Balloons for Controlled Roving/Landing on Mars

Jack A. Jones, Steve Saunders, Jacques Blamont, and Andre Yavrouian

Jet Propulsion Laboratory, California Institute of Technology

Abstract

Until now, the only practical balloon systems proposed to explore the martian atmosphere have been superpressure balloons, which fly at a constant altitude, or short-lived helium balloons, which precariously drag a snake through all types of surface weather, or a day/night combination of the two. For the first time, two novel atmospheric balloon systems now appear quite viable for *controlled* balloon landings at selected martian surface locations. These balloons could soft-land payload packages, such as lightweight surface roving vehicles. The two balloon approaches and a land rover concept are described below, along with a combination of the two approaches.

Solar Hot-Air Balloons: These "Montgolfiere" balloons are named after the 18th-century French brothers Joseph-Michel and Jacques-Etienne Mongolfier, who first flew hot-air balloons. Using entirely solar heat, they are ideal for landing at the martian poles during summer or for shorter flights at lower latitudes. Recent tests have already confirmed the ease of altitude deployment and filling of these solar hot-air balloons. Furthermore, actual landings and reascents of solar hot-air balloons have been recently demonstrated by JPL, using a novel, lightweight, top air vent that is radio controlled. **One particularly useful application of these balloons is their use as a parachute to soft-land packages that are up to 50% of the total entry mass, which represents a fivefold improvement over present retrorocket landing systems.**

Variable-Emissivity Balloons: A second atmospheric balloon system uses a variable-emissivity superpressure helium balloon that can land at night at any martian latitude. These balloons would be gold-coated, superpressure helium balloons during both night and day. They could land at prescribed targets by exposing a section of the upper white balloon surface to the radiant cooling of deep space during the night. This reduces the temperature and pressure in the balloon to create negative buoyancy, thus causing descent, while replacement of the gold top cover causes reascent. Specific areas could be targeted for landings by using atmospheric currents at various altitudes, similar to techniques used by balloonists flying over the Earth.

Inflatable Roving Vehicles: JPL has recently fabricated and tested a number of roving vehicles with large inflatable balloons that act as tires. One version, with 75-cm-diameter wheels, has already demonstrated the ability to make large traverses in JPL's simulated "Mars Yard." A full-scale version, with 1.5-m-diameter wheels, should be capable of climbing large rocks ($\leq$ 0.5 m), traveling reasonably fast ($\approx$ 500 m/h) and far ($\approx$ 10 km), and yet have very low mass ($\approx$ 6 kg).

Low-Cost Combined Atmospheric/Surface Mission: A simple, solar hot-air balloon would act as a parachute to land a 6-kg inflatable rover. The balloon would then rise to a 3-km altitude while carrying a 2-kg camera/magnetometer/communications package for the remainder of daylight hours. The entire package would then soft-land at dusk. Total Mars entry mass would be about 20 kg, and the mission could be flown to Mars at very low cost ($\approx$ \$5M total launch costs) via one of the CNES Ariane 5 GTO piggyback launches.

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1. Aerobot Background

The exploration of the solar system has proceeded in several phases, beginning with flyby missions, proceeding to orbiters, then to probes and landers, and finally to mobile vehicles that operate on the surface and in the atmosphere.[1] For the most accessible planetary bodies, Venus and Mars, we are now entering the phase of mobile exploration of the surface and atmosphere.

Mobile atmospheric exploration of the planets is in some respects ahead of mobile surface exploration. In 1985, the Soviet Vega mission successfully deployed two balloons into the upper atmosphere of Venus. A Soviet-French-American experiment tracked these balloons for two days on the side of the planet visible from Earth at an altitude of 54 km, determining wind velocities and characterizing atmospheric turbulence. A French-Russian team recently was working on the development of a balloon mission for the 1998 launch opportunity to Mars. This experiment was to be equipped with imaging cameras and meteorological and geochemical sensors. It was designed to operate in the lower atmosphere of Mars and make excursions to the surface during the night. Unfortunately, funding was cut off due the disintegration of the USSR, as well as concerns about forced nightly landings during bad weather.

2. Altitude Control Concepts for Mars Balloons

Until recently, the only practical balloon systems proposed to explore the martian atmosphere and surface have been superpressure helium balloons, which fly at a constant altitude, or short-lived zero-pressure balloons that drag a precarious snake through all types of surface weather, or a day/night combination of the two.[15] The following subsections describe the first two viable means to actually *control* balloon landings on selected martian surface sites.

2.1 Solar Hot-Air Balloons

2.1.1 Background. Solar-heated balloons are nothing new. In fact, they are commercially available as novelty items[12, 13] and have even been banned in Italy due to interference with commercial aviation.[14] Accurate altitude control of solar balloons, however, is new, although it certainly appears feasible using the techniques employed by commercial fuel-powered hot-air balloons and by the French CNES[10] on stratospheric hot-air balloons. These balloons use vents in the top to allow hot air to escape, thus temporarily reducing buoyancy and allowing descent. Closure of the vent allows reascent.

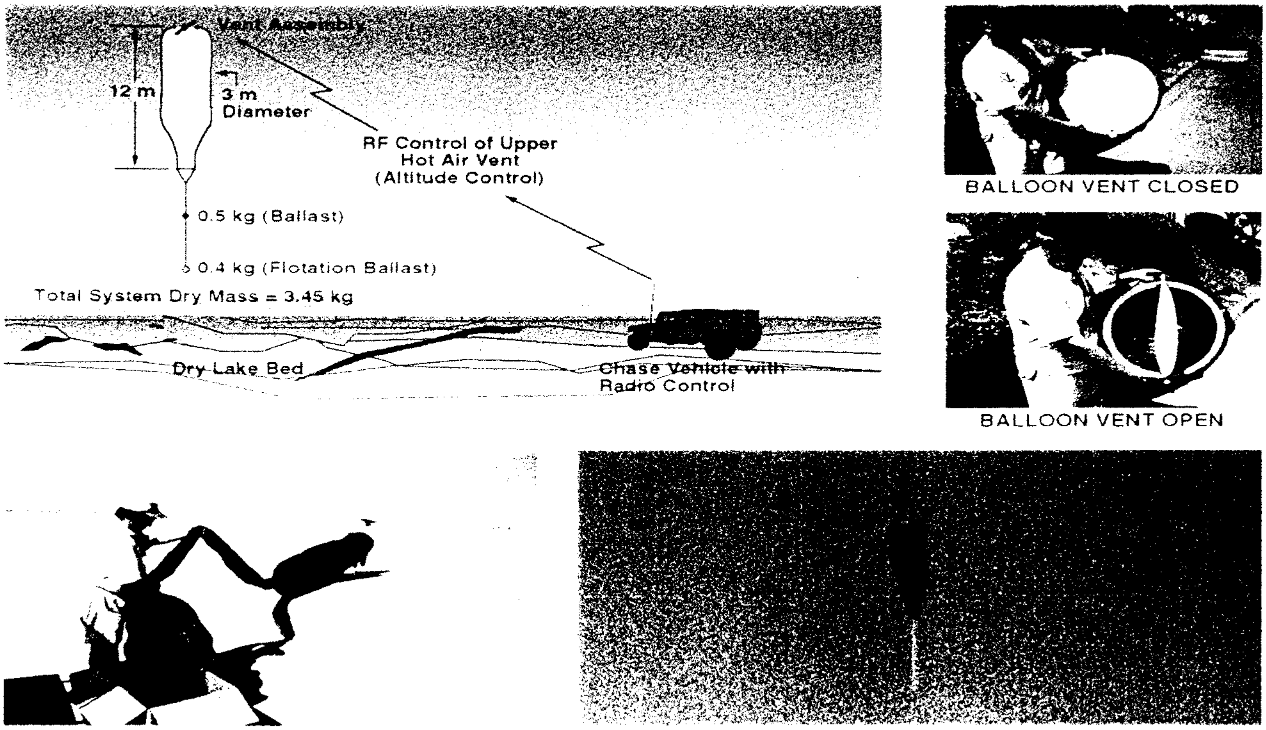
The extremely long martian polar summer (up to 0.95 Earth year) and high martian axis inclination (23.6°) create ideal conditions for "solar polar" hot-air ballooning for long periods (Figure 1). Tests have already been initiated that have confirmed ease of altitude deployment and filling of solar-heated hot-air balloons, and more tests are in progress to confirm analytical predictions of buoyancy.

Figure 1. Mars Solar Hot-Air Balloon

2.1.2 Solar Balloon I Test Results On September 5, 1997, a team of three JPL engineers (Jack Jones, Andre Yavrovian, and Dave McGee) traveled to El Mirage Dry Lake, in Southern California's Mojave Desert, to attempt the world's first remote-controlled landing and reascent of a solar-heated Montgolfiere. The balloon, fabricated from 12-µm (0.0005-in.) black polyethylene, was approximately 3 meters in diameter by 12 meters tall when fully inflated. The total mass of the balloon system was 3.45 kg, including 0.9 kg of ballast and payload.

The balloon had an upper vent (Figure 2), approximately 51 cm (20 in.) in diameter, that could be opened by radio control, thus allowing hot air to escape. This first free-flying attempt was simply to establish feasibility and did not carry any instrumentation other than the vent receiver and actuator.

The balloon was filled by holding the lower ring into the wind. After several minutes of heating up, positive buoyancy was attained, and the balloon was allowed to float with the wind, while still tethered. Eventually, the balloon was set free and allowed to rise. The balloon was raised



BALLOON VENT CLOSED

BALLOON VENT OPEN

BALLOON DEPLOYMENT

ASCENT AND SUCCESS

Figure 2. Solar Montgolfiere I Test Flight

and lowered in altitude by radio-controlling the vent position several times as it was chased at speeds of about 11 m/s (25 mph) across the dry lake bed. After one actual soft landing and reascent, it was necessary to crash-land the balloon near the edge of the dry lake in an attempt to salvage the balloon in the very windy conditions that had by then developed.

2.1.3 Solar Balloon II Test Results The second solar balloon was designed to be very similar to the first, although it was slightly larger. A weather sonde was added as a payload to measure ambient temperature, pressure, and altitude. In addition, a thermistor was added 2 meters below the vent to measure balloon gas temperature, and a potentiometer was added to the vent to confirm the opening/closing angle.

The balloon was launched from Santa Catalina Island, about 40 km offshore from Los Angeles. It rose almost straight up for about 500 m, and then it caught the upper winds and drifted slowly toward the mainland. After attaining about 1 km in altitude, the vent was opened, and the balloon started to descend about 2 minutes later.

A series of vent opening and closing signals was sent until ultimately the balloon's ballast was soft-landed on the ocean briefly, followed by reascent. The soft-landing maneuver was repeated several times until the balloon dipped too low and eventually got slightly wet, ending the tests.

A plot of the balloon altitude versus time is shown in Figure 3, along with a plot of the vent cover position. The balloon direction (ascent vs descent) is seen to change within 1 or 2 minutes after each changing of the vent position. By "getting the feel" of these altitude changes during

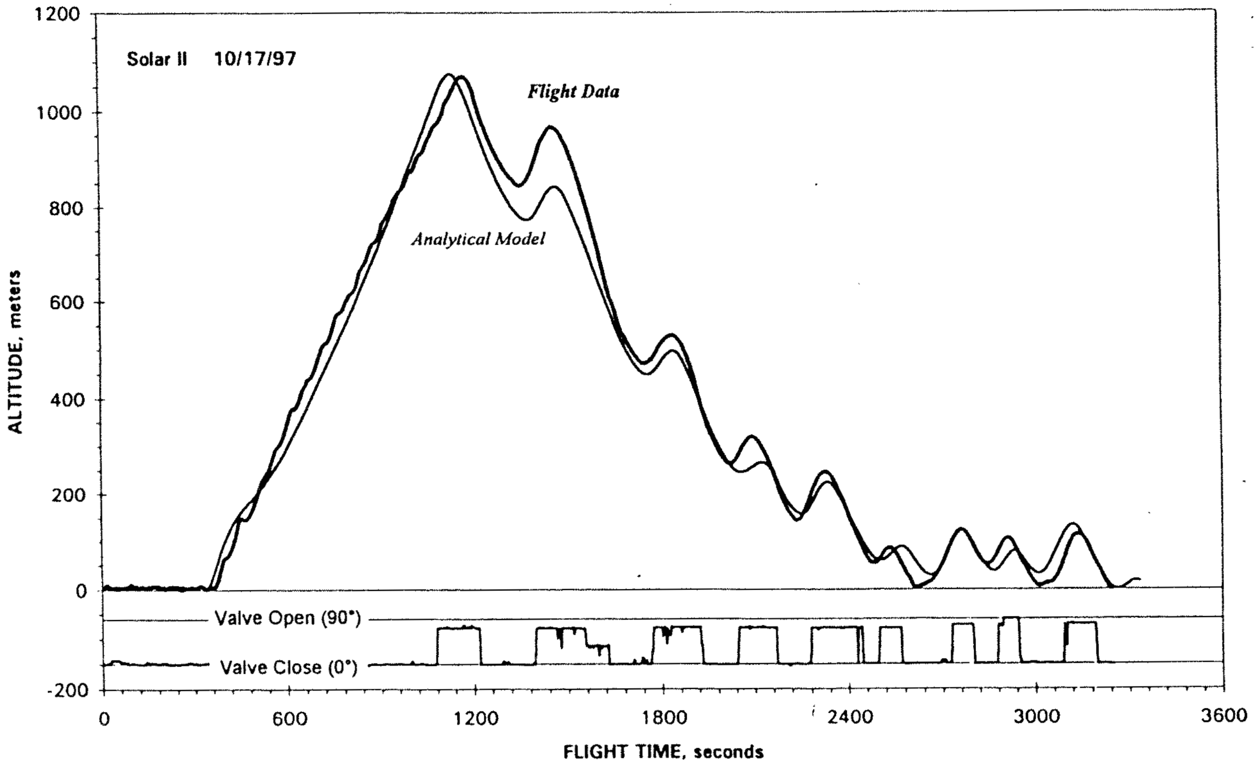


Figure 3. Solar Montgolfiere II Altitude vs Time

the test, the experimenters were able to actually soft-land the payload three times on the ocean surface. Thermal analyses of the mission coincided very closely with actual test results when the upper air vent openings and closings were taken into account (Figure 3).

2.2 Variable-Emissivity Balloons

Further evaluation during a brief study for JPL's Advanced Concepts Office has shown that an alternate design, known as a variable-emissivity balloon, may also be capable of allowing controlled landings on Mars. These landings could occur at the lower nonpolar latitudes, which can be reached by the polar hot-air balloons only during daylight excursions. The variable-emissivity balloons would be gold-coated, superpressure helium balloons during both night and day. They could land at prescribed locations by exposing a section of the upper white balloon surface to the radiant cooling of deep space, thus reducing the pressure/density in the balloon to create negative buoyancy (Figure 4), thus causing descent. Replacement of the gold top cover would cause reascent.

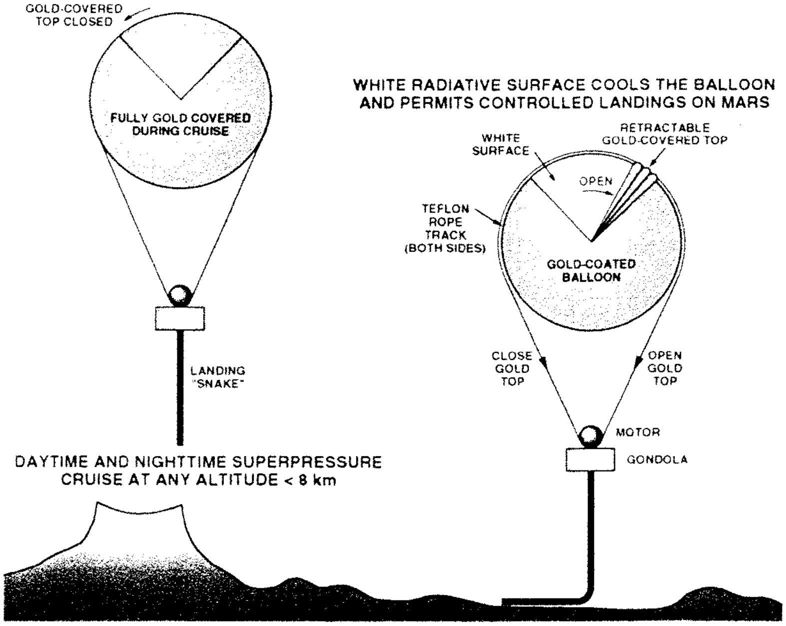


Figure 4. Mars Variable-Emissivity Balloon

For a 15-kg payload, total floating system mass is about 93 kg for the variable-emissivity helium balloon. Superpressure during the day is about 120 Pa (0.02 psi), and during the night the pressure drops to about 20 Pa (0.003 psi). The nighttime overpressure is similar to that predicted for the recent JPL MABS Mars balloon design,[16] but the daytime overpressure is only about half that of MABS, due to the new model's higher convective/lower radiative tie to the Mars ambient atmosphere. The design is sized for a constant 6.5-km altitude, although this can be varied to lower altitudes (less mass) or higher altitudes (more mass). Ambient pressures for the solar balloon are higher, since they are assumed to float near the surface. While the solar hot-air balloon can land during the day, the variable-emissivity helium balloon has the landing option available only at night. Current night vision amplification optics can be used to turn the starlit Mars landscape into readily viewable images, with chilled optics increasing signal-to-noise ratios.

3. Inflatable Roving Vehicles

A quarter-scale inflatable rover (38-cm-diameter wheels, scaled up four times in Figure 5), and a half-scale inflatable rover (75-cm-diameter wheels) have already successfully demonstrated that inflatable rover technology can be used to build lightweight, strong vehicles that can climb rocks

Figure 5. Full-Size Representation of Inflatable Rover

about 1/3 the height of the wheel diameter.[18] Since it is generally believed that about 99% of the martian surface contains rocks that are less than 0.5 m high,[19] an inflatable vehicle with 1.5-m-diameter wheels should be capable of climbing rocks up to 0.5 m high, thus being able to traverse the vast majority of the martian surface.

For each of these rovers, the design is relatively straightforward, with a minimum of both mass and complexity. Each front wheel has a separate, independent motor to allow variable torque in climbing rocks. The trailing wheel acts merely as a torque stabilizing device and is pulled over rocks by the combined drive of the front two wheels. The fourth inflated sphere, above the wheels, represents a simulated inflatable photovoltaic power source, although the existing small-scale rovers are actually operated by battery power.

4. Combined Mission

Perhaps the best use of hot-air balloons on Mars is as a parachute to soft-land packages that are too massive to be neutrally buoyant. After landing a heavy payload, the balloon can rise with a much lighter imaging payload and remain aloft until is soft-lands at dusk. **Using this technique, up to 50% of a Mars entry vehicle can be soft-landed as usable payload. This compares with less than 10% using present (Pathfinder-type) retrorocket landing systems.**

An example of a possible mission scenario is shown in Figure 6, in which a solar balloon parachutes an inflatable rover to the surface of Mars and then ascends with an imaging system. For a Mars atmosphere entry mass of 20 kg, total soft-landed payload would be 8 kg (6-kg rover plus a later landed 2-kg imaging system), and the system could be piggybacked to geosynchronous transfer orbit (GTO) *at no cost* on one of the CNES Ariane 5 launches. Total ΔV to Mars is then only about 1.4 km/s, which could be provided by an additional propulsion system ($\approx$ \$5M). Both the rover and the balloon imaging system could communicate to an exiting Mars orbiter ('01 or '03) at 128 kb/s.

5. Conclusions

For the first time, two novel atmospheric balloon systems now appear quite viable for *controlled* balloon landings on selected martian surface locations. The first balloon system is a solar-heated hot-air balloon that has been successfully tested at low altitudes on Earth, with high-altitude tests planned for the spring of 1998. The second system, which would land on demand at night, is a variable-emissivity superpressure helium balloon system, with preliminary Earth tests planned for later in 1998.

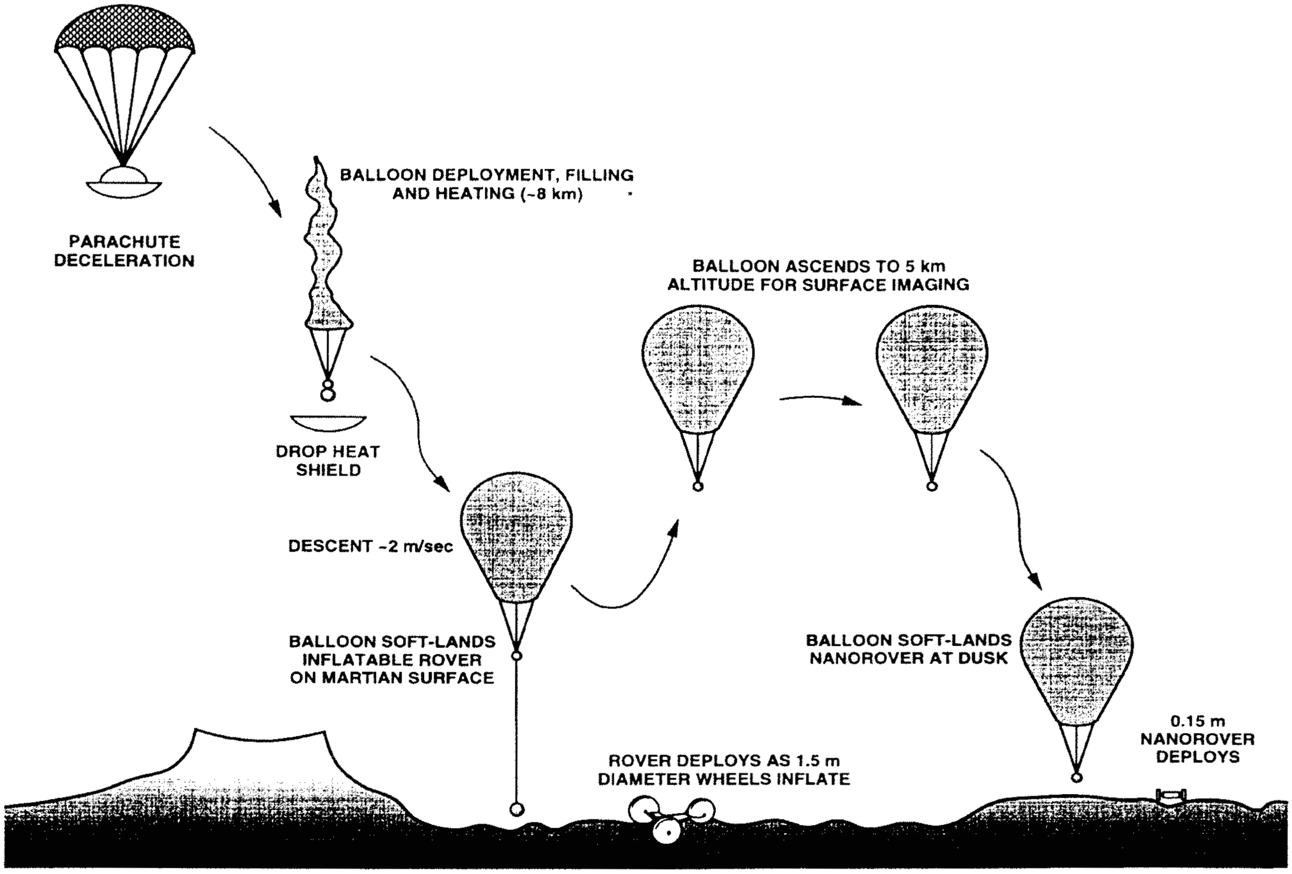


Figure 6. Mars Solar Balloon Mission Scenario

Preliminary tests of a rover using large inflated balloons as tires are also very promising. It appears possible to fabricate a 6-kg rover with half the mass of Pathfinder's Sojourner, but with a range and speed about 100 times those of Sojourner.

Perhaps the most important conclusion of this study is that, by using the solar balloon as a parachute, up to 50% of a Mars entry vehicle mass can be soft-landed as usable payload. Thus, one can increase usable payload mass or decrease entry vehicle mass (or a combination of the two) by about a factor of five. Upon confirmation with high-altitude tests, this capability may have a tremendous impact on the design of future Mars missions.

6. Acknowledgments

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