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Mars 2001 Aerobot / Balloon System Overview

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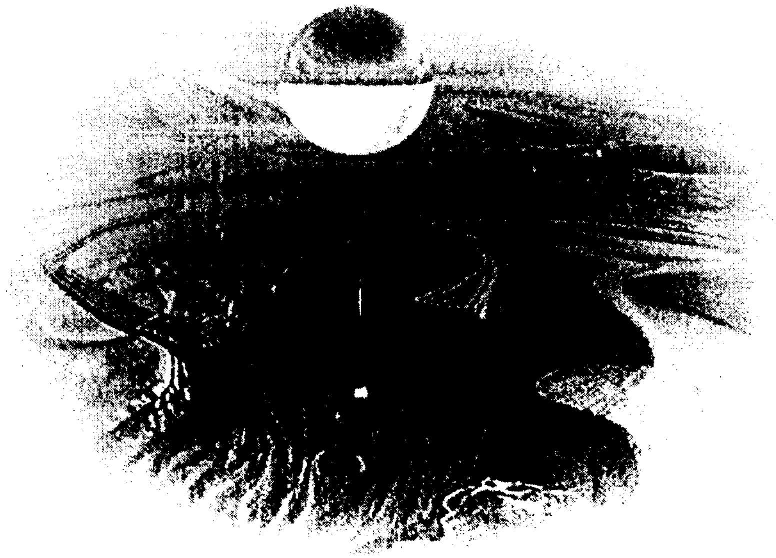

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Abstract

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 05 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 to relay communications capabilities and a 90 day mission duration. Key assumptions of the study included 1) a gondola mass of 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 and technical readiness provided early and significant NASA investment in balloon system technology is initiated.

Background

In the mid- 1980's, 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 "landing 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, duc 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 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 bc the level of supperpressure but instead may bc 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 Entrv 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 factor-cd in both the prc-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 arc unpredictable but follow a the thin Martian atmosphere makes entry difficult. Atmospheric entry at a low locution 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 scc 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 ($270° \leq L_s < 3600$), Mars is closer to the sun than during the northern hemisphere summer ($90° \leq L_s < 1800$). 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, Icss 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.

Wc 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

Table 3 BLM Design case parameters.

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

Table 4. Northern Design Case (NDC)

	Location W Longitude	N Latitude	TI [S1 units]	albedo [-]	K = a/TI [1000/S1]	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° c N Lat c 60°, Alba Patera.

Table 5. Equatorial Design Case (EDC)

	Location W Longitude	N Latitude	TI [S1 units]	albedo [-]	K = a/TI [1 OOOISI]	Topo [k m]
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° c 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 [S1 units]	albedo [-]	K = a/TI [1000/S1]	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 anc Albedo BLM inputs., - 60° < N Lat <-30°, Cimmeria

Table 7. Global Design Case (GDC)

	Location W Longitude	N Latitude	TI [S1 units]	albedo [-]	K = a/TI [1000/s1]	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

Balloon Flight System

The pert'ormarwc of superpressure (SP) balloons have been well documented. Balloons of the size required for a Mars mission have been successfully flown in excess of 100 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.

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: I) macro and localized stress distributions such as load introduction, 2) the total mass of components and their distribution, 3) scam design for strength, gas integrity, and geometry, 4) accessories such as fillings, 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, which offers advantages for ease of reefing, load introduction during the D&I, improved fabrication advantages such as ease of maintaining tolerances, 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 dcscribcd later.

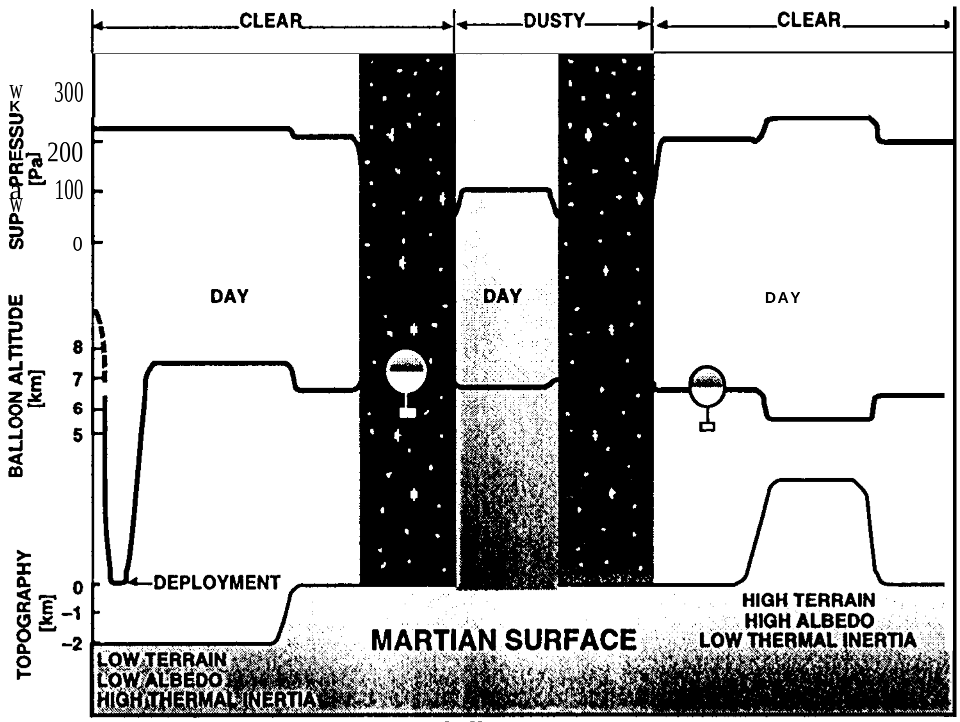

Figure 2. Mars superpressure balloon response to its environment

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, [hereby very intolerant of defects which all balloons have. Pursuit of

Deployment. Deployment considerations included: I) 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 for use in determining balloon geometry and payload/spacecraft mass distributions during the deployment process. As a result of stability concerns and mass distributions, it was decided that the balloon should be suspended 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 being determined by the time it takes for the system to slow to an acceptable dynamic pressure under the main parachute which results in a stable system and the time for gas filling which is dependent on the amount of gas and the rate it must be injected 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 dcscribcd in figure 4. below.

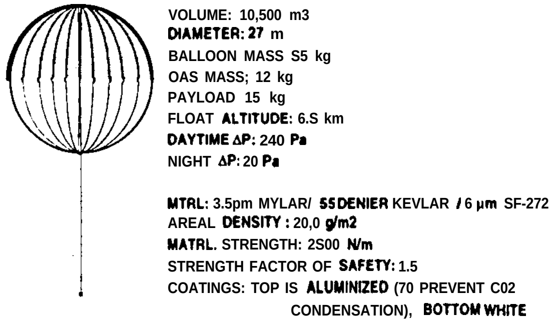

Figure 4. Baseline balloon design

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, we aimed to incorporate the technology for on-board, high-precision knowledge of the balloon position and orientation which when used on-board for science sequencing, and balloon task sequencing, promised 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

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 l-day prediction accuracy requirement for Altitude, Latitude and Longitude was respectively 100 m, 10 km and 100 km. Accuracy over a week 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 60s.
- Data/Computer system sleep-mode wake-up time less than 3 sec
- On-board clock accuracy better than 20s.
- Short term stability of oscillator for one-way Doppler of 1^{10}.
- BalhW/Probe drop activation time less than 60s.

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

<u>Gondola Science Imaging</u>

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

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 1000X1OOO 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

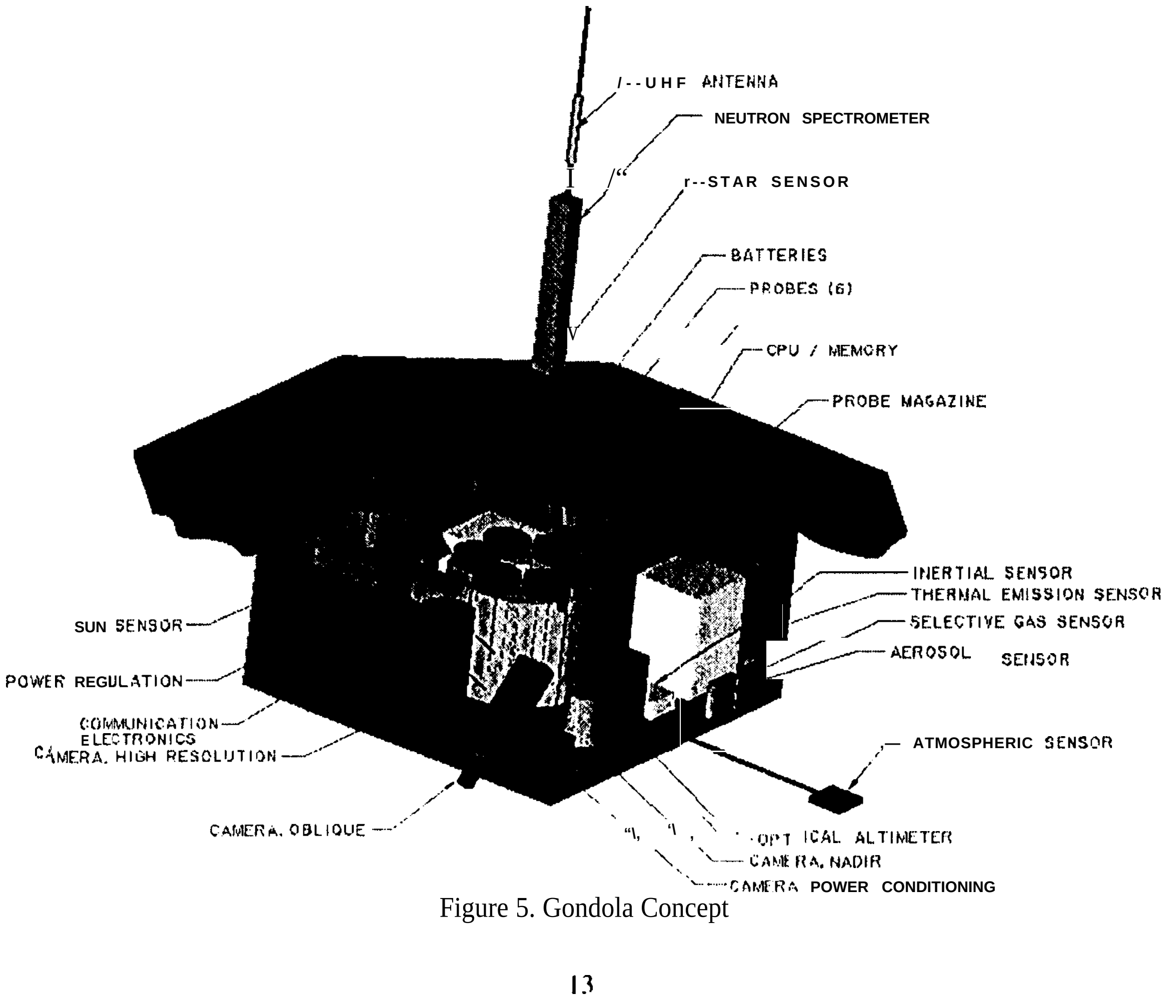

Figure 5. Gondola Concept

Another technique for motion blur compensation is to time the image data readout in synchrony 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. The data also indicates that the exposure time for a maximum l-pixel blur would be 3.3 ms or faster.

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 200m 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 planetary 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 with respect to vertical, and its pointing and line-of-sights. 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 motion could be used to control the exact

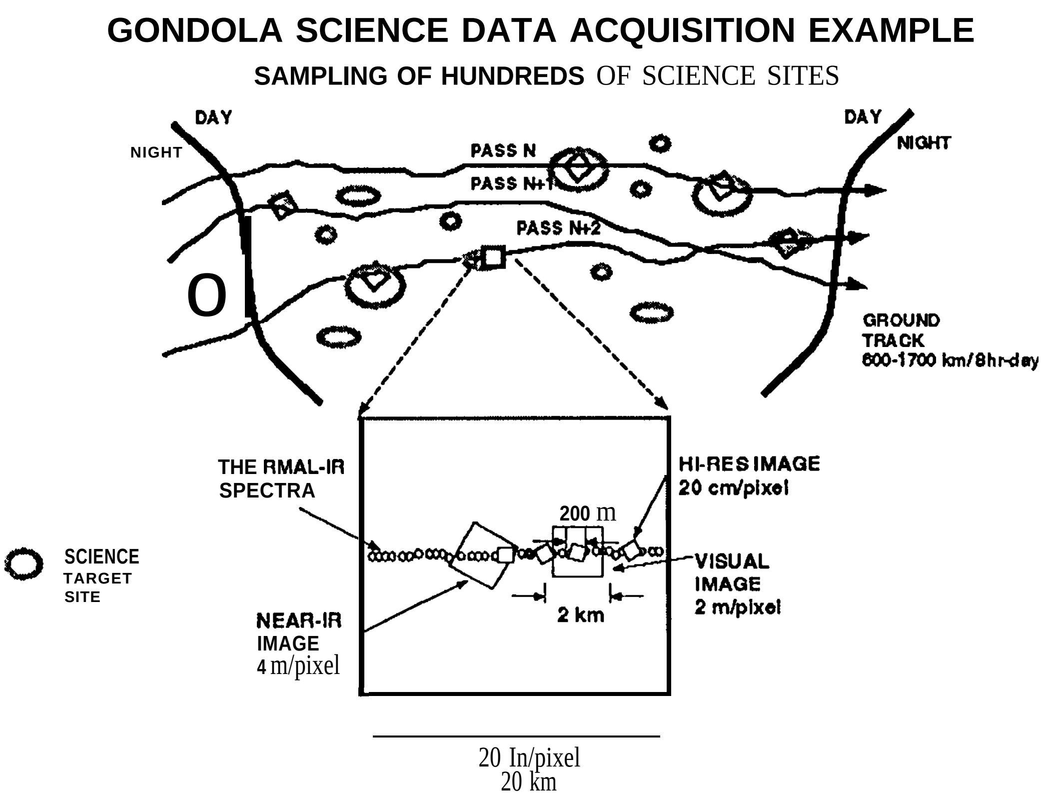

Figure 7. Science sequence concept

requirements were estimated to be 32.2 W-hr and night-time needs were estimated to be 7.3 W-hr.

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 planetary 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 night-time 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, 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 ballast packages were assumed to total **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 list the considerations which were addressed to some level as part of MABS gondola design:

- Coll~l~lcrci:ll -Off-The-Shelf (COTS) parts vs Custom components.
- Instrument computers vs General Purpose Computer
- AS IC/DSP vs General Purpose Computer
- Position/Attitude sensitivity as function of sensor selection and design parameters
- On-board I -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 Shattering 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 exe-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 Spaccprobc/Discovery design to reduce the non-

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 systcm 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 kcy technology requirements for this mission have been identified and a technology plan has been constructed. A baseline mission and systcm 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

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