

# RETURN TO THE RED PLANET: AN OVERVIEW OF THE *MARS PATHFINDER* MISSION

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## Abstract

The *Mars Pathfinder* Project is being developed to demonstrate new concepts for use in future missions to Mars, and to conduct focused, but significant, scientific observations of the planet. Scheduled for launch in December 1996 and arrival in July 1997, *Mars Pathfinder* is the second project in NASA's Discovery Program, a new initiative to conduct small, low-cost interplanetary missions with a maximum three year development period. An overview of the Mars Pathfinder mission is presented, covering the salient features of the spacecraft and its payload, and some of the more unusual engineering aspects of the mission. Special emphasis is given to the spacecraft's atmospheric entry, descent, and landing system, which makes use of both propulsive and airbag impact attenuation elements.

## Introduction

The *Mars Pathfinder* Project is the second mission in the Discovery Program, a new series of small, relatively low cost space missions initiated by the National Aeronautics and Space Administration (NASA). The development cost of *Mars Pathfinder* is 171 million dollars, excluding launch services and flight operations costs, spread over a three year period which began in October 1993. Its primary purpose is to demonstrate key concepts and technologies for eventual use in future missions to Mars employing instrumented landers. In addition, Mars Pathfinder will conduct scientific investigations of the geology and elemental composition of Martian rocks and soil, and the structure and dynamics of the planet's atmosphere. The spacecraft will also deploy a small, free-ranging surface rover to serve as an instrument deployment mechanism, and to conduct additional technology experiments. The development cost of the rover is 25 million dollars, funded separately by NASA from the lander.

## Mission Overview

*Mars Pathfinder* represents the first attempt by NASA in 20 years to land an automated space vehicle on the planet Mars. Its principal objective is to demonstrate low-cost technological concepts for transporting payloads to the Martian surface and operating small science stations there. The Project's schedule calls for concurrent development of the spacecraft and its associated ground systems in a three year period, as opposed to the six to eight year development period of other recent planetary missions. The *Mars Pathfinder* mission will be performed with a single spacecraft, launched by a *Delta II-7925* rocket equipped with a Payload Assist Module (PAM) upper stage, from the Cape Canaveral Air Force Station. The launch window is a 23-day period beginning on December 5, 1996.

The spacecraft's interplanetary trajectory is illustrated in Fig. 1; the tick marks denote 15 day intervals. After launch, the vehicle takes six to seven months to reach Mars, depending upon the actual launch date. During this period, a series of four trajectory correction maneuvers (TCMs) are planned to remove launch vehicle injection errors and subsequent guidance errors from the flight path. Tracking, telemetry, and command operations will be conducted using the 34 m and 70 m ground stations of NASA's Deep Space Network (DSN). Precise navigation during this period is accomplished with tracking data derived from the ground-spacecraft radio link.

Upon arrival at Mars on July 4, 1997, the spacecraft will enter the Martian atmosphere directly from its interplanetary trajectory, decelerate with the aid of a parachute and rocket braking system, and reach the surface with a speed at landing of 10 to 30 m/s. Shortly before landing, the spacecraft deploys an airbag system to cushion itself from the impact and subsequent bounces and rolling motion on the

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surface. After coming to rest, the spacecraft will autonomously deflate and retract the airbags, then upright itself with a system of three motor-driven petals. The motor drive/petal system is capable of uprighting the spacecraft regardless of its orientation after landing.

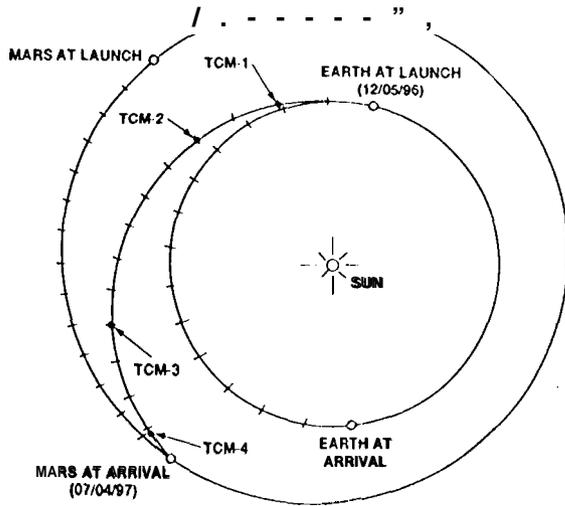


Figure 1: Interplanetary Trajectory

Once landing and petal deployment are completed, the spacecraft shall begin its primary mission, lasting for 30 Martian solar days or so/s (about 24.6 hr). During this phase, the lander will acquire science and engineering data characterizing the Martian environment and the performance of various subsystems. In addition, the microrover will be deployed and operated for a planned 7sol period. If the lander and rover continue to perform well after their respective primary missions are completed, the lander may continue to operate for up to one Martian year, and the rover for up to 30 SOIS.

### Flight System

An exploded view of the *Mars Pathfinder* spacecraft, or flight system, is shown in Fig. 2. The flight system consists of three primary assemblies—the cruise stage, entry vehicle, and lander, which also carries the rover internally. A mass breakdown of the flight system is given in Table 1. The total launch mass will be approximately 860 kg, within the 910 kg capability of the *Delis II-7925* rocket. In its launch and interplanetary cruise configuration, the flight system is about 2.6 m in diameter and 1.5 m in height.

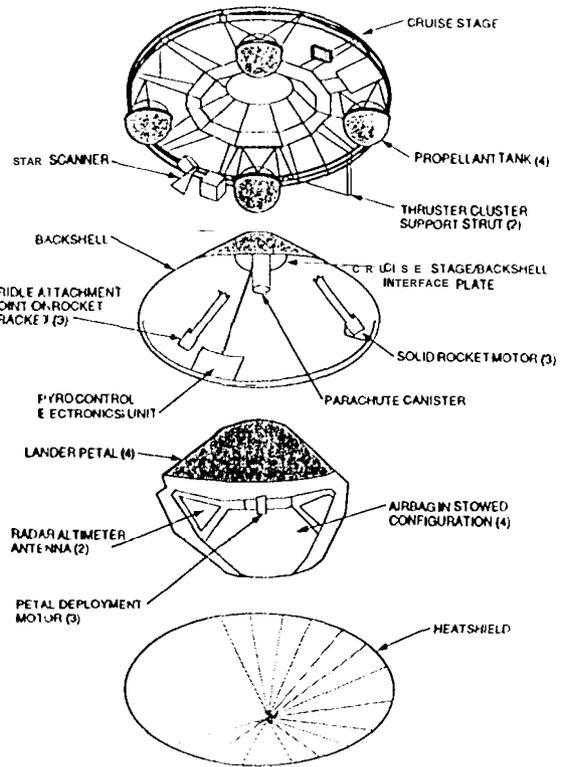


Figure 2: Flight System Exploded View

Table 1: Flight System Mass Breakdown

Component	Mass (kg)
cruise stage (dry)	210
propellant	75
entry vehicle (including lander)	560
lander	335
total launch mass	860

### Cruise Stage

The upper disk-shaped portion of the spacecraft, called the "cruise stage", provides power generation: attitude determination and control, and midcourse propulsion capabilities for the interplanetary phase of the mission. Attached to the upper surface of the cruise stage (not visible in Fig. 2) are an array of solar cells, a medium-gain radio antenna, two sun sensors, and an adaptor for securing the spacecraft to the launch vehicle's upper stage during boost.

Two additional sun sensors are attached to the sides of the circular structure. Eight 4.45 N hydrazine thrusters mounted in two clusters are used for both attitude control and midcourse guidance. In flight, the entire spacecraft is spin-stabilized at 2 rpm in an Earth-pointed attitude. The orientation of the spin axis is maintained within a tolerance of 3 deg by the attitude control system. The cruise stage is attached to the backshell by explosive bolts. These bolts are detonated shortly before atmospheric entry.

### Entry Vehicle

The entry vehicle, consisting primarily of the backshell and heatshield shown in Fig. 2, protects the encapsulated lander during entry into the Martian atmosphere. Its design and configuration are based on the entry capsule developed for the successful *Viking* mission of the 1970s through extensive wind tunnel testing.<sup>2</sup> Both the heatshield and backshell are constructed of lightweight composite materials capable of withstanding the 25 g entry deceleration loads. The heatshield exterior is covered with a 19 mm thick layer of ablative material, while the backshell is covered with a network of small heat absorbing tiles for thermal protection. As shown in Fig. 2, the backshell houses a variety of other components, including the parachute and its deployment canister, the solid rocket motors and firing circuitry comprising the rocket-assisted deceleration (RAD) subsystem, and the heatshield separation springs (not shown in Fig. 2).

### Lander

The lander appears in its stowed configuration for flight in Fig. 2. Structurally, the lander consists of four "petals" arranged in a tetrahedral shape. Attached to the underside of each petal frame is an airbag, a solid propellant gas generator designed to inflate the airbag and keep it pressurized until landing is completed, and a small electric actuator for post-landing airbag retraction. Three of the petals are attached by another set of actuators to the fourth, or base, petal, to which the lander's electronic components and science instruments are mounted.

An illustration of the lander in its deployed configuration is provided in Fig. 3. As indicated above, the lander carries the primary electronic systems and the science instruments of the flight system. The onboard computer, as well as the command and data handling electronics, the radio frequency (RF) subsystem, and the power

distribution subsystem, are housed inside the thermal enclosure shown in Fig. 3. For surface operations, power is generated during the day by the three solar panels. The lander is also equipped with a silver zinc battery that is charged by the solar arrays during the daytime. Through the cold Martian night, in which the lander will experience temperatures as low as -80° C, the battery provides power to the computer and to heaters which maintain an acceptable temperature inside the thermal enclosure.

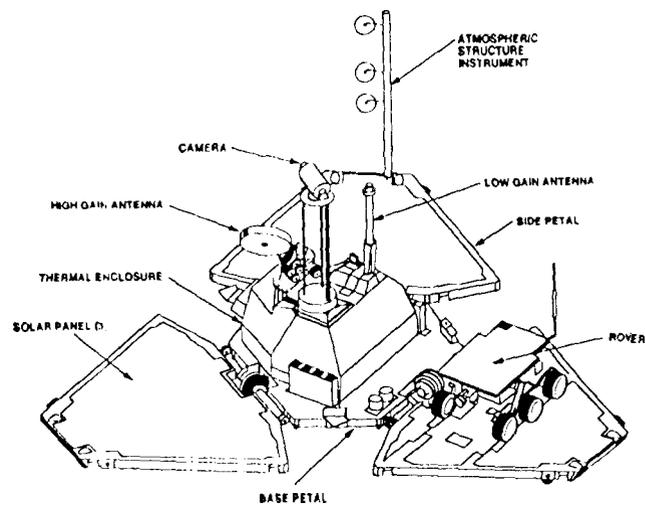


Figure 3: Lander Deployed Configuration

The flight computer is a space qualified derivative of the commercial R6000 32-bit microprocessor. This computer operates at a speed of 20 MHz, and is equipped with 128 MB of dynamic Random Access Memory (RAM), and 4 MB of non-volatile memory. Flight software, which is coded in the C programming language, controls all spacecraft functions, including command and telemetry processing, instrument operation, power distribution, and attitude determination and control.

Communication with the Earth is accomplished by the spacecraft's telecommunication subsystem, composed of the RF and antenna subsystems. The RF subsystem includes a turnaround transponder, command decoder unit, telemetry modulation unit, and a 13 W solid state power amplifier. This system operates at X-band (7.2-8.5 GHz) frequencies. A small 5 W backup transmitter and telemetry modulation unit, sufficient to satisfy the minimum mission objectives in the event of a failure in the primary transmitter string, are also incorporated into the system.

In the interplanetary phase of the mission, the RF subsystem uses the medium-gain antenna located on the cruise stage. With this antenna, uplink and downlink telemetry data rates of 250 b/s and 40 b/s can be achieved. The low gain antenna seen in Fig. 3 is used during entry, descent, and landing, and also serves as a backup to the lander's high gain antenna, also shown in Fig. 3. On the Martian surface, the low-gain antenna can support an 8 b/s uplink and up to a 300 b/s downlink. The steerable high gain antenna, on the other hand, can support a 250 b/s uplink and up to a 2700 b/s downlink.

### Science Instruments

*Mars Pathfinder* and its companion rover carry three science instruments. These are an imaging system, an atmospheric structure and meteorology package, and an Alpha/Proton/X-Ray Spectrometer (APXS), which is carried by the rover. The mass and power consumption of these instruments is summarized in Table 2.

Table 2: Science Instrument Characteristics

Instrument	Mass (kg)	Power Consumption (W)
Imager for Mars Pathfinder (IMP)	5.20	2.6
Atmospheric Structure/Meteorology Experiment (ASIMET)	2.04	3.2
Alpha/Proton/X-Ray Spectrometer (APXS)	0.74	0.8

The imaging system can acquire stereo images in color, through the use of 13 selectable filters mounted in the optics train. Images are recorded digitally using a Charge-Coupled Device (CCD). As shown in Fig. 3, the imaging system is mounted on a 1 m mast. It can be oriented in both azimuth and elevation by an electric drive system. The atmospheric instrument package consists of accelerometers, temperature sensors, and pressure transducers which record data during entry to support subsequent reconstructions of atmospheric

density, temperature, and pressure profiles. After landing, pressure and temperature measurements will be made daily by instruments located on the ASI/MET mast seen in Fig. 3.

The APXS, carried by the rover, is a duplicate of a similar instrument flown on the Russian *Vega* and *Phobos* spacecraft to Venus and Mars, respectively. This instrument will be the first of its type delivered to the surface of Mars. The APXS sensor head, mounted externally to the rover chassis on a mechanical deployment mechanism, contains a small amount of radioactive curium. When placed in contact with soil or the surface of a rock, the sensor head directs radioactive particles toward the sample surface, and by observing backscattered atomic particles and X-rays, can establish the elemental composition of the surface materials. The electronic components of the APXS are housed in a thermal enclosure mounted to the rover chassis.

### Rover

The rover, formally known as the Microrover Flight Experiment, has the dual purpose of performing technology experiments to assess microrover performance on the Martian surface, and serving as a deployment platform for the APXS, as described above. The rover has a total mass of about 15 kg, and is 63 cm long, 48 cm wide, and 28 cm wide. As shown in Fig. 3, it has six wheels, attached to a "rocker bogie" suspension which allows the rover to traverse obstacles as large as one wheel diameter (13 cm) in height.

The rover is powered by a 0.22 m<sup>2</sup> solar panel and a set of dry cell batteries, which together can provide up to 30 W of power during peak activity periods. Using its camera system, the rover navigates autonomously during traverses, employing a laser striping scheme to detect the presence of obstacles in its path. The rover can move at a top speed of about 1 cm/s. Commands and telemetry data are routed through the lander via a short-range, commercial UHF radio system. As mentioned previously, the electronic components of the vehicle, including its microprocessor, wheel drive system, power distribution system, radio system, APXS electronics, and navigation equipment, are contained in an insulated structure called the Warm Electronics Box. The WEB also contains three small heaters which are used during nighttime periods to reduce the temperature variations experienced by the electronic equipment.

## Entry, Descent, and Landing

Although lasting less than one hour, the entry, descent, and landing events comprise the most complex and difficult phase of the mission. The overall sequence of events is illustrated in Fig. 4. One hour prior to cruise stage separation, the spacecraft begins the process of shutting off all of the electronic systems on the cruise stage. In addition, the coolant of the heat rejection system used for thermal control of the lander during cruise is vented to space 15 minutes prior to cruise stage separation. The explosive bolts used to perform the separation push the cruise stage away from the entry vehicle with a relative velocity of about 0.3 m/s.

At cruise stage separation, the spacecraft is at an altitude of about 12,000 km, traveling at a speed of approximately 6100 m/s, as indicated in Fig. 4. After separation, the entry vehicle begins to encounter the upper reaches of the Martian atmosphere 30 minutes later, at an altitude of about 125 km. At this point the entry vehicle has accelerated to a speed of over 7600 m/s due to the increasing gravitational pull of Mars. As it approaches the atmosphere, the flight computer starts the parachute deployment algorithm, which uses accelerometer data to determine the proper time at which to deploy the parachute. In order to ensure a safe entry, the flight path angle of the spacecraft must be controlled to within  $\pm 1$  deg by the ground-based navigation system.<sup>3</sup>

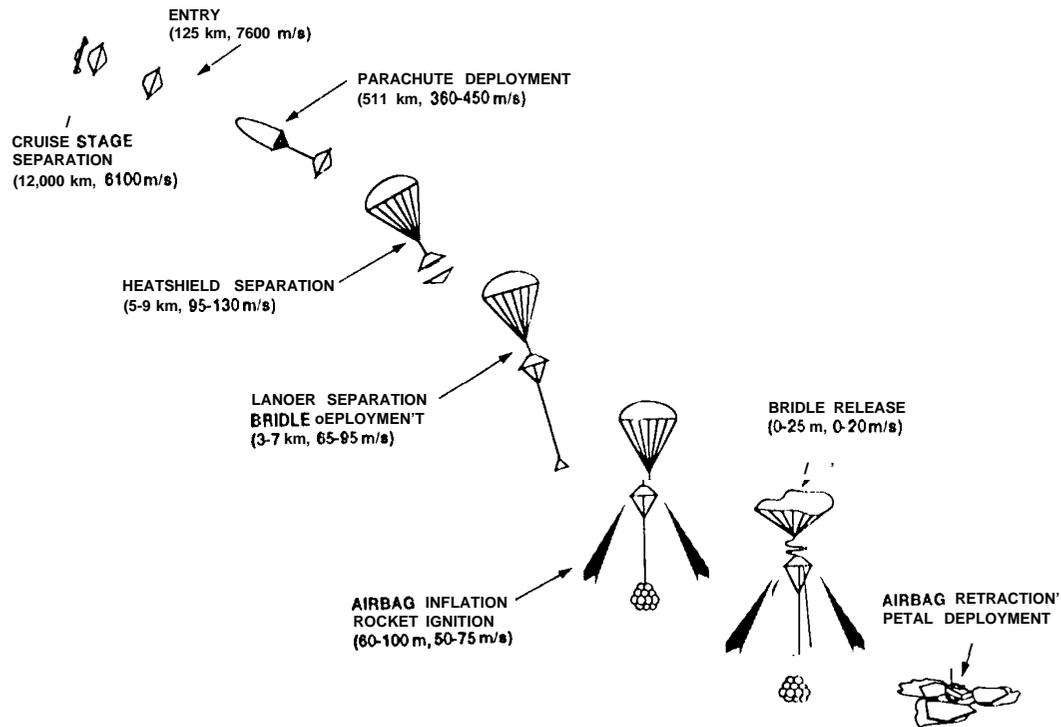


Figure 4: Entry/Descent/Landing Sequence of Events

Due to its use of a direct entry trajectory, *Mars Pathfinder* enters the Martian atmosphere with a velocity nearly 80% larger than that of the two *Viking* landers. To minimize development costs, the *Viking* entry vehicle configuration was adopted for *Mars Pathfinder*. Using the wind tunnel data base created during the design of the *Viking* mission and flight experience gained during Space Shuttle missions, the aerodynamic stability of the

*Mars Pathfinder* entry vehicle and the performance of its thermal protection system have been validated at the higher entry velocity primarily with computational methods, rather than through wind tunnel testing.<sup>1,2</sup>

As shown in Fig. 4, parachute deployment occurs at an altitude of 6 to 11 km and a velocity of 360 to 450 m/s, between 125 and 170s after entry. These dispersions are due to the effects of

acceleration sensing errors and errors in the pre-flight modeling of the atmospheric density profile and entry vehicle aerodynamics. The parachute is deployed from its canister by a mortar ejection system. Like the entry vehicle, the parachute configuration and deployment scheme are based heavily on the parachute decelerator system developed for the *Viking* landers.'

Once the parachute has been deployed, the flight computer fires six explosive bolts 20 s later that separate the heatshield from the backshell. These bolts hold a set of springs in compression during cruise, which expand once the bolts are detonated, pushing the heatshield away from the backshell with a velocity of 1 m/s. After another 20 s has elapsed, another set of explosive bolts securing the lander to the backshell interface plate shown in Fig. 2 are detonated, allowing the lander to separate from the backshell and deploy a series of suspension lines called the lander bridle.

### Terminal Descent System

An illustration of the spacecraft in its terminal descent configuration is provided in Fig. 5, showing how it appears once bridle deployment has been completed (see Fig. 4). The parachute employs the disk-gap-band canopy type developed through an extensive test program in the *Viking* era.<sup>4</sup> The parachute shroud lines are attached to a single suspension line designed to absorb the effects of any spinning motion of the backshell, bridle, and lander relative to the parachute canopy. The lander bridle consists of the triple bridle and the attached single bridle line seen in Fig 5, which suspend the lander below the backshell

The bridle is deployed by a metal tape that is wound on a payout reel mounted in one of the lander petals. As suggested by Fig. 5, this deployment tape is attached to the underside of tire backshell interface plate. The triple bridle and single bridle lines are folded in a stowage compartment located in the same petal as the payout device prior to deployment.

Once the lander/backshell separation nuts have been detonated, the drag force of the parachute unreels the deployment tape from the payout device, which acts as a centrifugal brake to modulate the forces experienced by the parachute shroud lines and the tape itself. The bridle lines are simply guided out of their stowage compartment;

during deployment, the weight of the lander is carried only by the deployment tape. The length of the deployment tape and bridle lines are designed to provide a smooth transition of the lander load to the bridle once the deployment tape has completely unwound. Due to the offset of the bridle attachment point on the lander petal from the lander's center of mass, the lander's base petal is canted about 20 deg from the horizontal once deployed, as shown in Fig. 5. The entire bridle deployment process takes about 5s.

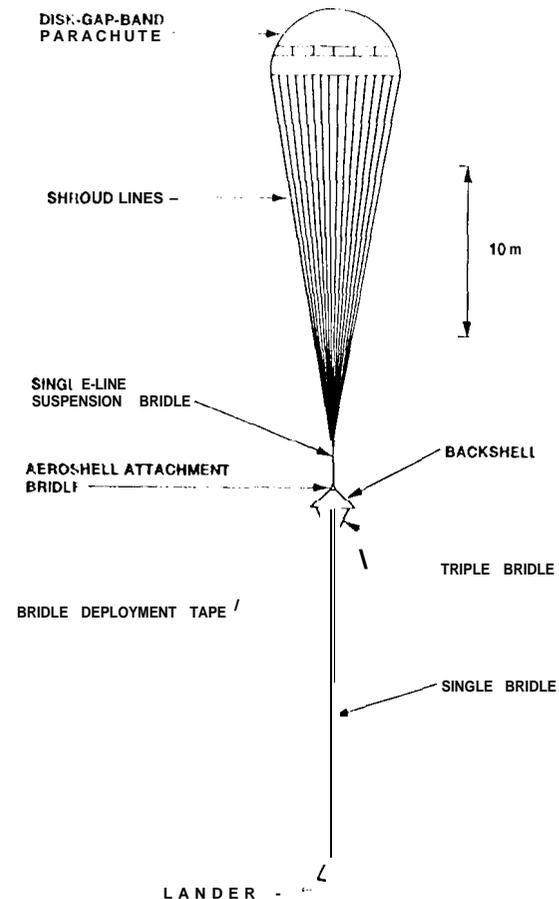


Figure 5: Terminal Descent Configuration

Once bridle deployment is completed, the spacecraft is 2 to 5 km above the Martian surface, descending at a terminal velocity between 50 and 75 m/s (see Fig. 4). At this point a radar altimeter carried by the lander is activated by the flight computer. The radar altimeter uses two rectangular antennas to range to the surface, which are mounted in one of the openings between the lander petals, as indicated in Fig. 2.

## Automatic Landing System

*Mars Pathfinder* relies on a hybrid rocket braking/airbag impact attenuation system for landing. This system is significantly different from the propulsive vernier systems used for terminal descent and landing in the *Surveyor* Lunar missions and the *Viking* missions.<sup>5,6</sup> A block diagram of this system is shown in Fig. 6. After the altimeter has been activated the flight computer starts the ignition algorithm, which uses radar data to predict the altitude and time at which the solid rocket motors mounted in the backshell (see Fig. 2) should be ignited. The ignition algorithm also determines when to fire the airbag gas generators, and the length of time the rocket motors should be allowed to burn prior to firing the bridle release mechanism to free the lander.

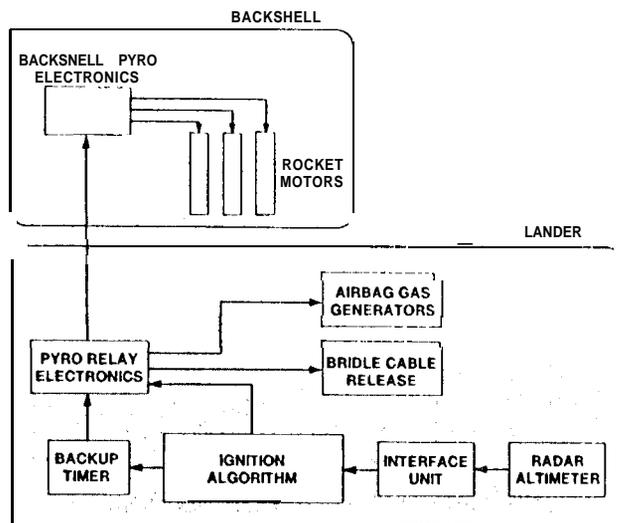


Figure 6: Landing System Block Diagram

The radar system (mentioned briefly above), comprised of the altimeter and its two antennas, is an off-the-shelf unit that has been used extensively on a variety of military aircraft. The unit is a wide-beam (60 deg) "first-return" system; that is, it senses the distance between the lander and the nearest point on the surface, independent of the lander's orientation. It is capable of sensing altitude with an accuracy of 1% or better over an altitude range of 15 to 1500 m.

The ignition algorithm uses altimeter data to estimate the lander's altitude and descent rate profile. During each computation interval, the current altitude and descent rate estimates are

used to predict the time remaining before rocket ignition. The time of ignition and the time of bridle release are computed so that the descent rate of the lander will ideally be zero at the time of bridle release, at an altitude approximately 10 m above the surface. Due to the effects of horizontal winds and dispersions in the rocket thrust profile, the lander's velocity at bridle release can be as large as 20 m/s (primarily in horizontal components), as indicated in Fig. 4. At impact, the velocity of the lander is in the 10 to 30 m/s range. The airbag gas generators are fired 2 s prior to rocket ignition. Firing times for the gas generators, rocket motors, and bridle cable release are also loaded into backup timers at regular intervals, to guard against power interrupts or other anomalous events that may adversely affect the flight computer.

The airbag subsystem includes four sets of bag assemblies, solid propellant gas generators, and actuator systems for post-landing airbag deflation and retraction.<sup>7</sup> An illustration of the fully inflated airbags is given in Fig. 7.

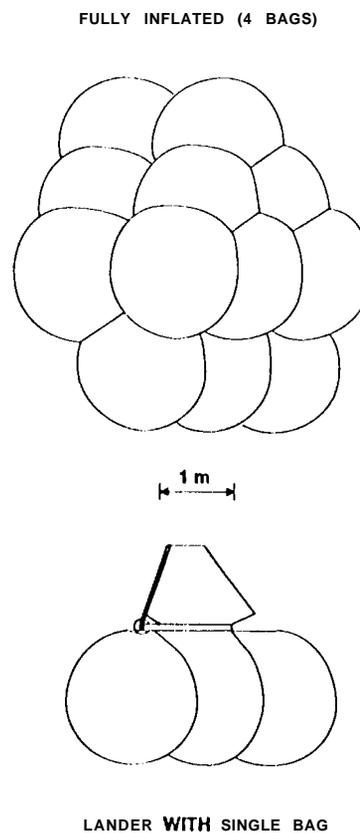


Figure 7: Airbag Subsystem Configuration

The airbags are constructed of two separate layers of polyester fabric. Each bag assembly consists of a pressure vessel, which contains the gas produced by the gas generators, and an outer layer covering approximately 60% of the surface of the pressure vessel, called the abrasion layer. The abrasion layer is intended to protect the pressure vessel from puncturing or tearing due to an impact on rocks or other irregular obstacles. When fully inflated, the internal pressure of the airbags is approximately 2.0 psi, compared to the 0.1 psi atmospheric pressure on the surface of Mars.

Each gas generator contains two different propellant grains. An inflation charge brings the airbags up to their full inflation pressure rapidly upon ignition. A second, slower burning sustain charge keeps sufficient pressure in the airbags for up to 2 min after inflation to accommodate the bouncing and rolling motion that may be experienced by the lander after its initial impact.

Once the lander and airbag system impact the surface, the flight computer starts another algorithm that uses accelerometer data to detect when the vehicle has come to rest. At this point, roughly 5 min have elapsed since atmospheric entry. After coming to a halt, gas purge flaps are opened to allow the airbags to deflate.

After allowing 30 min for deflation, the flight computer starts the airbag retraction/lander petal deployment algorithm. This algorithm senses the orientation of the lander, again using accelerometer data, and determines the proper sequence for the retraction of each airbag, and ultimately the deployment of each lander petal. The petal/motor drive system is capable of uprighting the lander regardless of its initial orientation after landing. The entire retraction/deployment process can take up to 2 hr. Once the lander is fully deployed, the flight computer initiates a stored sequence of commands to begin its planned surface operations.

### Summary

The *Mars Pathfinder* mission combines ambitious technical objectives with a fast-paced development schedule and a relatively modest budget. Many elements of the flight system are already in fabrication. The entry/descent/landing system is currently undergoing an exhaustive test and validation program, consisting of an

overlapping matrix of Monte-Carlo computer simulations, and component- and subsystem-level tests. The Project is progressing rapidly toward the opening of the launch window in December 1996.

### Acknowledgments

The author is indebted to many colleagues in the Mars Pathfinder Project. Special thanks are due to Richard Cook, Robert Manning, Brian Muirhead, Dara Sabahi, and David Spencer for their assistance in preparing this paper. The work described herein was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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