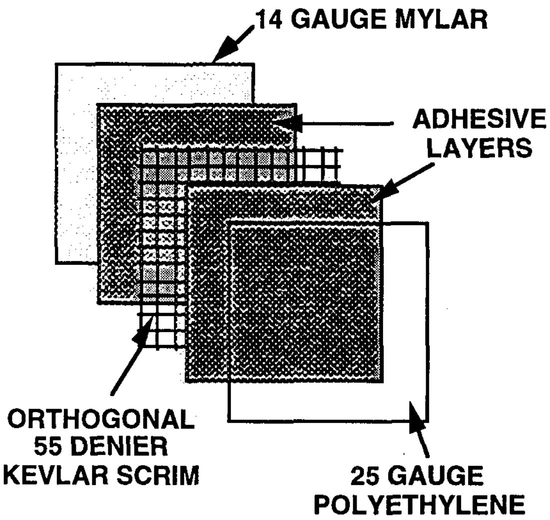

Figure 3. Schematic representation of candidate composite material

Flight Performance

Several factors must be considered if a balloon is to survive for an extended mission duration. These factors include the desired payload float altitude, altitude stability, thermal optical properties, gas selection, CO_2 condensation, ultra-violet degradation, dust collection, diffusion and effusion, and of course the overall flight environment. Various performance and design studies were performed using the balloon design tool. In addition, there was a review of previous SP flight data. It was determined from the SP flight data that we could achieve a 90 day mission based on projected diffusion and effusion gas losses. It was also determined that the balloon temperatures based on the extreme environment, came dangerously close to the atmospheric CO_2 condensation point thereby necessitating an aluminized top hemisphere of the balloon to prevent condensation from taking place during the cold Martian nights.

Deployment/Inflation System

Equally challenging as the material design and in fact driving it was the method of deploying and inflating the balloon during descent through the Martian atmosphere. The deployment and inflation systems are extremely tied to each other as well as the balloon structure/shape, the balloon envelope material, and spacecraft volume and mass. They are a system and one cannot be modified without it affecting all of the other systems. As a result, the spreadsheet design tool was used extensively to determine the interaction between the various systems and to determine mass allocations and distributions.

Deployment. Deployment considerations included: 1) packaging of the balloon such as density, folding method, etc., 2) method of deployment such as gravity or mechanical feed, and location within the overall flight train, 3) container design such as toroidal, cylinder, etc., 4) reefing method if required, 5) sequencing of the events, and 6) the overall loading on the balloon envelope and gondola from the deployment process and parachute opening shock.

A survey was performed of air launched balloon systems to establish baselines for a possible design. Information was compiled on the various systems which included the successful Soviet/French VEGA and the U.S. Off-Board Jammer System (OBJS) as well as others. Of particular help was the detailed amount of work , data and assistance provided by CNES/Toulouse concerning their Mars '96 development efforts. Although the Mars '96 Martian Aerostat system encountered difficulties during the two high altitude drop-and-deploy tests, the information and lessons learned identified key stability problems. A stability model was developed as part of this study effort for use in determining balloon geometry and payload and entry vehicle mass distributions during the deployment process. As a result of stability concerns and mass distributions, it was decided that the balloon should be suspended from the parachute and between the inflation hardware, gondola and heat shield.

Inflation. The inflation system design is influenced by: 1) the location of the system whether at the top or base of the balloon, 2) gas selection, 3) inflation rates, 4) mass of total system and distribution thereof, 5) stability and inflation/balloon interaction, 6) temperatures, 7) tankage and 8) sequencing. Of key concern was whether inflation could be completed before impacting the surface. The time allowed for deployment and inflation was determined by the time it takes for the system to slow to an acceptable dynamic pressure to insure a stable system plus the time it takes to inject the gas into the balloon. Although a top down inflation similar to the VEGA and Mars '96 designs was highly desired, stability analyses coupled with other system masses and physical geometry led to the placement of the inflation hardware at the base of the balloon, similar to the OBJS. The helium inflation gas was injected into the base of the balloon through a sonic diffuser. The gas proceeded up through the center of the balloon through a central load carrying inflation tube until where the gas exited into the top of the balloon.

Baseline Design

The baseline Mars balloon system is described in figure 4. below.

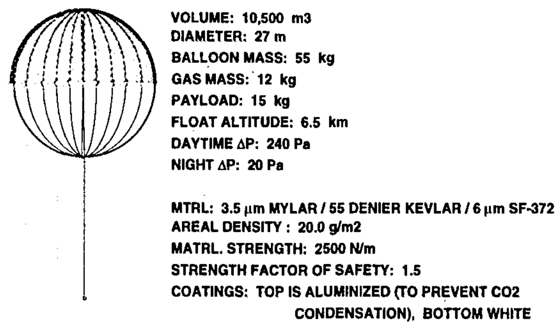

Figure 4. Baseline balloon design

Further details of the design studies and results are contained in (Ref. 6)

Gondola and Science Instruments

Gondola Design Objectives

Earlier Mars balloon concepts did not incorporate any autonomy for on-board decision making (Ref. 1,2). Even in the more advanced French concept, all science data was timer driven with localization of the balloon only possible after data acquisition using earth-based analysis of images, crude sun-sensor data, and Doppler analysis of orbiter relay of balloon communications. Global position accuracy was no better than about 30 km and available at this resolution only when Sun and Doppler measurements were simultaneously available. This resulted in a low "yield" of science data since data acquisition was not tied to specific science targets. When combined with the inherent limitations on the bandwidth of the communication link from the Mars balloon to Earth, the overall science return was severely compromised. In this study, the goal is to incorporate the technology on-board the balloon for high-precision knowledge of the balloon position and orientation. These data are used for science sequencing and balloon task sequencing on-board which promise to dramatically improve the overall science quality and data return from a Mars aerobot mission.

The specific study objective was to develop a balloon gondola concept capable of maximizing the science return from a 90-day balloon aerobot mission to Mars. Concepts and options relating to Mars Science Instruments, Mission Sequencing Concepts, Planet-Wide Position Determination, Earth Communication, Power Generation, Storage and Management, Integrated Structure and

Thermal Control, and Ballast/Micro-package Deployment, were all investigated as part of the effort. The emphasis was on identifying a very conservative point design that would serve as a starting point for detailed study and design iterations in the next phase of study. While an actual mission would be driven by a combination of cost and mass constraints, the initial effort was to be towards a minimum mass design. In the process, key technology development items were identified and the major trade issues requiring further investigation in later studies were specified. Also, a preliminary costing of an implementation phase was performed.

Gondola Design Approach

Given the time available for the study, it was decided to extensively leverage earlier gondola study and design and development efforts from the CNES Martian Aerostat program and the Mars Aerial Platform (MAP) Discovery proposal. The MFEX/Sojourner rover design experience on mechanical/thermal systems as well as costing data were also used in the study.

In order to minimize the mass of the system, it was decided to take an integrated approach for developing the science instruments and the gondola. The implication of this was to consolidate instrument data processing within the central data/computer system of the gondola with no separate CPU for each science instrument. Wherever possible the science instruments would be used to support on-board engineering functions such as navigation by means of ground images obtained by a science camera. Thermal control and mechanical structure would be integrated and power regulation and management would be consolidated.

It was also decided to adopt a reliability approach to gondola design involving the selection of high-reliability components for mission critical functions, augmented with higher-risk/high-payoff components for non-critical functions. Extensive testing would accommodate the incorporation of these additional elements.

Gondola Design Assumptions

With regard to gondola communications, it was assumed that relay communications would be possible by using either the MGS 96 or MSP 98 Orbiter communication links, with full availability of both orbiters during all communication opportunities to permit maximum data return. Image data would be compressed 10-to-1 to allow the return to accommodate the available communications bandwidth.

With regard to energy and power assumptions, the design was targeted for a reasonable worst case solar power/energy condition corresponding to a northern winter mission. Night-time science operations were minimized to conserve energy, and all energy calculations were made using an 8 hour day, followed by a 16 hour night. A moderately high optical depth of 1.0 was chosen for the float altitude corresponding to an optical depth of 1.7 at ground level. If the actual optical depth encountered was extremely high (i.e. > 2) then mission activities would be descoped by performing less imaging and thermal emission spectroscopy to stay within reduced power budgets.

It was also assumed that Radioisotope Heating Units (RHU's) would be acceptable for meeting the thermal design needs. This assumption allowed the use of lumped thermal models in analyzing the gondola. A more detailed thermal analysis with careful configuration of thermally sensitive items and appropriate thermal inertias and sources could lead to a non-RHU thermal solution. However, this would have to be undertaken in the next phase of study.

Mission Requirements on Gondola

The gondola was required to carry a science payload with a mass of 3 kg, peak power of 3 W, and a volume of 3 liters. The peak data rate from the science instruments would be 500 kbits/s, with a maximum data storage requirement of 500 Mbits.

Communication capability was required for transmitting balloon engineering and science data to MGS '96, MSP '98 and MSP '01 spacecraft. It was a requirement that the gondola accept commands from both the MSP '98 and the MSP '01 spacecraft. The full range of balloon-centerd orbiter azimuth and elevation angles was to be used during any given pass. Storage of all engineering measurements start at entry to insure recording of deployment and inflation data which are later returned to earth.

Navigation requirements were distinguished between the accuracies that were to be achieved on-board the vehicle and those that needed to be achieved on the Earth after data return and analysis. On-board knowledge requirements for Altitude, Latitude and Longitude were respectively 1 m, 1 km and 5 km. Post-flight accuracies were for Altitude, Latitude and Longitude were respectively 1 m, 100 m and 1 km.

In addition to the sensor derived estimates of the aerobot position it was also desired to be able to predict the position of the aerobot into the future. The accuracy of these predictions would be dependent on the vertical balloon performance model and the planetary Global Circulation Models. A 1-day prediction accuracy requirement for Altitude, Latitude and Longitude was respectively 100 m, 10 km and 100 km. Accuracy for a week prediction was desired to be 200 m, 200 km and 500 km and a 30-day accuracy of 500 m, 500 km and 2000 km respectively in Altitude, Latitude and Longitude.

In addition a number of additional internal/derived requirements were also developed:

- Internal temperature ranges from -40°C to +40°C
- Tilt measurement better than +/- 5 minutes of arc.
- Altitude measurements better than +/- 1%.
- Sun Elevation/Azimuth measurements better than +/- 30 minutes of arc.
- Data/Computer system reset times less than 60 s.
- Data/Computer system sleep-mode wake-up time less than 3 s
- On-board clock accuracy better than 20 s.
- Short term stability of oscillator for one-way Doppler of 1^{-10}.
- Ballast/Probe drop activation time less than 60 s.

Figure 5 is a perspective conceptual view of the Mars Aerobot gondola. Figure 6 is a functional block diagram for the Mars Aerobot gondola.

Gondola Science Imaging

As science imaging of the Martian terrain is one of the most important objectives of a Mars aerobot system, some of the issues relating to data bandwidth and image quality are discussed.

The typical maximum data return is 480 Mbit for a mission at 40 deg latitude. Assuming that 90% of this data is given over to science images, indicates a total of 430 Mbits of science image data return. Compression of each 1000 x 1000 8 bit image by a factor of 10 gives 0.8 Mbits/image for a total return of 540 images/sol. The balloon's ground-track motion during an 8 hour period of day-light at an average speed of 60 m/s is 1728 km, and for a

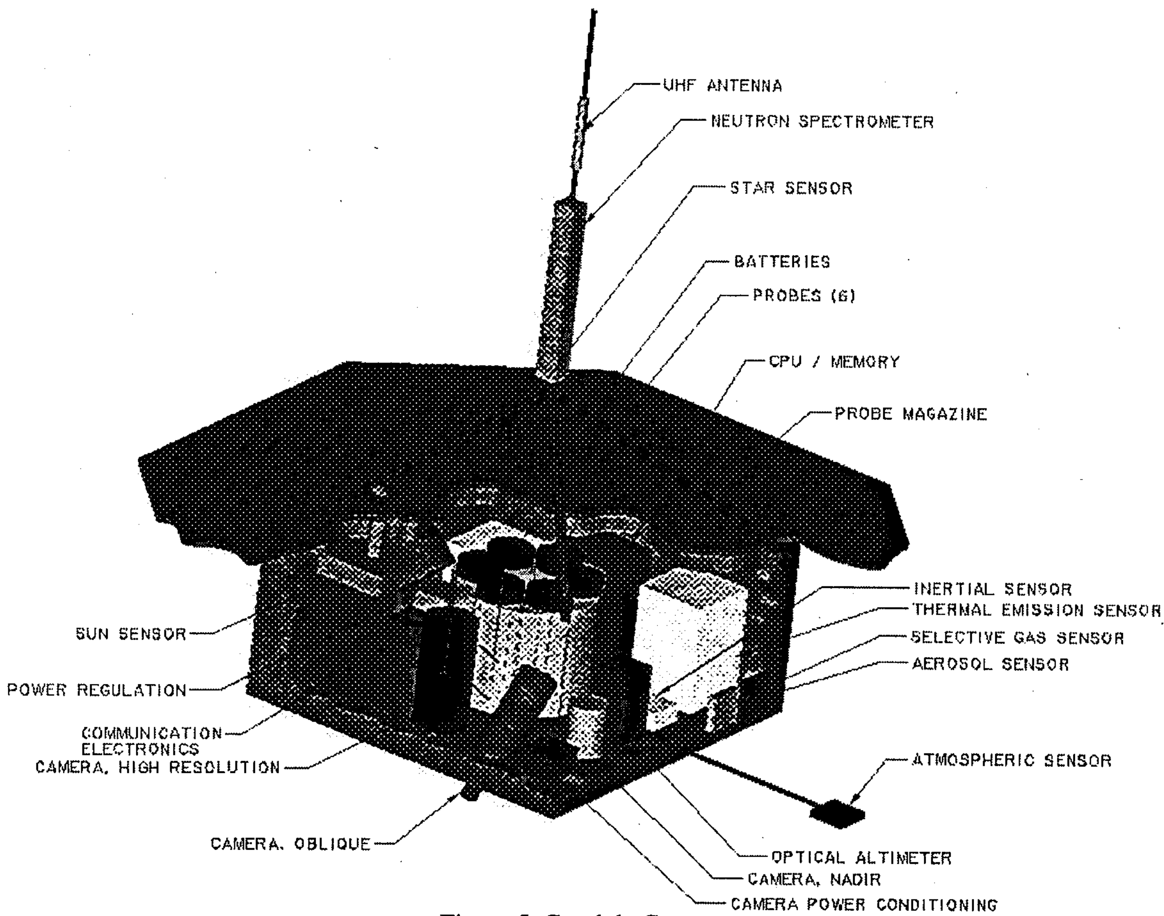

Figure 5. Gondola Concept

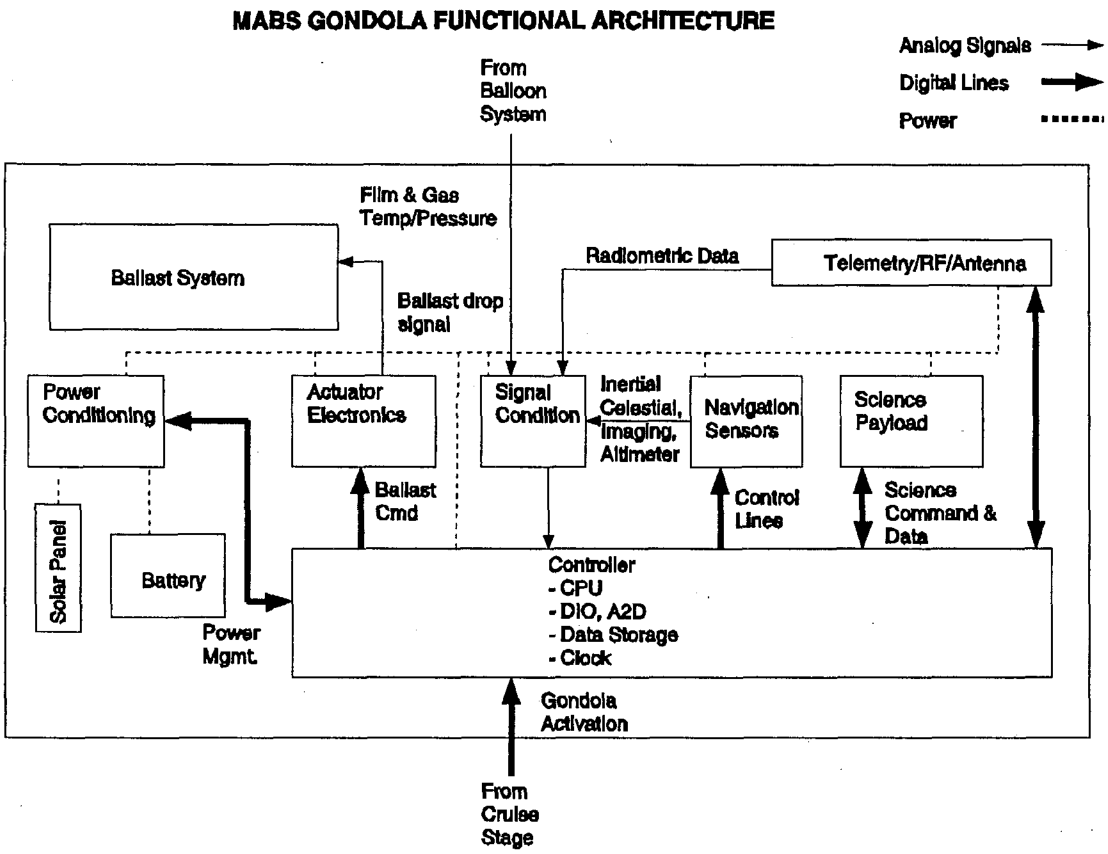

Figure 6. Gondola Functional Block Diagram

wind-speed of 20 m/s the ground-track motion is 576 km. Thus depending on the wind-speed the image return on average could range from approximately 1 image per kilometer of travel at low wind speed to a value of 1 image for every 3 km of travel at higher speeds. While these images could be uniformly spaced along the ground track, it is more meaningful to concentrate these images at specific science targets. It is also important that the images that are taken at high-resolution be also accompanied by a context image that allows the high-resolution image to be correctly interpreted.

There are several issues that impact the definition of an appropriate imaging strategy. The balloon at a float altitude of 6 km above the terrain will be able to obtain nadir pointed contextual (or framing) images with a footprint of 10 x 10 km at a resolution of 10 m/pixel, and nadir pointed high-resolution images with a footprint of 200 x 200 m footprint at a resolution of 0.2 m/pixel. Even a single high-resolution image requires a contextual framing image to be useful for subsequent localization of the high resolution data.

The rotational dynamics and ground track motion of the balloon platform requires that high resolution imaging employ one or more of the following motion blur compensation methods: fast exposures, motion stabilizing optical path elements, or careful timing of camera exposure/read-out. Even then, the yield of blur-free images may drop because of gusts, dim ambient lighting, or constraints on exposure due to filter wheel use.

Let d be the imaging distance, r be the resolution at the imaging distance, v be the balloon translation velocity, T_{roll} be the period of the balloon's roll motion about its vertical axis, T_{pend} be the pendulum period of the balloons swing motion, Ω_{roll} be the maximum roll angular velocity, Ω_{pend} be the maximum pendulum angular velocity, and θ be the maximum pendulum angle. Typical values derived from Mars Balloon/Atmospheric models and French/Wallops experiences with high-altitude balloon experiences indicate values of d = 6000 m; r = 0.2 m; v = 60 m/s; T_{roll} = 1200 s; T_{pend} = 30 s; θ = 0.25 deg; Ω_{roll} = 1.5 deg/sec; Ω_{pend} = 0.05 deg/sec. This data indicates that the effect of the pendulum motions is to contribute to an apparent ground-track motion of 6 m/s. If the pendulum swing is aligned with the ground-track motion then it is possible to time the camera exposures such that the pendulum induced motion effects compensate for the actual ground-track velocity.

Another technique for motion blur compensation is to synchronize the image data readout with the apparent ground-track velocity. This is possible only if the detector axes aligns with the ground-track motion, a condition that will occur once every 72 km for the data set discussed here. Analysis also indicates that the exposure time for a 1-pixel blur is 3.3 ms for a balloon ground velocity of 60 m/s.

To accommodate the imaging needs from a Mars balloon platform within the imaging context we have discussed, it is useful to define the notion of a Transect Image Set consisting of 1 context framing image, 10 successive overlapping or non-overlapping high-resolution images, and highly encoded results of interest operators/filters applied to up-to 40 additional high resolution images. Such a data set provides redundancy in case of unavoidable motion blur, a fully or partially connected "ground-truth" high resolution image swath 200 m wide of length 2 km inside a single 10 km framing image, and ultra-compressed useful science/mission data for remaining 8 km of the path.. This science data sequence is illustrated in Figure 7.

Science Sequencing Concepts

On-board state determination involves processing sensor data to obtain knowledge of balloon position in the form of latitude and longitude as well as distance vectors to specific targets. It provides information on orientation such as the tilt of the balloon platform, and its pointing and line-of-sights to targets. Furthermore, state determination allows computation of rate information such as the ground-track velocity, the climb rate, balloon gondola swing rate, and rotational speed of roll motion about the balloons vertical axis. Knowledge of this state information allows the Mars aerobot to optimally execute its on-board science and engineering sequences. For example, position information could be used to activate nadir pointed cameras as the aerobot over-flies a science target site. Accurate relative position information with respect to a target and knowledge of the balloon's orientation could be used to maximize oblique camera coverage of the target. To perform useful science with the specificity required by planetary scientists, on-board position accuracy better than 10 km would be desired with higher, target-relative accuracies of 1-2 km as the ultimate goal. Rate information on the balloons angular

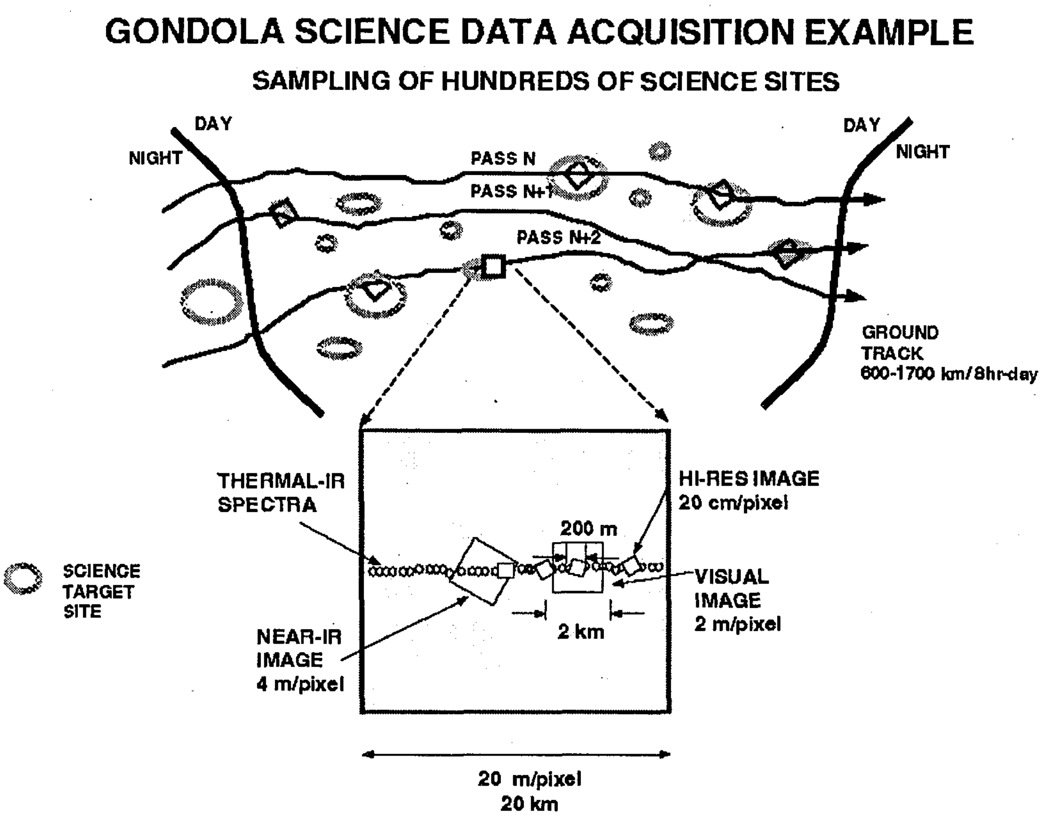

Figure 7. Science sequence concept

motion could be used to control the exact moment of triggering a camera, such that motion blur effects are minimized. Altitude climb rate data would be used by on-board sequence control to control ballast drops to avoid terrain hazards.

Post-flight state determination would be made by correlating aerobot images to planetary image databases, by more refined processing of various celestial sensor data, and by detailed analysis of Doppler data from orbiter return of balloon data.

At or near an important science target site it is desirable to take more images, possibly in different spectral bands. It may be desirable to increase the quality of an image transect by increasing image overlap between successive high resolution images, taking oblique view images in preferred directions, or obtaining higher quality images by careful timing of the exposures to minimize motion blur. Other actions that can be taken near science targets are to activate dormant sensors, and optimize the mix of sensor sampling activities and rates. One may also drop in-situ science micro-packages at such science targets.

Optimal science data return can be achieved in a number of ways. One technique is to exploit the capabilities of the on-board data systems by data buffering and increased ground-interaction through the command link. The aerobot would return "thumb-nail" images or data sets, and a subsequent command from the ground could be used to select the images that would be transmitted at high resolution. Another technique is to enhance the precision of the on-board sensors and position estimators. With this more careful targeting and state-driven sequencing of science data acquisition can be achieved. Yet another technique is to implement on-board recognizers for specific science data patterns. The aerobot would then tailor its sensor data acquisition in response to triggering signals from the science pattern or template recognizers.

Among the alternatives considered for sequencing were a Fixed Timer Sequence which would perform a timer reset at the night-to-day terminator and activate science data acquisition at fixed intervals. A variant of this method is an Earth-based timer sequence where the timer activation times are set from earth based on predicts of the next-day wind-blown path of aerobot. An on-board state-driven sequence would tie data acquisition to the balloon's on-board knowledge of its "state" i.e. latitude and longitude and a list of desired science targets. When the balloon knows it is near a target, it adapts its science gathering sequencing accordingly. A science-driven sequence would adapt data gathering in response to simple on-board analysis (data quality, pattern recognition) of science data. For example, if the on-board Neutron Spectrometer profile indicated water, then this could result in increased Thermal Emission Spectroscopy measurements. Finally, a Data Buffer Based Sequence would require only a summary report to be sent back to earth with the hi-resolution stored on-board to await an up-load selection command the next day. Of these techniques the methods based upon estimating the position of the aerobot and driving the science activity to the position state appears to be the most feasible, together with some limited data buffering to selectively control the transmission of high-resolution data sets.

<u>Science Instruments Summary</u>

The following strawman science instruments were selected for the MABS design:

<u>High-Resolution Nadir Camera</u>. Provides 200 X 200 m image at 0.2 m/pix resolution image for near ground-truth data in different spectral bands using a 6 position filter-wheel. Blur compensation is by using fast shutters and/or motion-stabilizing optical path elements.

<u>Wide-Angle Nadir Camera.</u> Provides 10 X10 km context for high-resolution images at 10 m/pixel resolution.

<u>Medium-Angle Oblique Camera.</u> Provides photo-geology side view images of mountainous/canyon targets for get-strata analysis.

<u>Thermal Emission Spectrometer (TES).</u> Provides mineralolgical information at 100 m resolution.

<u>Neutron Spectrometer.</u> Provides water, carbonates, nitrates composition two orders of magnitude better than orbital data.

<u>Atmospheric Sensors.</u> Supports atmospheric science, and balloon performance modeling.

<u>Aerosol Sensor.</u> Provides dust and aerosol concentrations.

<u>Selective Gas Sensor.</u> Provides information on water, methane gas levels.

A near IR spectral imager was also identified as a very desireable instrument to address surface mineralogy, but was included too late in the study to incorporate into the detailed gondola design

The total mass of all these science instruments was estimated to be 4950 g including contingency and margin ranging from 25% to 30%. Daytime and nighttime energy requirements were estimated to be 32.2 and 7.3 W-hr, respectively.

On-board State Estimation

On-board state estimation consists of determining the attitude of the gondola, as well as the position and height of the aerobot.

One quantity that needs to be determined is the tilt of the gondola with respect to the local vertical. This data is needed to support accurate measurement of the sun/star/moon elevation angles which are needed for position estimation. The tilt estimates are also used to distinguish between translation and rotation effects when using frame-to-frame image registration based methods of ground-track motion determination. Sensors that provide this information are clinometers under near steady state conditions, and accelerometers and gyroscopes in cases of significant pendulum and translation dynamics.

The other attitude measurement is the determination of the gondola angle with respect to true north. This data is useful in predicting the image rotation between successive frames when performing frame-to-frame image based motion determination. The absolute rotation angle is also needed to allow integration of translation accelerations and velocities obtained from the ground-track imaging or inertial sensors. Sensors that provided this information include a roll rate gyro for short term, moderate accuracy delta rotations, inertial estimator using the full 6 gyro and accelerometer measurements for short and medium term, high accuracy delta rotation, Sun and Phobos azimuth angle measurements for day-time absolute rotation, and Phobos and bright-star azimuth angle for nighttime absolute rotation.

Determination of the height of the gondola above the ground is needed to understand image scale when interpreting science images, and when performing frame-to-frame motion determination or landmark position determination. The data is also useful in supporting emergency ballast drops. Sensors that provide this data include laser rangers as well as radar altimeters.

The ground-track velocity is needed to understand the wind patterns and the long-distance balloon trajectory. The velocity can be integrated for high-accuracy knowledge of ground-track, as well as for compensating for measurements of orbiter-to-gondola Doppler measurements. Sensors to provide this information include inertial sensors, frame-to-frame image based comparison methods, Doppler radar, and celestial position differencing - especially at night when high accuracy position estimation using star/moon fixes is possible.

Determination of the gondola latitude and longitude is the primary means of supporting state-driven science sequencing. In addition this data is used to predict the location of the sun, moon and orbiter positions when performing celestial or radio-metric sensing. The sensing approaches that can achieve this include the low accuracy method of detecting terminator crossing, moderate day-time accuracy from successive Sun elevation measurements, higher day-time accuracy from successive Phobos/Sun elevation measurements, moderate/High nighttime accuracy from successive Phobos and/or Bright Star elevation sensing, moderate short and medium accuracy by inertial estimation (6-DOF rate and gyro), moderate accuracy information from radio metric data e.g. signal acquisition/loss or Doppler profiles of an orbiter signal, and very high target-relative accuracy by measuring deviation of unique, clearly discriminated landmark features in nadir and oblique low-resolution images (e.g. craters) from on-board map-based predicted values.

For the Mars Aerobot, daytime on-board position and velocity would be obtained by a sensor strategy that consisted of the following:

- Terminator crossing twice a day.
- Successive sun elevation measurements every 15 minutes
- Successive Phobos measurements during periods when Phobos is visible (approx 3 hrs), away from the sun, well illuminated, and when the balloon rotation aligns field-of-view.
- 2-4 orbiter (MGS, M98) fixes using signal acquisition/loss or Doppler
- Image frame-to-frame motion determination every few minutes when high accuracy knowledge of ground-track position or velocity is needed.
- Full 6-DOF inertial estimator if power budget permits.
- Landmark deviation based position determination in close vicinity of target after earth validation of approach based on received image analysis.
- Height measurements concurrent with imaging and radio-metric measurements.
- Doppler radar sensor if mass/power budget permits.

Nighttime on-board position and velocity would be obtained by a sensor strategy that consisted of the following:

- Successive Phobos elevation measurements when Phobos is visible (approx 3 hrs), illuminated, not in shadow, and when balloon rotation align field-of-view.
- Successive bright-star(s) elevation measurements every 15 minutes.
- 2-4 orbiter (MGS, MSP'98) fixes using signal acquisition/loss or Doppler
- Full 6-DOF inertial estimator if power budget permits.
- Doppler radar sensor if mass and power budget permits.
- Height measurements concurrent with radiometric measurements.
- Ground-track velocity estimation by differencing celestial position measurements.

An earth-based position estimate would be obtained by correlating nadir context frames returned by the aerobot with Mars maps. No VLBI techniques are anticipated.

The sensor set selected for the gondola consists of inertial sensors (3-gyro & 3-accelerometer), a Sun sensor, a Phobos and star camera, a laser or radar altimeter. The total mass of the sensor hardware is 1325 g including contingency/margin ranging from 5% to 30%. Day and nighttime energy requirements were estimated to be 3.0 and 0.9 W-hr, respectively.

<u>Earth Communication Approach</u>

The communication to Earth would be through the UHF Balloon Relay link of the MGS Orbiter (if still healthy) and the similar link through MSP '98 Orbiter. Redundancy would be achieved by gondola hardware to support both orbiter links. In addition, the command link capability of the MSP '98 orbiter would be used tailor the gondola mission for maximum science return in the form of new target lists, as well as providing orbiter ephemeris information to the aerobot for use with one-way Doppler measurements. The hardware implementation leverages the New Millennium Deep Space #2 mission and MGS UHF-link development, with some additional development (e.g. conventional transceiver) if on-board one-way Doppler measurement was found to be necessary.

The total mass of the communication systems was estimated to be 428 g including contingency. Day and nighttime energy requirements were estimated to be 2.2 and 4.4 W-hr, respectively.

<u>Data and Computer System</u>

The on-board computer and data system supports the compute intensive functions during day-time operations such as image compression; TES averaging and Fourier transforms; image-based ground-track motion determination and image analysis; and navigation sensing computations. Minimal operations are supported at night including Moon/Star based navigation and ambient sensor data acquisition.

The baseline system consisted of a Power PC-603E Multi-Chip Module Controller/Data-Storage unit that would support low-power features such as high/low processor clock rates and sleep modes. Power usage would be 5 W at 50 MHz clock, 3 W at 25 MHz clock, and 20 mW during sleep mode, with just enough power to keep-alive SRAM and bus-controller. In addition, low-dissipation energy sources in the form of linear regulators and/or direct power source operation with battery or capacitor would be used to support sleep mode operations at night thereby avoiding switching power supply pre-load power dissipation. Aggressive power management of active/inactive memory and I/O modules would result in substantial power saving. In addition, a field programmable gate array (FPGA) or micro-controller would be used to buffer data of low-rate sensors at night to avoid frequent wake-ups of the main processor. A 1 Gbit solid-state recorder would be used for on-board data storage.

The total mass of the computer and data systems was estimated to be 740 g including contingency/margin ranging from 5% to 30%. Daytime energy requirements were estimated to be 8.6 W-hr and night-time needs were estimated to be 7.9 W-hr.

<u>Power System</u>

The solar array size is designed for a surface optical depth of 1.7 at 40 deg N during the northern winter. High-efficiency GaS (21.5%) cells are used. An energy margin of 25%, a battery depth-of-discharge of 75%, a converter efficiency of 75%; and a battery efficiency of 80% are assumed for the design.

For a total estimate energy need of 124 W-hr, the system consists of a solar cell of area 0.76 m^2, with a mass of 1520 g (not including mechanical support structure), and a battery mass of 540 g.

<u>Mechanical/Thermal System</u>

The design here is for a light-weight multi-functional structure, with a "Warm Electronics Box" design inherited from the Sojourner rover system. The ambient thermal environment has less day/night variations than that of a rover, and the initial thermal design using a lumped thermal model, generic temperature requirements, and RHU's should be adequate. Detailed thermal options to be investigated in the next study include heat-pipes, and phase change materials. The mechanical system accommodates a ballast turret/controller to drop multiple 600 g science-probe ballast packages.

The total mass of the thermal and structural system was estimated to be 3155 g. In addition the total mass of the ballast packages was assumed to be 3000 g.

Mass, Energy Budgets Summaries

Table 10 summarizes the mass and energy budget for the gondola system.

Table 10 Mass and energy budget

Item	Mass	Day-Time Energy	Night-Time Energy
	(g)	(W-hr)	(W-hr)
Science Instruments	4950	32.2	7.3
Communication	430	2.2	4.4
Position & Attitude Sensors	1325	3.0	0.9
Computer and Data System	745	8.6	7.9
Power	2600	0.8	1.6
Structure, Thermal, Cabling	3155	0	0
Payload Total	13205	46.8	22.08
Ballast	3000	0	0

Gondola External Interfaces

The following interfaces were considered during the design of the gondola:

- Aeroshell Mechanical Interfaces - deployment latches, restraints etc.
- Deployment/Inflation System Data Interface
- Cruise Stage Power Interface
- Cruise Stage Thermal Interface
- Balloon Mechanical Tether Interface
- Balloon Sensors Data Interface

Gondola and Mission Design Considerations

The following considerations were addressed to some level as part of MABS gondola system design:

- Commercial-Off-The-Shelf (COTS) parts vs Custom components.
- Instrument computers vs General Purpose Computer
- ASIC/DSP vs General Purpose Computer
- Position/Attitude sensitivity as function of sensor selection and design parameters
- On-board 1-way Doppler localization vs On-board Signal acquisition/loss localization
- Star/Moon Tracker performance enhancement vs Star/Moon Tracker Mass/Cost
- Doppler radar vs Image frame-to-frame velocity determination
- Science Payoff vs Accuracy of Position Determination
- Imaging and TES Quality vs Optical Depth
- Fast Shuttering vs Motion-Compensation Optics
- Neutron Spectrometer Performance vs Mounting Location
- Flat vs Tilted Array vs Mission Latitude vs Optical Depth
- RHU vs Heater vs Heat Pipes
- Power vs Latitude of operation
- Night-time science vs Power/Energy system mass
- Integral exo-skeletal structure vs temporary Launch, Cruise, Entry and Deploy structures.
- Tether Length Sensitivity to Mass, Rotation and Shadowing

Balloon Delivery System

Design Overview

The balloon delivery system consists of the entry vehicle, which contains the balloon system, and the cruise stage which delivers it to Mars. The primary requirements of the balloon delivery system are to provide a controlled thermal environment in cruise, target the entry vehicle to the required entry corridor, and to decelerate the entry vehicle so that balloon deployment and inflation can begin. The delivery system for the MABS is designed for a Mars direct entry from the approach hyperbolic trajectory. The entry system design is derived from the Mars '98 architecture and uses the same 2.4 m diameter blunt cone aeroshell design with a cruise stage for external mounting of avionics, solar arrays and sensors. The balloon, gondola and all the support equipment is contained in the entry aeroshell. The cruise stage is spin stabilized during cruise and entry. Most of the spacecraft hardware is redundant. The blow-down propulsion system mounted on the cruise stage provides all the TCM delta V and attitude control in cruise. The direct entry draws heritage from the Discovery/Pathfinder direct entry system that is scheduled to enter Mars on July 4, 1997. The balloon/aeroshell is launched in an inverted configuration similar to Pathfinder and Mars '98. The cruise stage design and equipment layout is derived from an LMA Spaceprobe/Discovery design to reduce the non-recurring cost. A modest level of technology advance reduces mass and allow the use of a low cost Delta 7325 launch vehicle. The total balloon system mass of 212 kg can be accommodated with this lower mass cruise stage and the smaller diameter aeroshell of Mars '98.

Launch Configuration

The current best estimate for the MABS launch mass is 534 kg. which provides a 15% launch margin for the Delta 7325 capability of 616 kg. Table 11 summarizes subsystem masses. The aeroshell is supported on the launch vehicle in an inverted configuration. The 96 cm diameter cruise stage structure mates to the Delta upper stage adapter with a standard clampband. Figure 8 illustrates a possible launch configuration. The cruise stage attaches to the backshell at the other end of the 96 cm cylinder with an interface ring and six bolts. The entire stack is carefully balanced to meet the Delta center-of-gravity requirements for spin-up to 70 RPM for launch. An umbilical line runs from the balloon system through the backshell to the cruise stage. The cruise stage solar arrays is mounted to the back of the equipment deck.

Table 11. Reference Cruise and Entry System Mass Summary

Subsystem	Total Mass, kg
Power	47
Telecom	21
Ad&C	6
C&DH	11
Thermal Control	5
Structure Mechanisms	18
Propulsion - Dry	17
Propellant	175
Entry Vehicle*	385

* Includes 212 kg Balloon System

Flight Element Total	526
Launch Adapter	8
Total Launch Mass	534
Delta 7325 Capability	616
Launch Margin	15 %

Mechanical Design

The flight delivery system consists of the cruise stage, backshell, and aeroshell. A single monopropellant propulsion system mounted on the cruise stage provides all the propulsive requirements for cruise. Entry is spin stabilized so the propulsion system can be jettisoned at entry. The propulsion system consists of two propellant tanks and two Rocket Engine Modules (REM). Each tank carries 7.5 kg of hydrazine. Each REM consists of one aft pointing 22N (5#) thruster and two opposing 22N roll thrusters. The Delivery System design can fully support the mission requirements including meeting the dynamic requirements for balloon deployment.

The cruise stage structure provides the interface to the launch vehicle and provides mechanical support for the sensors, solar array, and antennas for cruise. The cruise stage thermal control is passive with specific coatings to reduce heating near Earth.

The aeroshell consists of the composite heat shield and the backshell which are coated with a 1.5 cm layer of SLA-561 ablator for dissipating the entry heat load. The entry ballistic coefficient of 50 kg/m^2 is lower than Pathfinder which aids in reducing parachute deployment velocity and opening shock. (The entry overload is only 15 g which is lower than Pathfinder). After the hypersonic phase, a drogue parachute is deployed from the top of the backshell. This parachute is

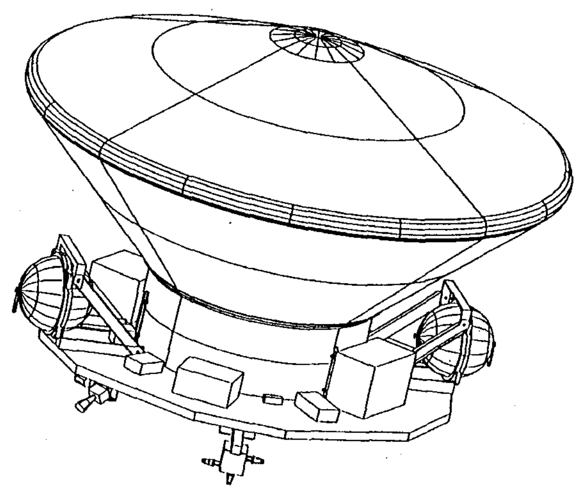

Figure 5. Mars Balloon Delivery System

similar to the Mars '98 design and is deployed by a mortar. The heatshield is released and dropped down on a long tether shortly after drogue parachute deploy. The drogue parachute is used to deploy a much larger main parachute that is used to reduce the dynamic pressure for balloon inflation. The mass of the heatshield is used to stabilize the balloon during inflation. The backshell and parachute are jettisoned at >0.5 kilometers altitude (relative to reference level) after balloon inflation is complete. Entry and deployment are planned over low lying terrain (0 to -2 km) to insure successful deployment before the system hits the ground.

Electronics

There are eight unique command and data handling (C&DH) cards (13 total with redundant cards) and eight unique power distribution cards to control the flight system in cruise and entry. The C&DH and power electronics are similar to Mars '98. The lander single board computer is an R6000 using the same Vx works operating system and interfaces as Mars '98. The lander software is the derived from Mars '98 and Stardust. The aeroshell also contains a barometric switch, timers, cable cutters, and a battery to implement deployment of the parachutes and aeroshell.

The lander telecom subsystem has been upgraded to use the Small Deep Space Transponder, SDST, to save mass and reduce cost. This also eliminates the separate boxes for the command decoder and the telemetry modulation units The SDST is redundant. There are redundant solid state power amplifiers located on the cruise stage. The cruise tracking passes occur every other day and are required to be at least four hours in length to satisfy navigation requirements. The cruise stage has a Medium Gain Antenna that is a horn design for the primary cruise link. The cruise stage also has a Low Gain Antenna that is used for emergency commands if necessary.

The attitude control system is derived from Discovery Stardust. The flight system is spin stabilized in cruise and uses sun sensors and redundant star cameras for attitude reference. The attitude control system is used to reduce the spin rate from 70 rpm at injection to 5 rpm for cruise.

Entry and Descent

The flight system is oriented to the desired entry attitude and the cruise stage is jettisoned at 5 minutes prior to entry. A jettisonable cruise structure allows for a clean aerodynamic shape for entry while reducing the entry mass and ballistic coefficient. The ballistic coefficient is 50 kg/m^2 with a coefficient of drag of 1.6. The heat shield shape is based on Viking and Pathfinder for which there is a large aerodynamics database. The drogue parachute is deployed at an altitude of about 7 kilometers altitude based on the calculated entry trajectory. The backshell is released at about 25 s after drogue parachute deploy. The main parachute is deployed when the backshell releases. The drogue parachute carries away the backshell but the heatshield is retained until balloon inflation is complete.

Heritage

The flight system has strong heritage from Viking/Pathfinder and Discovery Stardust. LMA built the aeroshells for both of these missions and is in the process of building the Mars '98 aeroshell. The aerodynamics for the 70° blunt cone aeroshell are well understood from Viking and Pathfinder. Mars direct entry will be demonstrated by Pathfinder and Mars '98. The disk-gap-band parachute design is the same design as Pathfinder and Mars '98. The cruise stage structure and electronics are the very similar to Discovery to minimize non-recurring cost.

New Technology

The cruise stage uses the Small Deep Space Transponder which will be demonstrated on New Millennium Deep Space 1 mission in 1998. No other new technology items were assumed in the study but several mass reductions are possible for a 2001 launch based on current technology development efforts.

Trades/Risk Assessment

The major flight system trades conducted included redundancy, the trajectory, and the delivery system configuration. Redundant lander hardware has been baselined to reduce mission risk and to take advantage of the similar Surveyor and Discovery hardware and fault protection. Six options were considered for the Delivery System design with varying technology level, launch mass, and heritage. Minimal new technology was used to allow development of a well understood design. The Discovery design for the cruise stage was selected since it was mass efficient and it was designed for spin stabilization.

The entry heating is well within the parameters of previous missions such as Pathfinder. The lower ballistic coefficient of the entry vehicle allows parachute deployment at lower velocities and lower loads than Mars '98.

Summary

The Mars 2001 Aerobot/Balloon System Study effort, using conservative design assumptions, has resulted in a feasible design for a long-duration mission to Mars. The key technology requirements for this mission have been identified and a technology plan has been constructed. A baseline mission and system concept has been defined well enough to generate rough estimates of a total mission cost. Excluding launch, cruise spacecraft, entry vehicle and project reserves, a Mars Aerobot mission is estimated at less than $50M (FY97$). The cost estimate is quoted in this manner because such a mission could piggyback onto a future planned Mars mission if the launch vehicle and entry vehicle are large enough to accommodate the balloon system. If a dedicated launch vehicle, cruise stage and entry vehicle are required, the cost of an Aerobot mission is approximately three times higher. The lower cost makes such a mission about twice the cost of the 1997 Pathfinder Rover. The upper cost level is roughly comparable to the cost of future dedicated Mars lander and orbiter missions.

The MABS study focused on the 2001 opportunity and up until October 1996, this opportunity was viable provided the advanced technology efforts had proceeded. These efforts did not go forward at that time which has resulted in 2003 being the next practical Mars Aerobot/Balloon opportunity.

What are the next steps for flying an aerobot at Mars? First and foremost an aerobot must be considered by the Mars program planners as another feasible tool for exploration and preparation for future missions including sample return. An aerobot can provide images at a scale and resolution relevant for scientifically valuable and safe lander and rover operation. In addition to providing scientists with a unique vantage point for exploration, an aerobot can contribute to the search for possible life. As an aerobot cruises above the Martian landscape it has the capability to explore literally hundreds of potentially interesting sites to exobiologists at a resolution relevant to identification of promising places to visit with landers and rovers.

Another key step in making a Mars balloon or aerobot mission a reality, is insuring that long-lead balloon envelop technology is pursued by NASA. The Ultra-Long Duration Balloon (ULDB) technology program for Earth scientific ballooning contributes to technology for a Mars balloon, however, because the Mars requirements are so unique it is critical that focused Mars balloon design technology goes forward if Martian aerobots or balloons are ever to be considered viable mission candidates in either the Mars Exploration or the Discovery Programs.

Advancement of autonomous navigation and control technologies allow the aerobot to take advantage of unique vantage points along its wind blown path. Such technology enables the aerobot to point cameras to predetermined targets of opportunities when the system is within close proximity. Furthermore, these technologies could trigger the release of small scientific packages at places of high interest.

The MABS design has demonstrated that an aerobot can fill the gap in data resolution between orbit and ground. In addition, aerobots are directly relevant to the Mars Exploration program goals and to future Mars surface sample return missions.

Finally, as an aerobot ranges over the Martian geography for purposes of discovery, people will identify with it and become engaged in the exploration as explorers themselves. Students will follow its progress across the planet and anticipate new sights, new discoveries and new mysteries of Mars.

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