Chapter 4
The Mars Missions

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4.1 Overview of Missions to Mars

Of all the planets of the inner Solar System, Mars is the most intriguing. While Venus is geologically our twin sister, its high surface temperatures, the result of a greenhouse effect run amuck, make it quite alien and a poor candidate for human exploration and search for evidence of present or past life. Mars, on the other hand, offers different opportunities. While today Mars is very cold and dry on its surface, and its atmosphere is a thin veil of mostly carbon dioxide (CO_2), there is a great deal of evidence that the planet may have had vast quantities of surface water. Since the days when Percival Lowell and Giovianni Schiaparelli peered at the red planet, reporting what they referred to as "Canali" or canals (this was an optical illusion, but it raised the scientific interest in Mars), data have been mounting of what appears to be extensive water erosion. Of course, where there is water, there is increased chance of present or past life. In addition, further evidence indicates that just beneath the surface of Mars may be permafrost containing frozen water. This water could become a resource for future manned exploration.

From the earliest years of space flight, Mars has been a favorite destination; however, it has not proven to be the easiest locale to reach. Table 4-1 provides a historical overview of unmanned missions to Mars [1–4]. As can be seen, only about one-third of the attempts have been successful, however, those that succeeded have provided a wealth of knowledge about our intriguing red neighbor.

Table 4-1. Historical overview of Mars missions.

Country/Mission	Launch Date	Purpose	Results
USSR*/Korabl 4	10/10/60	Mars flyby	Did not reach Earth orbit
USSR/Korabl 5	10/14/60	Mars flyby	Did not reach Earth orbit
USSR/Sputnik 22 or Korabl 11	10/24/62	Mars flyby	Achieved Earth orbit only
USSR/Mars 1	11/1/62	Mars flyby	Radio failed at 65.9 million miles (106 million km)
USSR/Sputnik 24 or Korabl 13	11/4/62	Mars flyby	Achieved Earth orbit only
US/Mariner 3	11/5/64	Mars flyby	Launch vehicle shroud failed to jettison
US/Mariner 4	11/28/64	Mars flyby	First successful Mars mission—arrived 7/14/65, returned 21 photos
USSR/Zond 2	11/30/64	Mars flyby	Passed Mars but radio failed, returned no planetary data
US/Mariner 6	2/24/69	Mars flyby	Arrived 7/31/69, returned 75 photos
US/Mariner 7	3/27/69	Mars flyby	Arrived 8/5/69, returned 126 photos
US/Mariner 8	5/28/71	Mars orbiter	Failed during launch
USSR/Kosmos 419	5/10/71	Mars orbiter/lander	Achieved Earth orbit only
USSR/Mars 2	5/19/71	Mars orbiter/lander	Achieved orbit 11/27/71—unfortunately lander crashed on surface
USSR/Mars 3	5/28/71	Mars orbiter/lander	Achieved orbit 12/3/71, lander soft-landed on Mars—sent 20 seconds of data, including an image of the surface—lander destroyed by a dust storm
US/Mariner 9	5/30/71	Mars orbiter	In orbit from 11/13/71–10/27/72—returned 7,329 photos
USSR/Mars 4	7/21/73	Mars orbiter	Flew past Mars 2/10/74—did not achieve orbit
USSR/Mars 5	7/25/73	Mars orbiter	Achieved orbit 2/12/74—lasted a few days after which contact was lost.
USSR/Mars 6	8/5/73	Mars flyby/lander	Arrived 3/12/74—lander crashed on surface—sent some atmospheric data back during descent
USSR/Mars 7	8/9/73	Mars flyby/lander	Arrived 3/9/74—lander flew past Mars after separation from parent spacecraft
US/Viking 1	8/20/75	Mars orbiter/lander	In orbit 6/19/76–1980; Lander 7/20/76–1982 Orbiter & lander returned thousands of photos
US / Viking 2	9/9/75	Mars orbiter/lander	In orbit 8/7/76–1987; Lander 9/3/76–1980 Orbiter & lander returned thousands of photos
USSR/Phobos 1	7/7/88	Mars/Phobos/lander	Lost en route to Mars

Table 4-1. Historical overview of Mars missions (cont'd.).

Country/Mission	Launch Date	Purpose	Results
USSR/Phobos 2	7/7/88	Mars/Phobos/lander	Lost en route near Phobos
US/Mars Observer	9/25/92	Mars orbiter	Lost just before Mars arrival
US/Mars Global Surveyor	11/7/96	Mars orbiter—data relay	Arrived 9/12/97—surface mapper; still operating
Russia/Mars 96	11/16/96	Mars orbiter/lander	Launch vehicle failed
US/Mars Pathfinder	12/4/96	Mars lander and rover	Landed 7/4/97—last transmission 9/27/97
Japan/Nozomi	7/4/98	Mars orbiter	Extend sun orbit due to propulsion problem—Mars arrival expected 12/03—missed Mars.
US/Mars Climate Orbiter	12/11/98	Mars orbiter—data relay	Lost on arrival at Mars
US/Mars Polar Lander / Deep Space 2	1/3/99	Mars lander/descent probe	Lost on arrival 12/3/99
US/Mars Odyssey	4/7/01	Mars orbiter—data relay	Arrived 10/24/01—Mars mapper and other science
Europe/Mars Express/Beagle II	6/2/03	Mars orbiter/lander	Arrived 12/25/03—orbiter successfully achieved Mars orbit—Beagle II lander lost during landing.
US/Mars Exploration Rover-A (Spirit)	6/10/03	Mars lander and rover	Arrived 01/03/04—successfully landed on the Martian surface—very successful mission
US/Mars Exploration Rover-B (Opportunity)	7/703	Mars lander and rover	Arrived 01/24/04—successfully landed on the Martian surface—very successful mission

* USSR or Union of Soviet Socialist Republics; dissolved in the early 1990s; most of the USSR space program is now in the Russian space program.

In the following sections, the technology and some of the challenges associated with the spacecraft and lander antennas used for the United States program of Mars exploration will be examined.

4.2 NASA Mars Orbiters/Landers

This section presents an overview of the antennas used on the many National Aeronautics and Space Administration (NASA) Mars orbiters and landers (without rover technology). However, it is mainly as an overview of the technology. In a few cases, a further detailed examination of the antenna technology is presented.

4.2.1 Mariners 3 and 4

The twin Mariner 3 and 4 spacecraft (Fig. 4-1) represented the United States entry into in-situ Mars exploration. Mariner 3 was lost shortly after

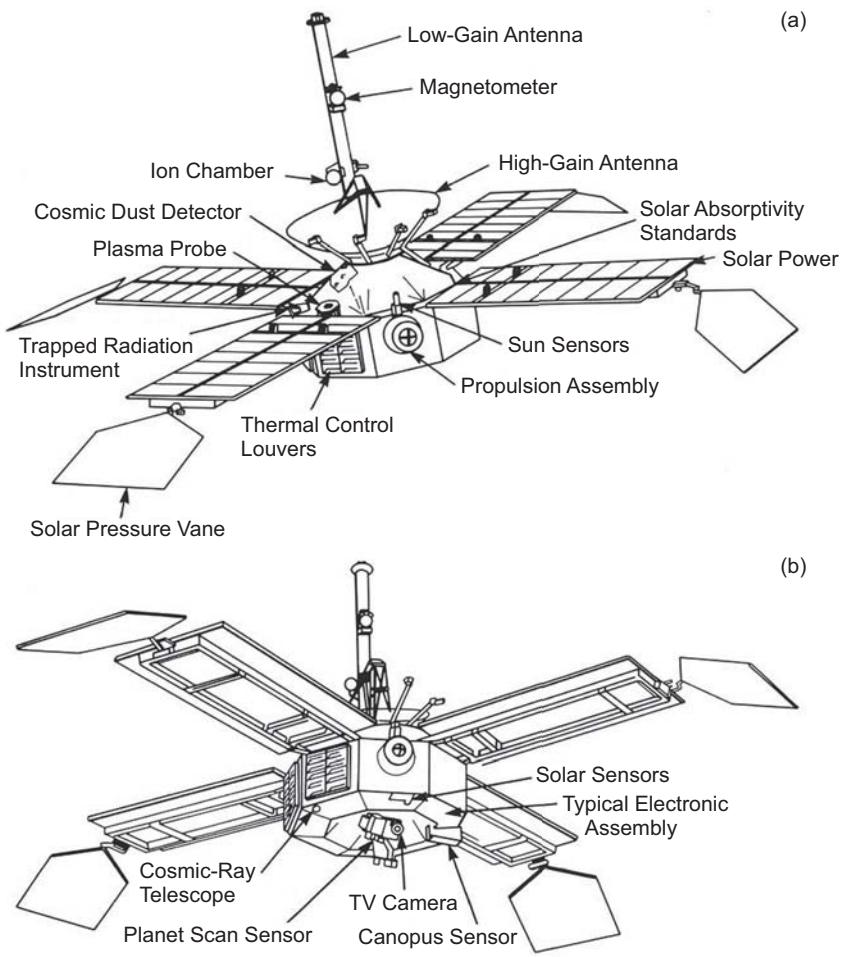


Fig. 4-1. Diagrammatic views of Mariners 3 and 4 (Mariner Mars 1964) spacecraft: (a) upper and (b) lower.

launch due to shroud separation failure; however, Mariner 4 achieved its mission objectives and returned the first comprehensive close-up views of the red planet [5,6].

Mariner 5 was originally intended as a backup to Mariner 4. When Mariner 4 successfully completed its mission, Mariner 5 was re-outfitted for a flyby of Venus. The antenna complement consisted of a high-gain antenna (HGA) and a low-gain antenna (LGA). The HGA was a 46×21-in. (116.8×53.3-cm) elliptical parabolic sector with a peak gain at S-band of 23 decibels (dB) mounted on the spacecraft so that the look angles to Earth

during the last half of the flight would fall within the main lobe of the antenna. The antenna's primary function was to transmit telemetry to Earth during the last half of the transfer orbit and for 20 days after planetary encounter during the video playback period. The S-band LGA was mounted on a 253.3-cm tall mast next to the HGA. Its function was to receive commands from Earth during the entire flight and to transmit flight telemetry to Earth during the first half of the mission when the spacecraft was near Earth and the look angles to Earth varied widely. The telecommunications system used a dual S-band 7-W triode cavity amp/10-Watt (W) traveling wave tube amplifier (TWTA) transmitter and a single receiver, which could send and receive data via the LGA and HGA [7].

Both the HGA and the LGA are further described in Chapter 3 in the Mariner 5 section.

4.2.2 Mariners 6 and 7

The Mariner 6 and 7 missions [8] used a twin set of spacecraft and employed a design very similar to the Mariner 3 and 4 spacecrafts (see Fig. 4-2). Both missions were considered a success. The antenna compliment was similar to the Mariner 3 and 4 system in that it contained both an LGA and an HGA. However, both designs were modified for improved performance [9].

The earlier Mariner LGA was a simple design, but it had some fabrication problems. Its conical feed and waveguide diameter had to be held to very tight tolerances, or polarization losses would be high due to the use of a circular polarization in the waveguide. Its return loss was high due to the manner in which the cruciform aperture was formed by crimping one end of the waveguide tube. The antenna also had high back radiation due to currents on the outer surface of the circular waveguide.

Using linear polarization from waveguide input to the aperture and converting to circular polarization at the aperture relieved tolerance requirements on the feed since linear polarization is less sensitive to dimensional changes than circular polarization. The aperture design was also modified to give the highest gain at the 40-deg cone angle while still above the minimum requirement at the 90-deg cone angle.

The LGA is shown in Fig. 4-3. It consisted of a circular waveguide mast with a series of mode-suppression pins. Toward the end of the waveguide, near the radiating aperture a four-pin polarizer was employed to provide circular polarization. The antenna achieved a gain of ~7.5 dB and a 3-dB beamwidth of 88 deg. This LGA design (or slight variations) was reused on Mariners 8 and 9, as well as the Viking orbiter spacecraft.

The Mariner 4 HGA gain was too low to support the higher data rate requirement, and its gain contours did not fit the trajectory geometry. For the higher gain, a 40-in. (101-cm) diameter circular diameter with a suitable left-hand circularly polarized (LHCP) turnstile feed was used (see Fig. 4-4). The

focal length to diameter F/D radio was chosen to use the existing Mariner 4 reflector forming tool.

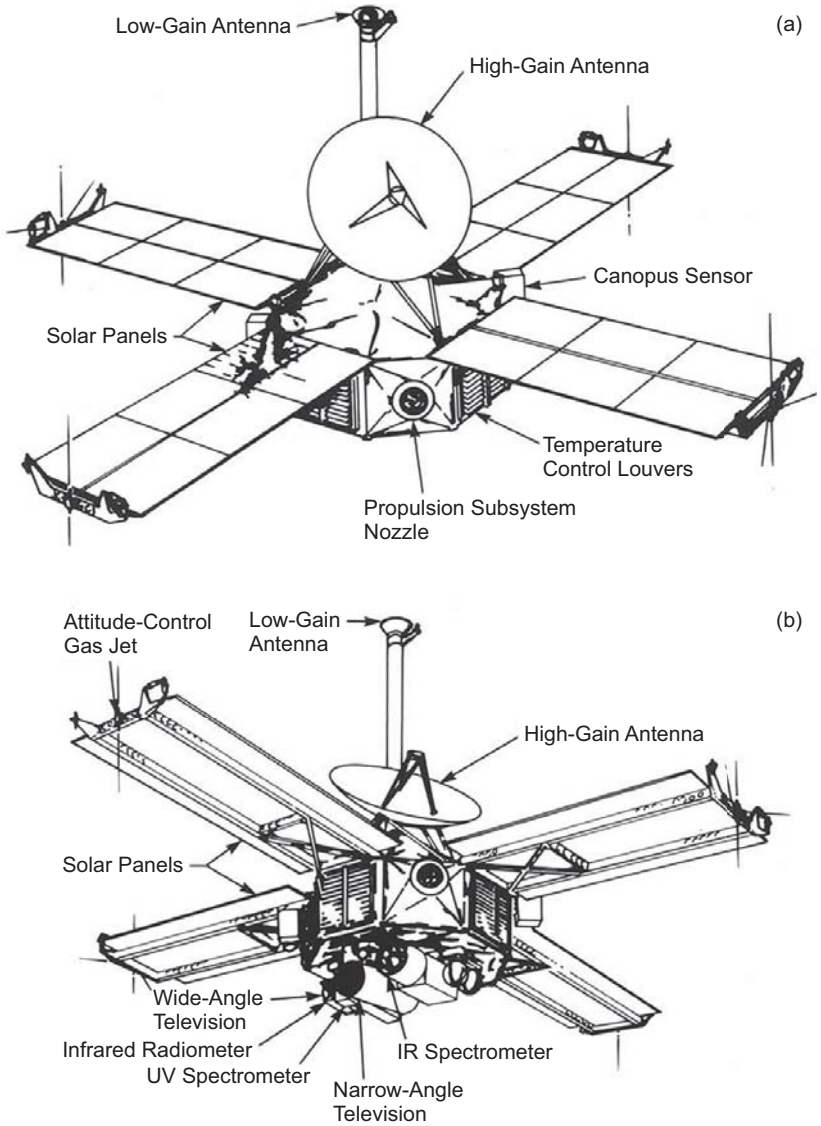


Fig. 4-2. Diagrammatic views of Mariners 6 and 7 (Mariner Mars 1969) spacecraft: (a) upper and (b) lower.

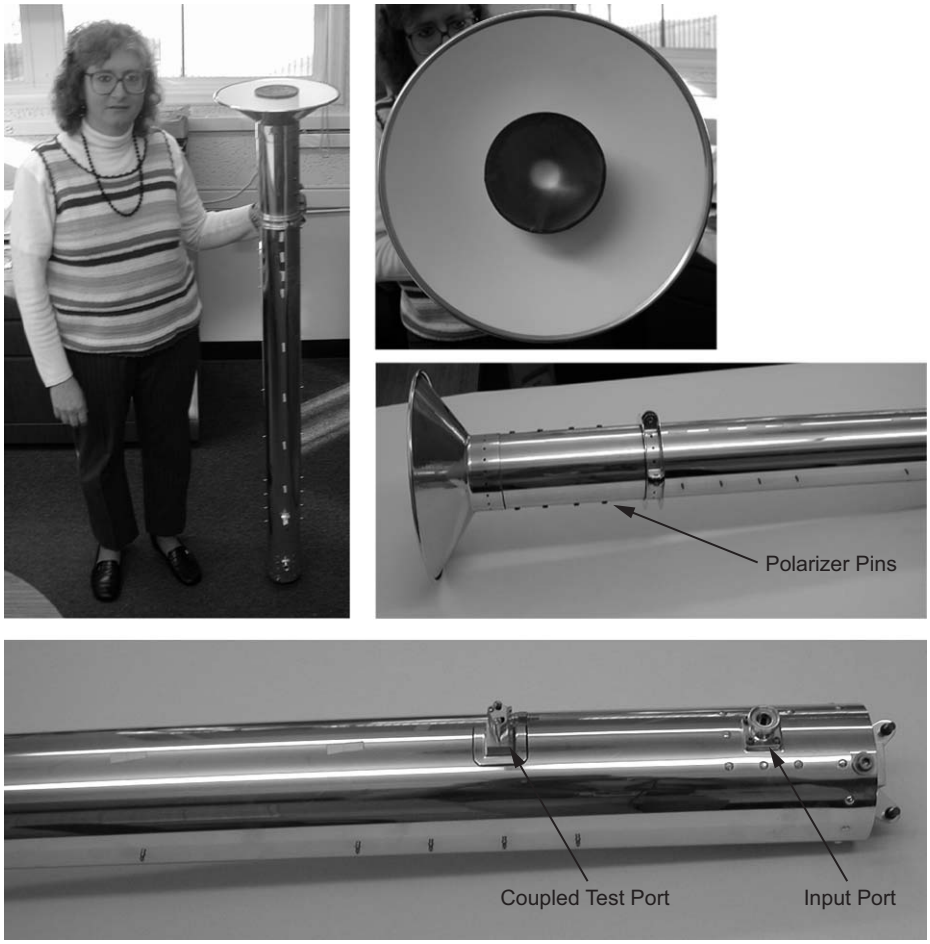


Fig. 4-3. Mariner S-band LGA (this particular unit was used for the Mariner 9 spacecraft).

4.2.3 Mariners 8 and 9

Mariners 8 and 9 were (once again) twin spacecraft [10]. Of the two, only Mariner 9 was successful, Mariner 8 failed on the launch pad. These spacecraft represented a gradual evolution of Mars-bound craft. They used a slightly modified S-band LGA on a 1.44-m long mast. They also employed a medium-gain horn antenna in addition to a Mariner 7-type high-gain parabolic antenna. Telecommunications were facilitated via dual S-band 10 W/20 W transmitters and a single receiver.

Fig. 4-4. Mariner 9 HGA with spacecraft mockup at the Jet Propulsion Laboratory (JPL) Mesa Antenna Range.

4.2.4 Viking

The Viking spacecraft represented the first U.S. attempt to land on Mars [11,12]. It could also be considered the first truly successful mission of its kind, although the Soviet Mars 3 did successfully land and did return a fuzzy video of the surface before succumbing to a violent sand storm.

The twin Viking spacecraft (Viking 1 and Viking 2) each consisted of an orbiter and a landing module, as shown in Figs. 4-5 and 4-6. Upon arrival into Mars orbit, the lander module was deployed to the surface, leaving the orbiter behind as a signal relay from the Martian surface back to Earth as shown in Fig. 4-7 [13].

The orbiter antenna compliment consisted of a fixed S-band HGA, the now familiar S-band LGA on a mast, and an ultra-high frequency (UHF) quadrafiler helix mounted on a ground plane.

The lander antennas [14,15] included a gimbaled S-band HGA direct-to-Earth link, an S-band turnstile LGA direct-to-Earth link, and a UHF turnstile antenna for link with the orbiter. The use of a direct-to-Earth link in conjunction with an orbiter relay link became the standard model for all future surface-operation missions.

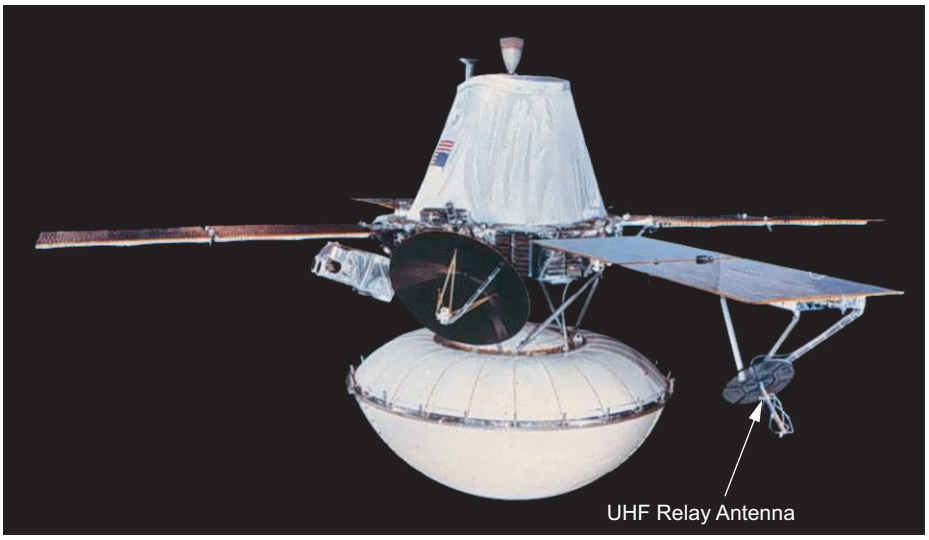


Fig. 4-5. Viking orbiter.

The Viking spacecraft begin a trend toward highly populated/integrated spacecraft. Evidence of this is seen as its traditionally isolated LGA field of view is impinged upon by various spacecraft assemblies. In addition, the highly populated lander incorporated two LGAs in close proximity to the top deck instruments. This trend makes antenna pattern predictions very difficult (particularly at UHF). To retire some of the uncertainty, mathematical models are sometimes employed, but as a safer approach, mock-ups of the vehicles are constructed, and antenna patterns are measured.

Of some interest is the use of UHF as the surface-to-orbiter link frequency. It was highly desirable to cover as much of the planet at a single time as possible in order to maximize the available link time with the lander. During the early years of balloon-borne and other high-altitude experiments on Earth by the French and others, it was determined that UHF provides a broad and very pervasive coverage, bending around objects and generally facilitating a reasonable link. The UHF band thus became the choice for surface links with the first Mars landers, and that tradition continues through the present.

Another point of interest that is of particular importance for landers on the Martian surface is the potential for ionization and multipactor breakdown within and around the antennas and their associated microwave components. On the surface of Mars, the atmospheric pressure is approximately 4–12 T (533 Pa–1600 Pa) versus 760 T (101,325 Pa) at sea level on Earth. These low pressures, also known as critical pressures, are nearly ideal for the occurrence of ionization of the antennas with powers as low as 5 W. This ionization

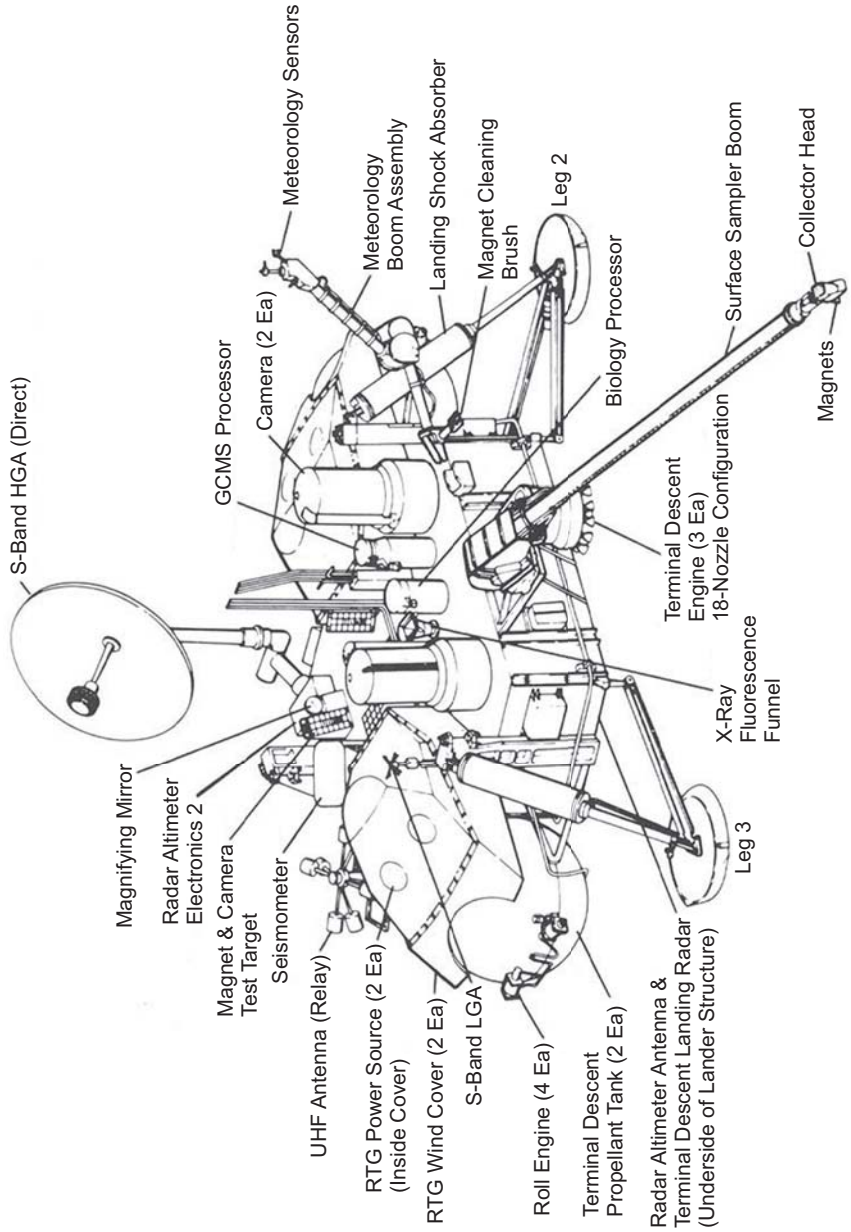


Fig. 4-6. Viking lander detailed diagram (RTG = radioisotope thermoelectric generator; GCMS = gas chromatograph-mass spectrometer).

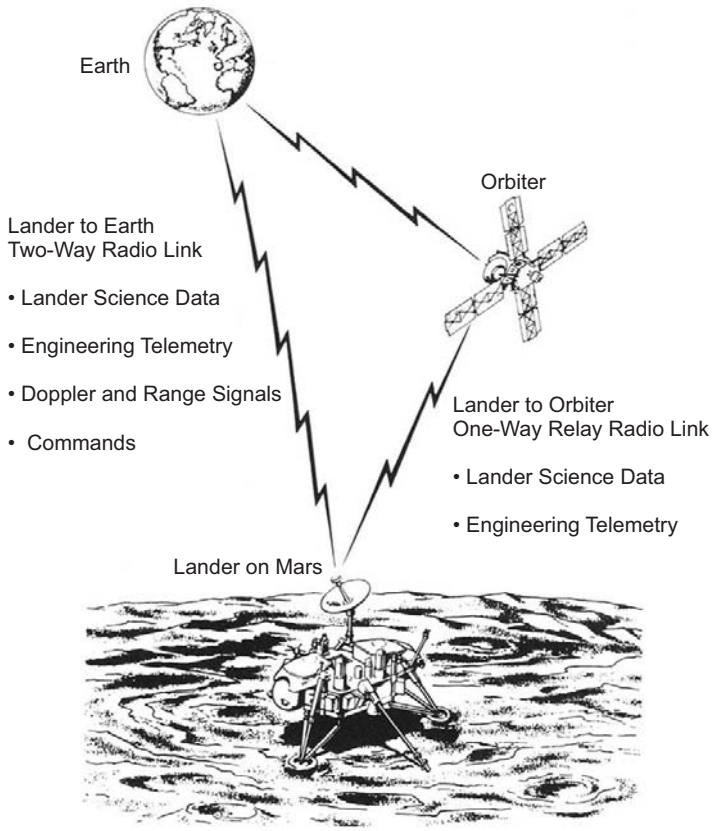


Fig. 4-7. Viking–Earth–Orbiter–Lander communication links.

phenomenon and its impact on the antenna design is discussed in more detail in Section 4.3.2. In order to mitigate the occurrence of the ionization for the Viking UHF antennas, the radiating elements have their ends rounded. This avoidance of sharp points in the presence of electric fields is a well-known approach to avoid coronal ionization in high voltage systems and other applications. At the low Martian pressures, the use of large radii may not be enough. As seen in Fig. 4-8, the radiating elements are also covered with foam-filled end caps. The figure shows one of the end caps removed revealing the high-radius radiating elements. The addition of the foam-filled cap provided further minimization of the corona potential. This is discussed further in Section 4.3.2.

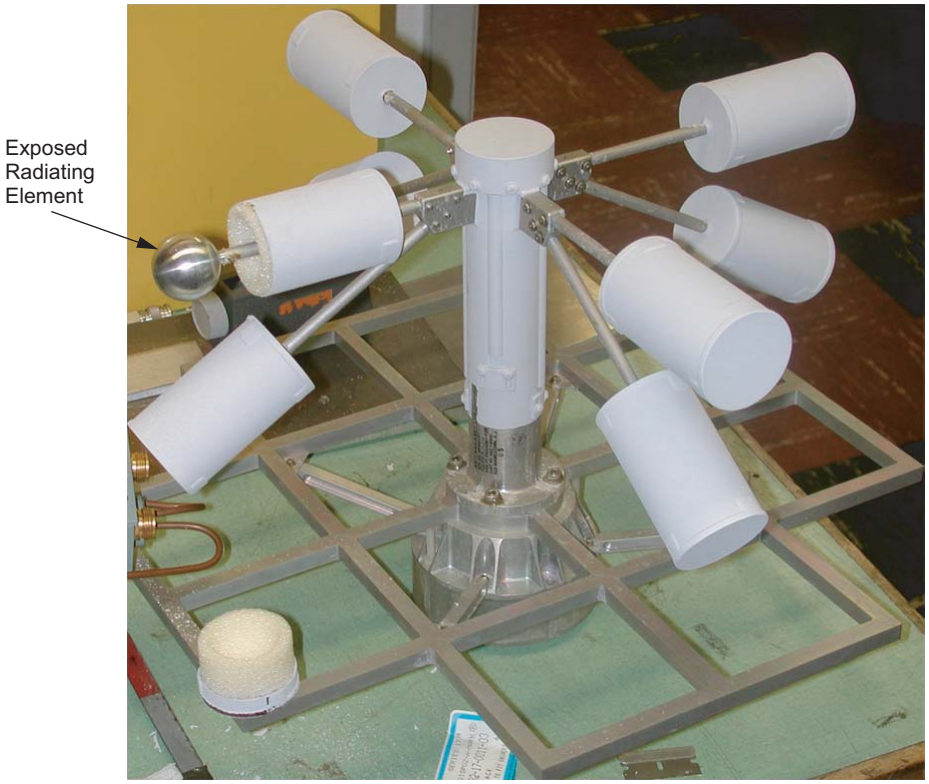


Fig. 4-8. Viking lander UHF "turnstile" antenna.

4.2.5 Mars Observer

After an absence of nearly 20 years from the Martian scene, on September 25, 1992, the U.S. launched the Mars Observer (MO). This began a concerted effort to thoroughly explore the red planet and gather information about, water, potential life, and the building blocks for a possible manned mission. The MO spacecraft, unfortunately, was lost (probably due to a thruster malfunction) just prior to Mars orbit insertion [16]. While this was a great disappointment, it was followed four years later by the very successful Mars Global Surveyor and the Mars Pathfinder lander/rover missions.

The MO orbiter (see Fig. 4-9) used a mechanically articulated X-band 1.5-m HGA on a 5.5-m long boom [17]. It also used a choked circular X-band waveguide LGA. This was the first NASA spacecraft in a long series to follow which employed the choked circular waveguide LGA. One set of variations of this design is detailed in Section 4.3.1. The spacecraft also employed a long UHF helix antenna that was to be used as a communications link to a Russian

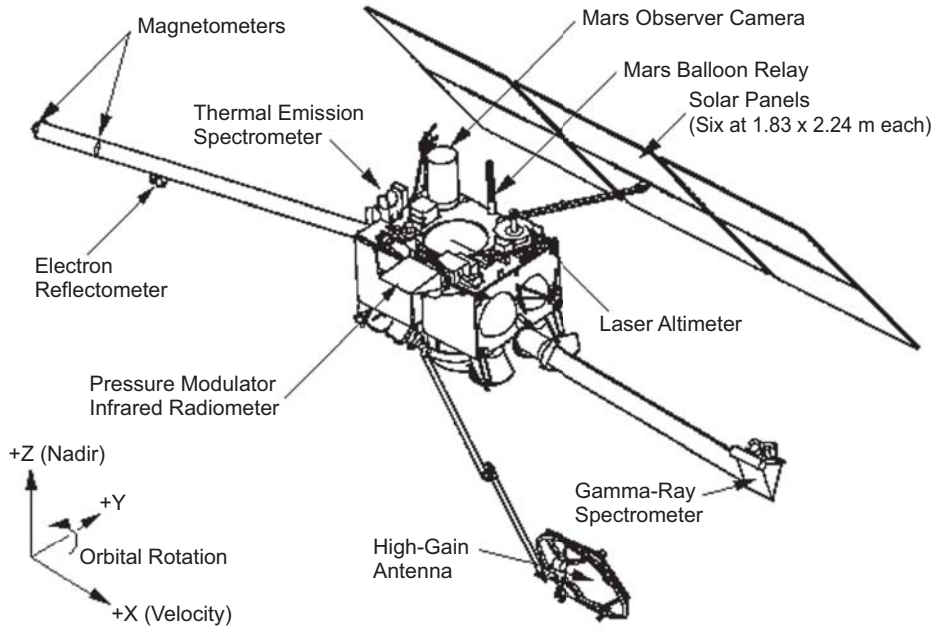


Fig. 4-9. Mars Observer spacecraft diagram.

surface balloon experiment (Mars Balloon Relay) that was to arrive in 1994. The Russian mission never materialized.

As can be seen, this next generation of spacecraft had switched from S-band as the primary link frequency to X-band. This evolution began with the twin Voyager spacecraft and continued on through the end of the 20th Century. The wider bandwidths and other features made this frequency band an obvious choice over the S-band frequencies. In addition to using the X-band frequencies for the primary link to Earth, the MO spacecraft was set to begin a push to an even higher frequency/wider bandwidth links. The MO HGA had a set of Cassegrain optics, which employed a special purpose subreflector (see Fig. 4-10). The backside of the HGA subreflector was itself a prime focal-fed reflector. A Ka-band feed was mounted out at the focal point of this small reflector, facilitating an “experimental” Ka-band link. This experiment was to provide information to radio scientists and telecommunications engineers that would lead to the possible evolution from X-band to Ka-band telecom [18].

4.2.6 Mars Global Surveyor

As a continuation of the mission to Mars, the Mars Global Surveyor (MGS) [19] yielded a wealth of data. It also was to serve as a UHF relay for Mars surface missions that were planned by the Europeans and others. Those surface

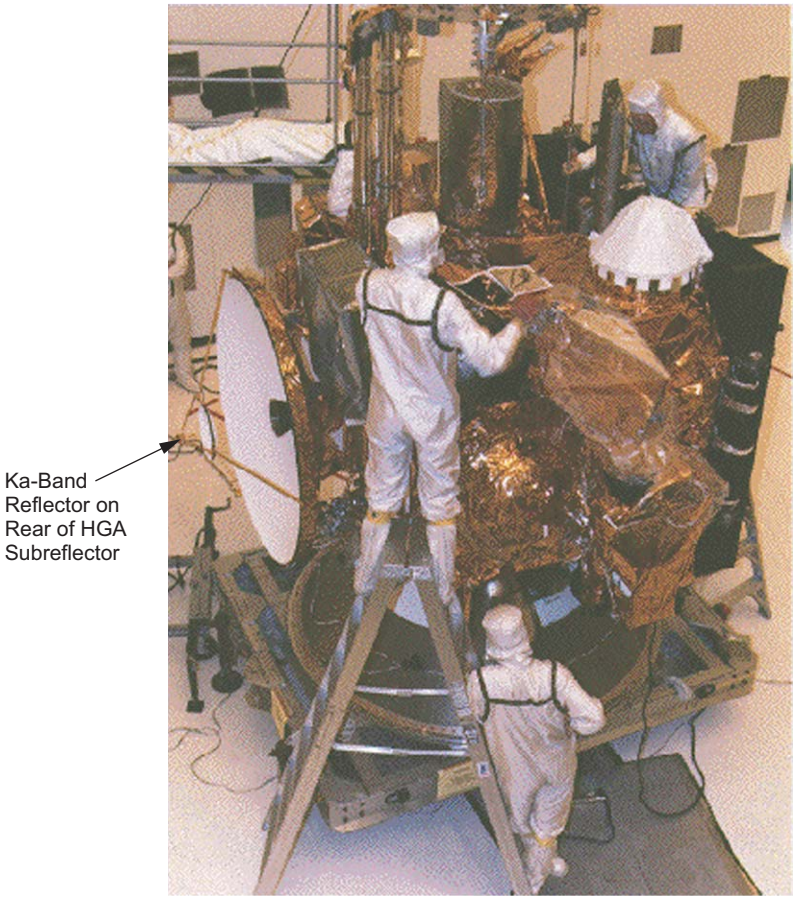


Fig. 4-10. Mars Observer spacecraft during assembly and checkout.

missions never materialized; however, due to the longevity of the spacecraft, this UHF link was used (in concert with Mars Odyssey) to support communications with the twin Mars Exploration Rovers (Section 4.3.2).

The MGS spacecraft design borrowed many features of the MO spacecraft [20]. In fact, this mission was in some ways a replacement of the MO mission. The craft uses the same UHF surface link helix antenna. It also uses the MO HGA design (Fig. 4-11) except that it employs a germanium Kapton radome over its aperture whereas the MO HGA had no radome. The MGS HGA does not utilize the dual-purpose subreflector (the back side of the subreflector could be used as a small prime focal-fed reflector) for a Ka-band link, instead, the telecommunications engineers decided to implement a Ka-band link "experiment" using a dual-band feed at the Cassegrain antenna feed point. This Ka-band link would thus take full advantage of the HGA aperture. The dual-

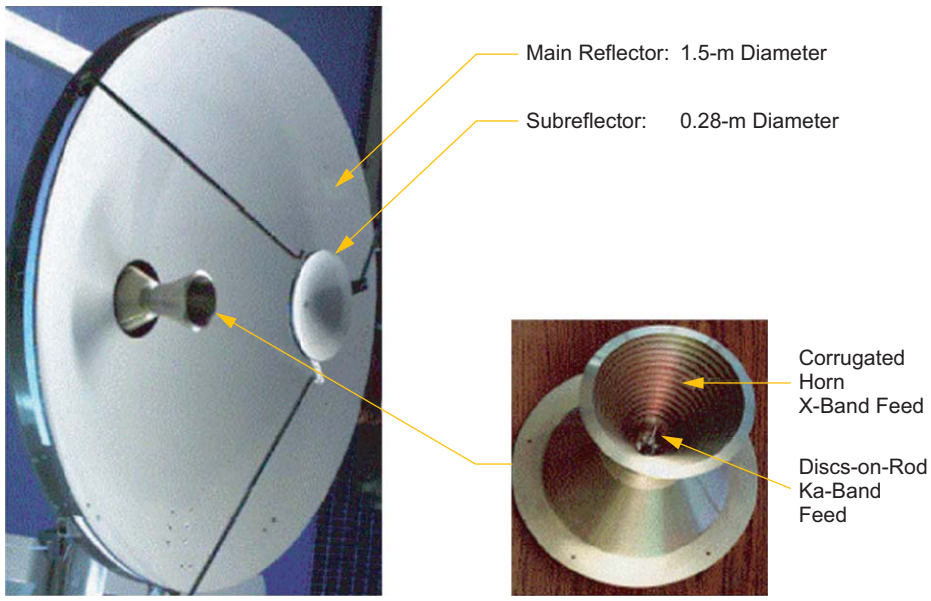


Fig. 4-11. Mars Global Surveyor HGA.

band feed incorporated a coaxial fed X-band corrugated horn and a disc-on-rod Ka-band feed down the center of the X-band horn (a detailed description of a very similar dual-band feed for the Mars Reconnaissance Orbiter mission is shown in Section 4.4).

One other difference between the MGS and the MO spacecraft antenna complement is that MGS employs a set of microstrip patch LGAs (two receive LGAs and two transmit LGAs) in place of the choked circular waveguide design (see Fig. 4-12). Each LGA has a boresight gain of about 6.5 dBi (X-band uplink and downlink) and a half-power beamwidth of about ±40 deg. The LGAs include a pair of circularly polarized microstrip path antennas, tuned to 8.4 GHz (transmit) and tuned to 7.1 GHz (receive). The circular polarization was achieved by using a 3-dB hybrid and feeding the patches at orthogonal feed points [20].

The MGS spacecraft uses a 25-W traveling wave tube amplifier (TWTA), which is mounted in a module on the back of the HGA, in order to minimize RF loss and to reduce power requirements. This approach to minimizing RF path losses became a model for all the future orbiters described in this chapter. The Ka-band experiment utilized a 1-W amplifier for this link.

4.2.7 Mars Climate Orbiter

The Mars Climate Orbiter (MCO) together with the Mars Polar Lander (MPL) had the objective of studying the Martian climate history [21].

Fig. 4-12. LGAs used on the Mars Global Surveyor spacecraft.

Unfortunately, this spacecraft was lost when it crashed into the planet due to an error in unit conversions in the navigation software.

The MCO (see Fig. 4-13) used a 1.3-m HGA with a 15-W solid-state power amplifier (SSPA) mounted at the back of the two-axis gimbaled reflector, a transmit-only medium-gain antenna (MGA), and one receive-only LGA. The orbiter also was to serve as the primary link for the MPL via a helix antenna driven by a 10-W UHF radio.

The MGA was a square flared horn mounted to the prime-focal fed HGA through a hole in its aperture approximately two-thirds of the way out from the center of the reflector.

4.2.8 Mars Polar Lander

The Mars Polar Lander (MPL) was to work in conjunction with the Mars Climate Orbiter in an effort to explore the climate history of Mars [22]. In a spate of bad luck, this lander mission also met with an unfortunate fate. The lander successfully reached Mars and entered the atmosphere for a rocket-controlled soft landing. It is thought that a software error caused the lander's rocket engines to turn off too soon, dropping the craft from a large height.

The MPL utilized a fixed X-band medium-gain antenna to communicate with the Earth during the cruise phase. During the surface operations, the lander was to communicate via a UHF link between the Mars Climate Orbiter and/or the MGS. As a backup to the UHF link, a direct-to-Earth (DTE) link via an articulated X-band MGA could also be used.

In addition to the lander functions, the MPL carried two micro-probes called Deep Space 2 (see Fig. 4-14). These microprobes were to eject from the

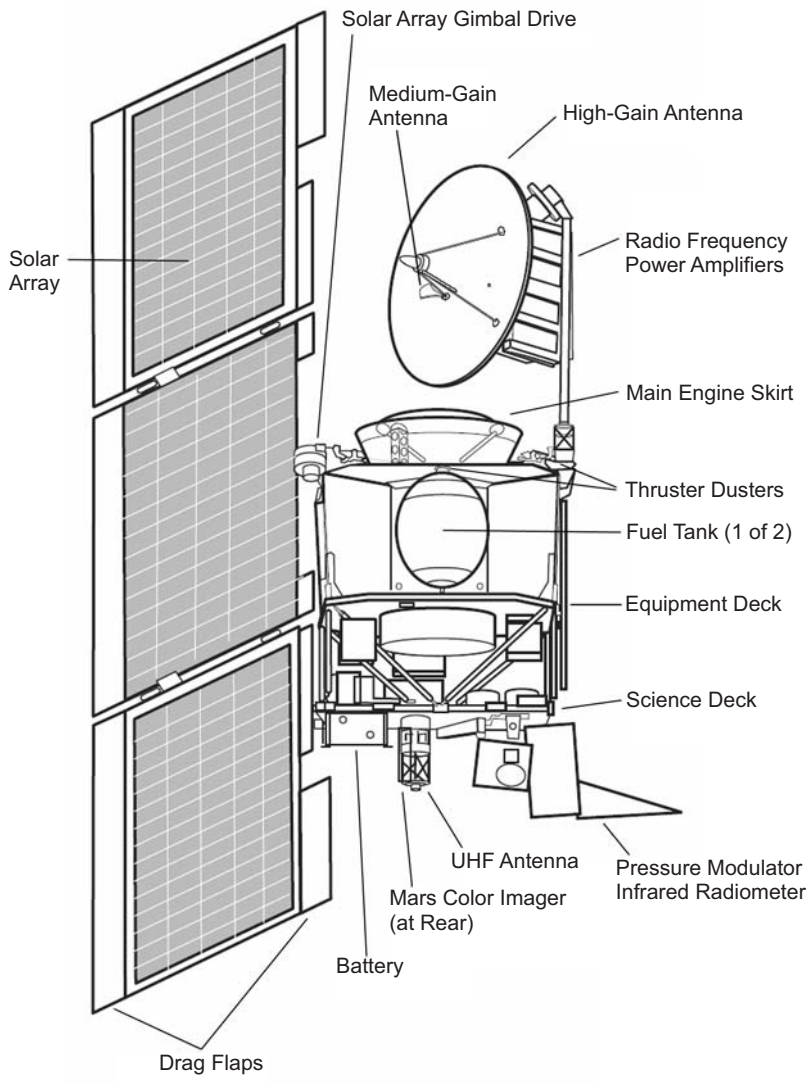


Fig. 4-13. Mars Climate Orbiter spacecraft.

orbiter and be shot into the Mars surface as penetrators. The microprobes each had a small UHF radio with a monopole antenna, and they were to relay their data back through the UHF system on the orbiting MPL spacecraft [23].

4.2.9 Mars Odyssey

The Mars Odyssey spacecraft (launched April 7, 2001) has continued the detailed exploration of Mars with the specific objectives of mapping chemical elements and minerals on the surface of Mars, looking for water in the shallow

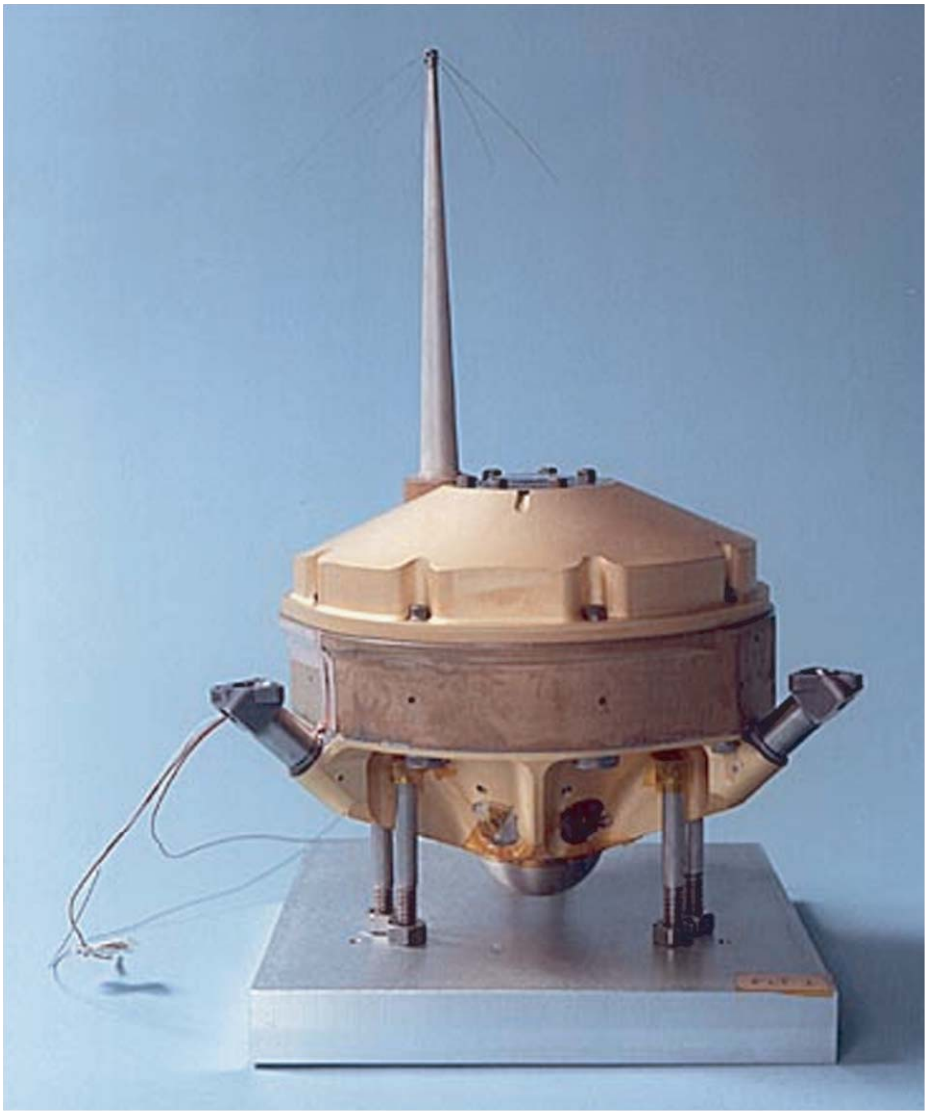


Fig. 4-14. Deep Space 2 microprobe—UHF antenna matched using top-loading "whiskers" [26].

subsurface, and analyzing the radiation environment to determine its potential effects on human health [24]. The spacecraft design followed many of the characteristics that began with and continued on from the Mars Observer spacecraft [25].

The Mars Odyssey telecommunications package is quite similar to the MGS and MCO spacecraft. It consists of a boom-mounted HGA with an MGA

mounted within its reflector aperture (like the Mars Climate Orbiter). It also has a four-arm quadrafiler helix UHF antenna (Fig. 4-15) for communications with any surface vehicles that may arrive during its tenure. The height of the antenna is 26.7 cm, and the diameter is 16.5 cm. Odyssey is one of the primary relay links for the Mars Exploration Rovers.

4.3 Mars Rovers

This section provides a detailed description of antennas used on the Mars rovers, the Mars Pathfinder, and the twin Mars Exploration Rovers (Spirit and Opportunity). It includes antenna design information as well as special considerations and constraints applied to the designs.

4.3.1 Mars Pathfinder

The Mars Pathfinder mission represented the first U.S. attempt to return to the surface of Mars since the 1975 Viking Missions [26]. This mission was considered to be highly successful, and it generated an excitement about the

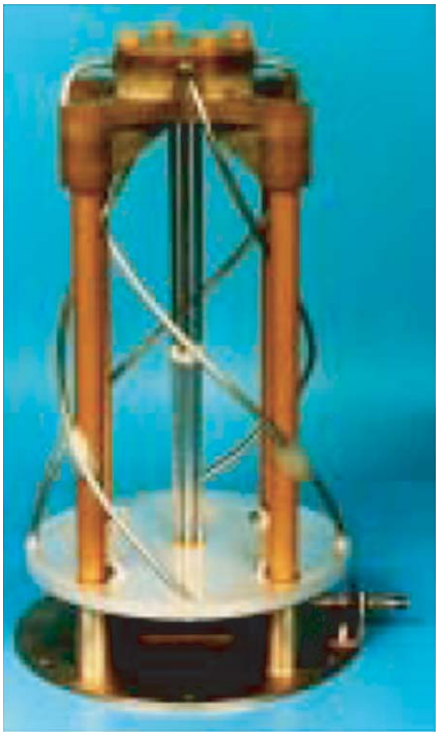
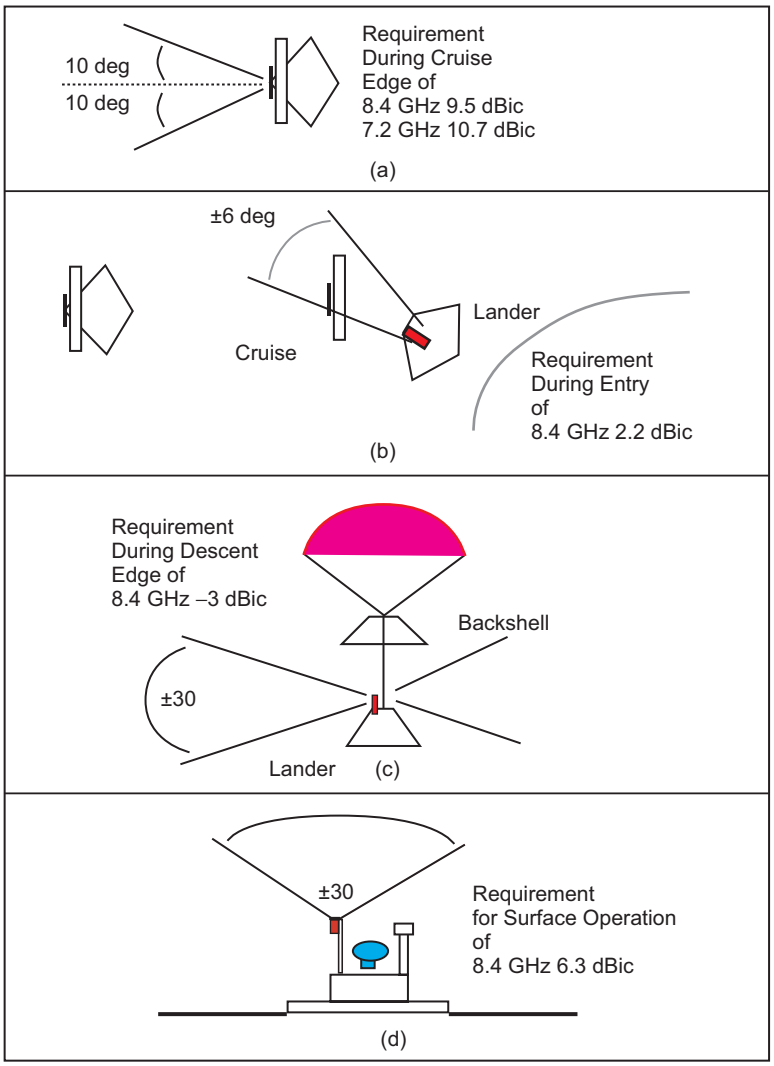


Fig. 4-15. Mars Odyssey four-arm quadrafiler helix UHF antenna.

space program and Mars the likes of which had not been seen since the first Apollo missions. The Pathfinder mission was a product of a paradigm shift in the U.S. unmanned exploration program in that it sought to develop the spacecraft lander in a more cost-effective manner. Under this new approach, some of the formal approaches to space flight hardware development and production were relaxed. An emphasis was placed on a close-knit team effort that employed old and new ideas to address the very challenging task of landing a small rover, called Sojourner, onto the surface. The resulting approach was a unique and highly integrated spacecraft architecture and a novel method of entry, descent, and landing. The integrated approach had a rather dramatic effect on the antenna assembly. With a goal of maintaining communications with the Earth throughout all phases of cruise, Mars entry, descent, and landing, a novel "antenna stack" design was developed [27]. The following subsections provide a detailed examination of the Mars Pathfinder antennas used throughout the mission.

4.3.1.1 Mars Pathfinder Communications During Cruise, Entry, Descent, and Landing. With the objectives of high reliability, high performance, low mass, and low cost, the spacecraft antenna subsystem enabled the Mars Pathfinder spacecraft to transition through four configuration changes en route to its landing site—using only one switch and no pyrotechnic events while maintaining constant telemetry. Continuous telemetry, an important mission goal, provided all possible engineering data, including failures, for use as proof of spacecraft design.

The four mission phases are shown in Fig. 4-16, along with the associated gains and edge of coverage requirements. As seen in Fig. 4-16(a), the first portion of the mission employed an MGA during the spacecraft's cruise to Mars. The radiating aperture of this antenna consisted of a simple flared aluminum conical horn, which achieved a 13.1 decibels referenced to a circularly polarized, theoretical isotropic radiator (dBic) 10-deg edge of coverage RHCP gain at its downlink frequency of 8.4 GHz and 10.8-dBic 10-deg edge-of-coverage RHCP gain at the uplink frequency of 7.2 GHz. In order to accommodate launch vehicle interface requirements, the antenna was flush mounted to the spacecraft cruise stage. The antenna geometry was adjusted so that the side lobe region of the pattern maintained a relatively flat 30-dB floor (with no nulls) so that spacecraft maneuvers during cruise could be made without loss of signal. This antenna performance was validated using a full-scale mockup of the spacecraft cruise stage. Unfortunately, as the cruise stage design progressed a launch adaptor ring, which raised the edge of the cruise stage ring 1 to 2 in. (2.5–5.0 cm), was added to the spacecraft. This design change was not captured in the cruise stage mockup.



(a) Cruise from Earth to Mars; used MGA located on cruise stage.
(b) Entry; after cruise stage ejection before lander/backshell separation; used LGA located in backshell.
(c) Descent; after backshell separation through landing; used descent antenna located on top of lander petal.
(d) Surface operation; initial downlink of entry, descent, and landing telemetry and emergency communications; used lander LGA.

Fig. 4-16. Mars Pathfinder requirements vs. mission phase [28].

This ring caused an obstruction of the MGA pattern over a small azimutal angle in the pattern. Since the spacecraft was spun at a few revolutions per minute during cruise, there was a periodic drop out of the signal during flight.

While there was an operational work-around for this difficulty, this provides a good example of the risks associated with highly integrated spacecraft whose antennas are placed in close proximity to spacecraft structure.

Upon reaching the planet (July 4, 1997), the cruise stage and MGA were jettisoned; exposing the backshell LGA, and a choked circular waveguide horn antenna, which up to this point functioned as waveguide feeding the MGA (see Fig. 4-17). It had a broad field of view with a ±6-deg edge of coverage and an RHCP gain of 6.3 dBic at 8.4 GHz, and it only functioned to transmit data back to Earth. The unique feature of this waveguide/antenna was that it employed innovative self-aligning slip-fit waveguide interfaces, allowing passive transitions during the stage separations. Cruise stage separation marked the beginning of the entry phase of the mission (Fig. 4-16(b). Although the Martian

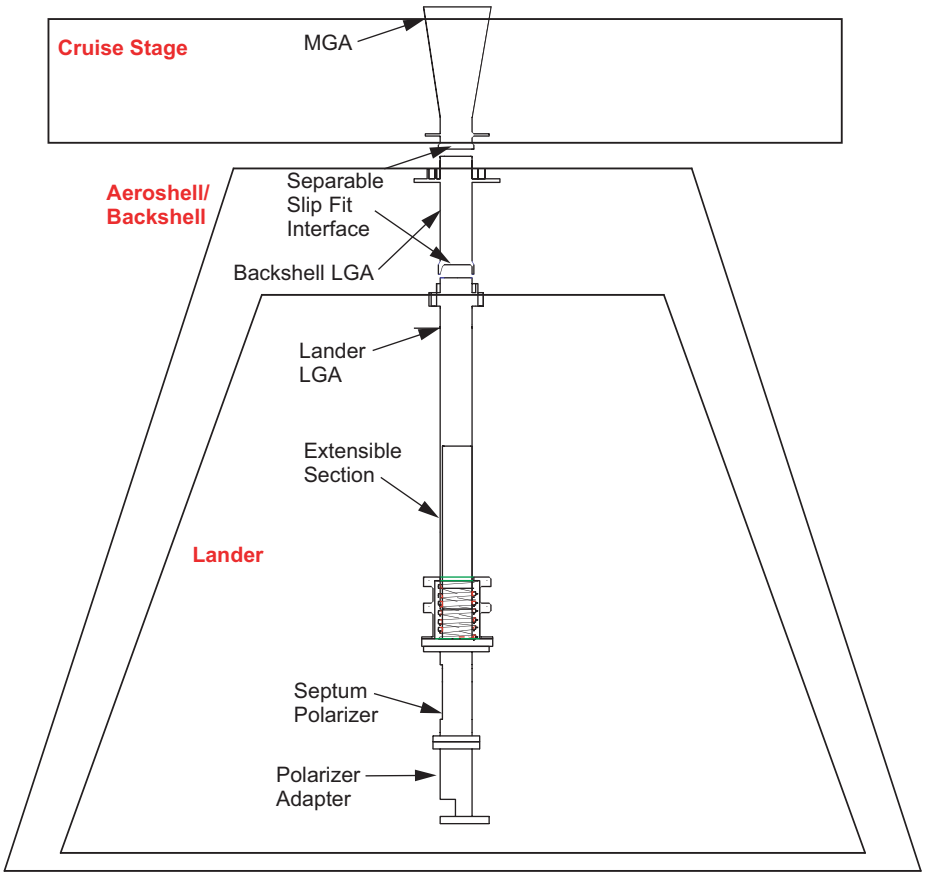


Fig. 4-17. Exploded view of Mars Pathfinder antenna assembly including lander LGA, backshell LGA, and MGA. The MGA was mounted to the cruise stage and was ejected with the cruise stage; the backshell LGA was mounted to the aeroshell/backshell; it separated from the lander LGA when the lander dropped away from the backshell.

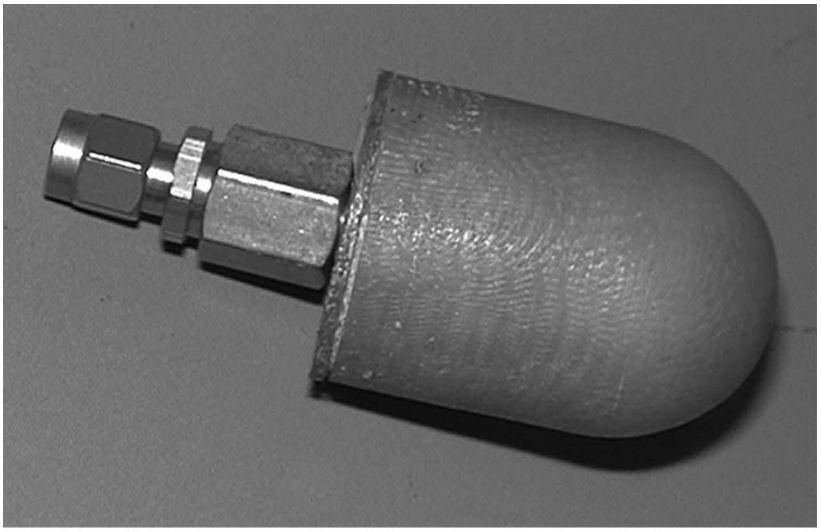
atmosphere is very thin, it still causes significant friction and generates very high surface temperatures on the entry vehicle. The spacecraft was protected by an ablating thermal tile heat shield. In order to protect the antenna and the open transmission line, ceramic-coated Lockheed HTP-6 shuttle tile was employed. A radome/plug prevented the superheated gas from flowing through and down the waveguide assembly. Additional tile material was placed over the choke rings. Since an annular interface region between the backshell LGA and the MGA was left exposed, and the superheated gas stream approached temperatures of 2000 deg F (1366 K, above the melting point of aluminum), the backshell LGA material was chosen to be beryllium copper, a high-temperature metal with excellent RF properties. Arcjet tests at NASA's Ames Research Center verified that this combination of beryllium copper and shuttle tile provide adequate thermal isolation.

Following the ballistic entry, the spacecraft deployed a descent parachute that reduced the spacecraft speed and altered the Earth probe angle, as shown in Fig. 4-16(c). Once the parachute was deployed, the bottom of the heat shield was ejected, and the lander was lowered via a tether from the backshell, separating the backshell LGA from the lander LGA. The backshell-LGA-to-Lander-LGA interface employed a slip fit similar to the MGA-to-backshell-LGA interface. Originally, it was hoped that descent communications could be achieved through the Lander LGA, a choked circular waveguide horn, but the required coverage region in conjunction with overwhelming spacecraft blockage made this unfeasible. As the spacecraft descended, it spun on the tether and swung in a pendulum-like motion. This, in addition to the Earth's location at the horizon, gave rise to the requirement for an antenna with a torroidal pattern whose coverage extended ±30 deg. This descent antenna (DEA) (see Fig. 4-18) was accessed by switching via a waveguide transfer switch just prior to parachute deployment. The DEA consisted of a simple X-band disc-cone wire antenna. The antenna was fabricated from a 0.25-in. (0.635-cm) diameter semi-rigid cable with its center conductor exposed approximately ¼ of a wave length. A small conical skirt was used as a "ground plane," and a top-loading disc at the end of the exposed center conductor was used for matching. The antenna used a thimble-shaped Astroquartz radome. The antenna assembly was mounted on a small spring-loaded mast, which popped up after the backshell aeroshell ejected.

During operations it was found that the descent antennas provided marginal link returning data in a sporadic fashion. In particular, during the high-temperature entry, an unexpected blackout occurred. It is speculated that this may have been caused by plasma effects.

At the appropriate altitude, retro-rockets fired to bring the probe to a complete stop many meters above the surface. The tether was released, dropping the lander, which deployed an array of large airbags to cushion the impact of landing. After the lander was grounded, the airbags deflated and

(a)



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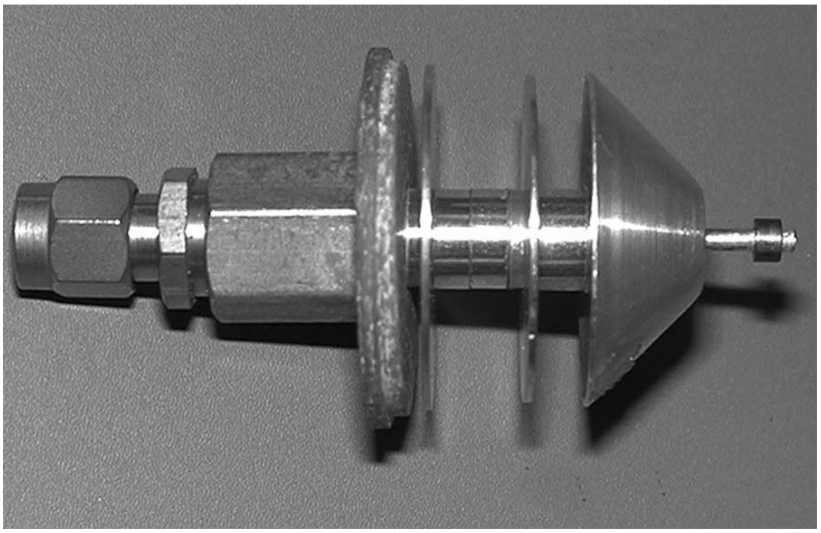


Fig. 4-18. Mars Pathfinder descent antenna (DEA): (a) with radome and (b) with radome removed.

retracted, and the pyramid-shaped lander, composed of a base and three petals, opened (Fig. 4-16(d)). The action of the opening petals served to right the lander, regardless of which side it would have landed.

After the lander came to a roll stop and prior to opening the lander, signals were sent back to Earth via the small descent antenna. It was not certain whether the lander would crush this antenna due to impacts from bouncing on the airbags. Further, there was no guarantee that the lander would come to a

stop in an upright position; the DEA was located atop the lander petals, so there was a 1-in-3 chance it would have been broadcasting into the ground. (Actually the center of gravity of the lander skewed the odds to better than 1-in-3 toward causing it to roll into its upright position.) However, almost on cue, a set of tones was received from the tiny antenna shortly after it was estimated that it should have come to rest on the surface.

4.3.1.2 Communications Link Between Lander and Earth. Once upright, the opened lander revealed the LGA, a two-axis gimbaled HGA, a camera on a deployable mast, a small robotic rover, and a number of other instruments (see Fig. 4-19). The lander LGA was then used to download a replay of the sequence of events that occurred during the entry and descent in the event that the real-time communications had been interrupted. Following this transmission, the antenna subsystem was switched to the actuated HGA array (a printed dipole array). The HGA consisted of an array of printed dipoles, which was used for all major direct-to-Earth communications. The Lander LGA was

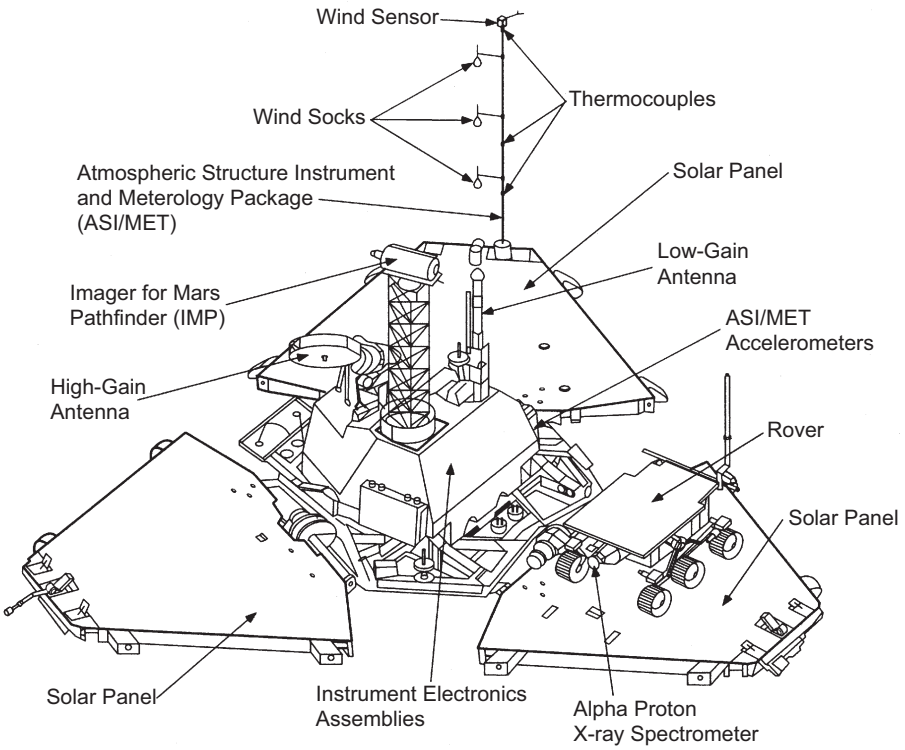


Fig. 4-19. Mars Pathfinder lander in its deployed (opened) configuration.

used periodically throughout the mission to relay commands and telemetry. Its broad-beam LGA pattern (7-dBiC boresight gain with an approximately ±40-deg 3-dB beamwidth) made it useful during periods when the HGA could not be actuated into view of Earth.

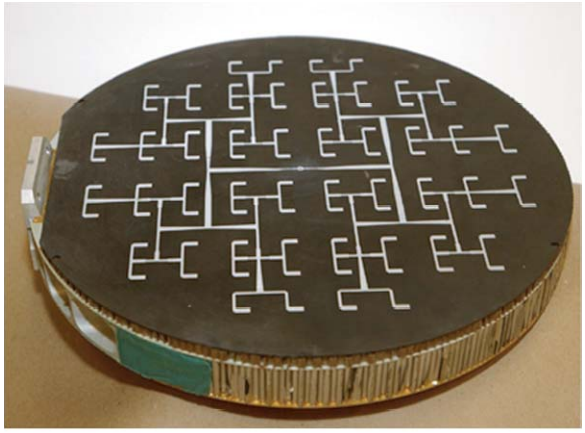
The lander LGA functioned as the transmission line feeding the 17-W signal from the warm electronics box (WEB) mounted X-band SSPA to the backshell LGA and MGA. This dual transmission line/antenna feature made it an innovative and challenging design. Large launch and entry displacements between the backshell and the lander (the two items it connects) made use of a single rigid waveguide impossible. Other constraints made flexible waveguide or coaxial cable impractical. However, by constructing two sections of circular waveguide of different diameters, a tube-within-a-tube extensible waveguide was formed. The two sections, connected with a compression spring contained by a cylindrical spring retainer (Fig. 4-17), allowed the waveguide to shorten and lengthen.

Mechanical/electrical discontinuities throughout the antenna subsystem were among the many engineering challenges of this antenna system design. Some sources of these discontinuities included two diameter steps in the waveguide, one at the interface between the polarizer and the first tube of the extensible waveguide section, and the other at the interface between the two tubes of the extensible waveguide section. A linear taper was used to counter the effects of the second of these waveguide steps. Another source of discontinuity was interactions with and between the pair of ceramic radomes used in the lander and backshell LGAs. It was necessary to adjust the thickness of these radomes to prevent filtering effects at the operating frequencies.

The HGA was used for the majority of the data transfer between the lander and the Earth. This antenna was designed and manufactured by Ball Aerospace and Technologies Corporation. It consisted of an array of printed dipoles mounted over a ground plane (separated by a Nomex honeycomb layer) (see Fig. 4-20). It also made use of a set of printed meander-line polarizers to achieve the required circular polarization. The polarizers were layered atop the printed dipoles and were separated by a Nomex honeycomb layer. Due to the resonant nature of the dipole elements, this antenna functioned best over a transmit frequency band (8.4 GHz) with a better than 1.2:1 voltage standing wave ratio (VSWR) but provided acceptable performance at the receive frequency band (7.1 GHz) achieving better than 2.4:1 VSWR. The antenna transmit and receive gains were 24.5 dBic and 20.6 dBic, respectively.

4.3.1.3 Communications Link Between Rover and Lander. The microrover telecommunications system used a two-way UHF radio link between the lander and the rover. The microrover radio had a signal range similar to a walkie-talkie. The telecommunications system was composed of two UHF radios and two UHF whip antennas. The microrover radio was located inside the Rover

(a)



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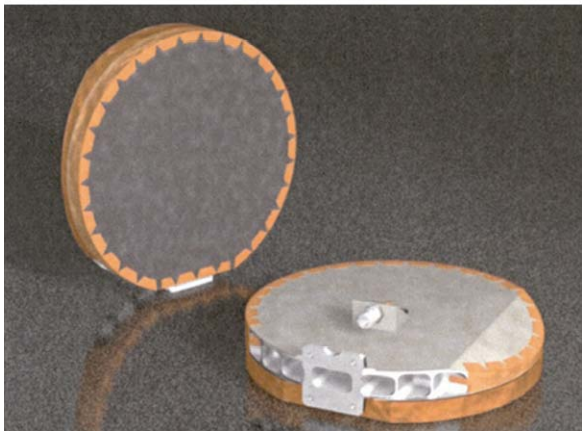


Fig. 4-20. Mars Pathfinder HGA (same design used for MER) designed and fabricated by Ball Aerospace: (a) dipole array exposed prior to installation of the meanderline polarizer layer and (b) final product.

WEB where it was protected from the extreme cold of the Martian environment. The radio was connected to the microrover antenna using a short piece of coaxial cable that passed through the wall of the WEB (see Fig. 4-21). Table 4-2 provides a list of specifications for the lander UHF antenna.

The antenna patterns of Fig. 4-22 were taken on the JPL Mesa Antenna Range using a static lander model. A flight-like lander-mounted rover equipment (LMRE) antenna was mounted to the LGA (mast and placed a height of 83 cm from the ground. A radio modem operating in continuous wave (CW) mode was used to transmit a 459.7-MHz, 100-mW signal from the LMRE antenna to a receiving antenna attached to a spectrum-analyzer receiver.

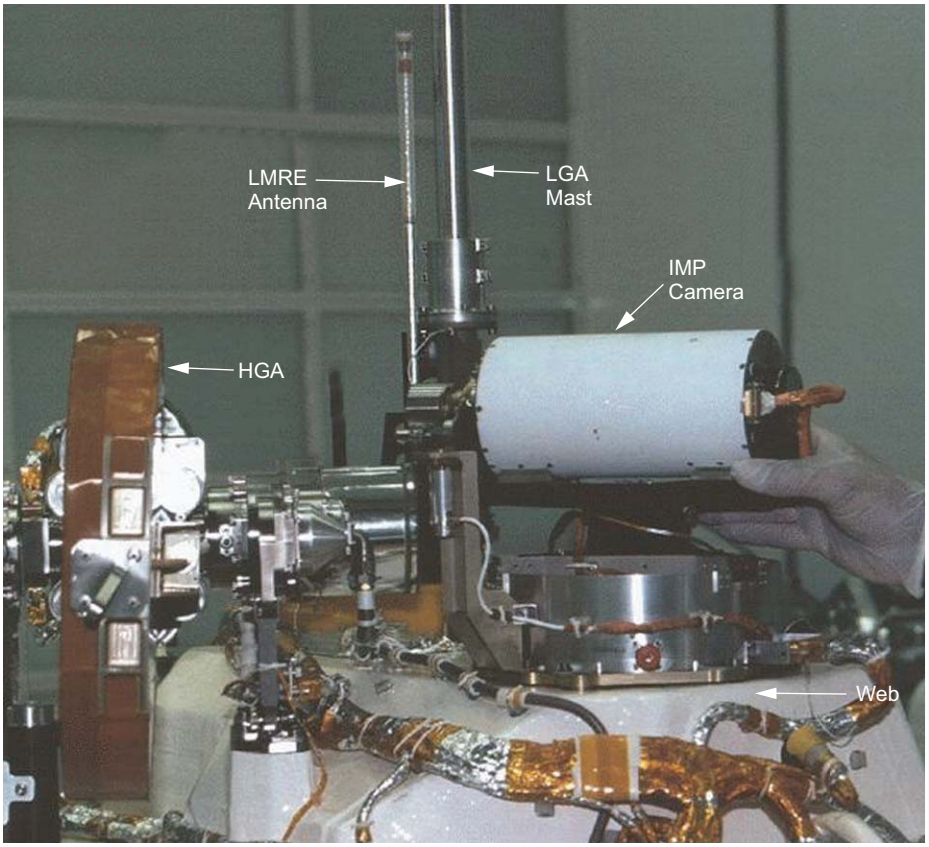


Fig. 4-21. Mars Pathfinder LMRE antenna atop the warm electronics box (WEB) mounted to the lander LGA [31].

The receive antenna was a flight-like rover antenna set to a height of 80 cm and connected to the receiver via a coaxial cable. The antenna pattern taken at a distance of 3 m looks quite irregular. In particular, at 10 deg and 330 deg, there are noticeable null zones. This is due primarily to scattering and out-of-phase reflections of the RF energy from the metallic components (e.g., LGA, HGA, Imager for Mars Pathfinder (IMP) mast, and solar panels) of the lander structure. Farther away, beyond 5 m, the LMRE antenna is away from this near-field scattering, and the shape of the antenna's radiation pattern becomes better defined.

The Pathfinder rover antenna (see Fig. 4-23) specifications are provided in Table 4-3. The rover antenna radiation patterns of Fig. 4-24 were taken on the JPL Mesa Antenna Range using a static model rover. A flight-like rover antenna was mounted to the rover mast and placed a height of 83 cm from the ground. A radio modem operating in CW mode was used to transmit a

Table 4-2. Mars Pathfinder lander LMRE UHF antenna specifications.

Parameter	Value
Overall length	33.6 cm
RF: connector type	Coaxial SMA
RF center frequency	459.7 MHz
RF bandwidth	16 MHz for <2:1 VSWR
RF gain	1.4 dBi-vertical polarization
Free space match	1.25:1 VSWR at center frequency
Materials	Fiberglass tube, aluminum tube, Teflon supports

459.7-MHz, 100-mW signal from the rover to a receiving antenna attached to a spectrum analyzer receiver. The receive antenna was a flight-like LMRE antenna mounted to the receiver at a height of 80 cm. The antenna pattern taken at a distance of 2 m looks quite irregular. This is due to near-field distortion and scattering of the RF energy. Farther away, beyond 3 m, the rover antenna is in the far field, and the true shape of the Rover antenna's radiation pattern becomes more visible.

4.3.2 Mars Exploration Rovers

The Mars Exploration Rover (MER) mission consists of a twin set of rovers (Spirit and Opportunity) [28]. These rovers were intended to be an incremental evolution of the Mars Pathfinder design. The key difference between the two spacecraft/rover designs is that whereas the Mars Pathfinder configuration consisted of a small rover and a stationary lander/base station, which hosts most of the mission instruments and the telecommunications equipment, the MER configuration uses a single large rover which carries all the instruments and telecommunications equipment. The lander is merely a shell used to carry the rover to the ground. One spacecraft design objective for the MER mission was to employ as much heritage from Mars Pathfinder as possible. As a result, the antenna assembly looks very much like the Pathfinder design. The “antenna stack” approach was once again employed; the same HGA design was used. There were some variations, which are discussed in the following subsections.

4.3.2.1 Cruise Stage Antennas. Whereas the Pathfinder program used a single low-medium gain antenna to facilitate the link back to Earth during cruise, the MER mission required a higher gain to provide sufficient link margin, particularly when the two craft approached Mars. This led to a high-medium gain antenna design. In order to satisfy the need for a broad-beam antenna for wide-angle applications (such as emergency situations), an LGA was also

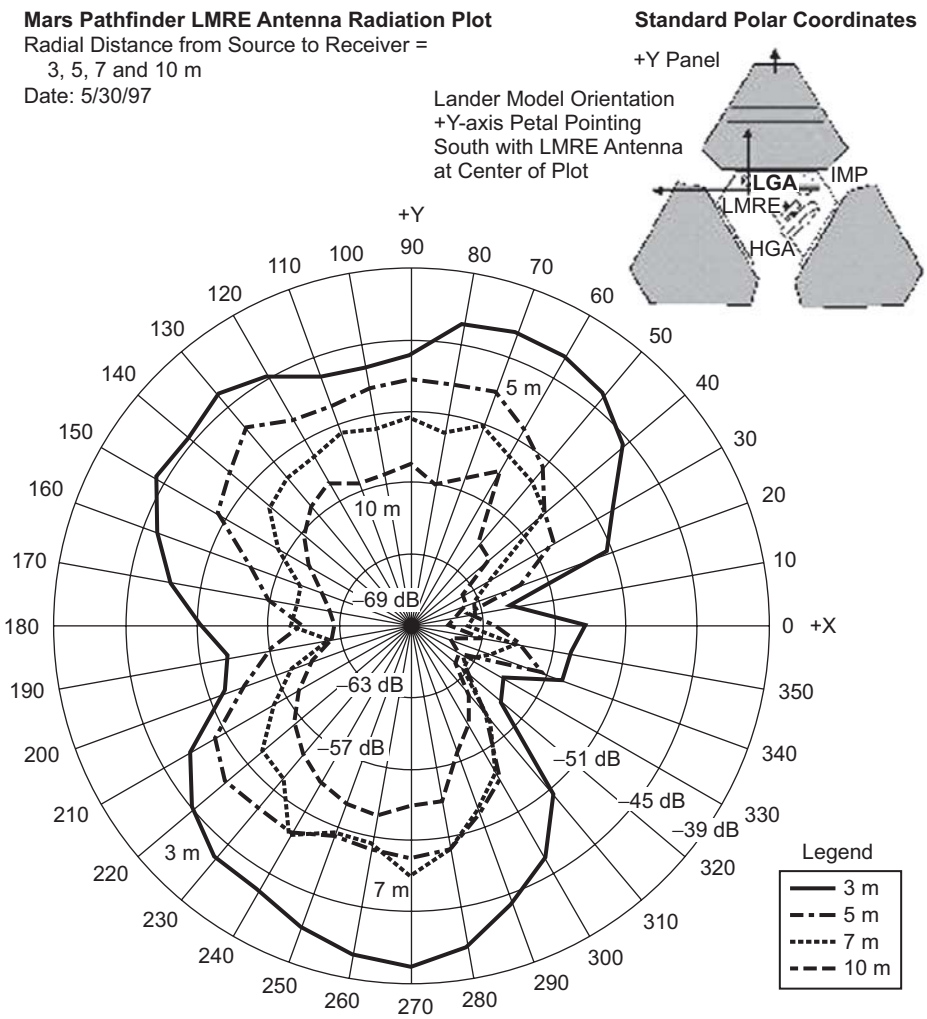


Fig. 4-22. Mars Pathfinder LMRE antenna pattern measurements [32].

added. Figure 4-25 shows the MGA and LGA mounted on the cruise-stage mockup.

The MGA consists of a simple smooth wall conical horn with an aperture that produces approximately 19 dBic at the transmit frequency of 8.439 GHz (18 dBic at the receive frequency of 7.181 GHz). The antenna is in series with a hybrid septum polarizer designed and manufactured by Atlantic Microwave Inc. to achieve the required LHCP. This polarizer design was used on several previous JPL missions (including on the Mars Pathfinder spacecraft) at the bottom of the antenna stack (see Fig. 4-17). This hybrid polarizer also provides access to a RHCP feed port. While this was not used during flight, this port was

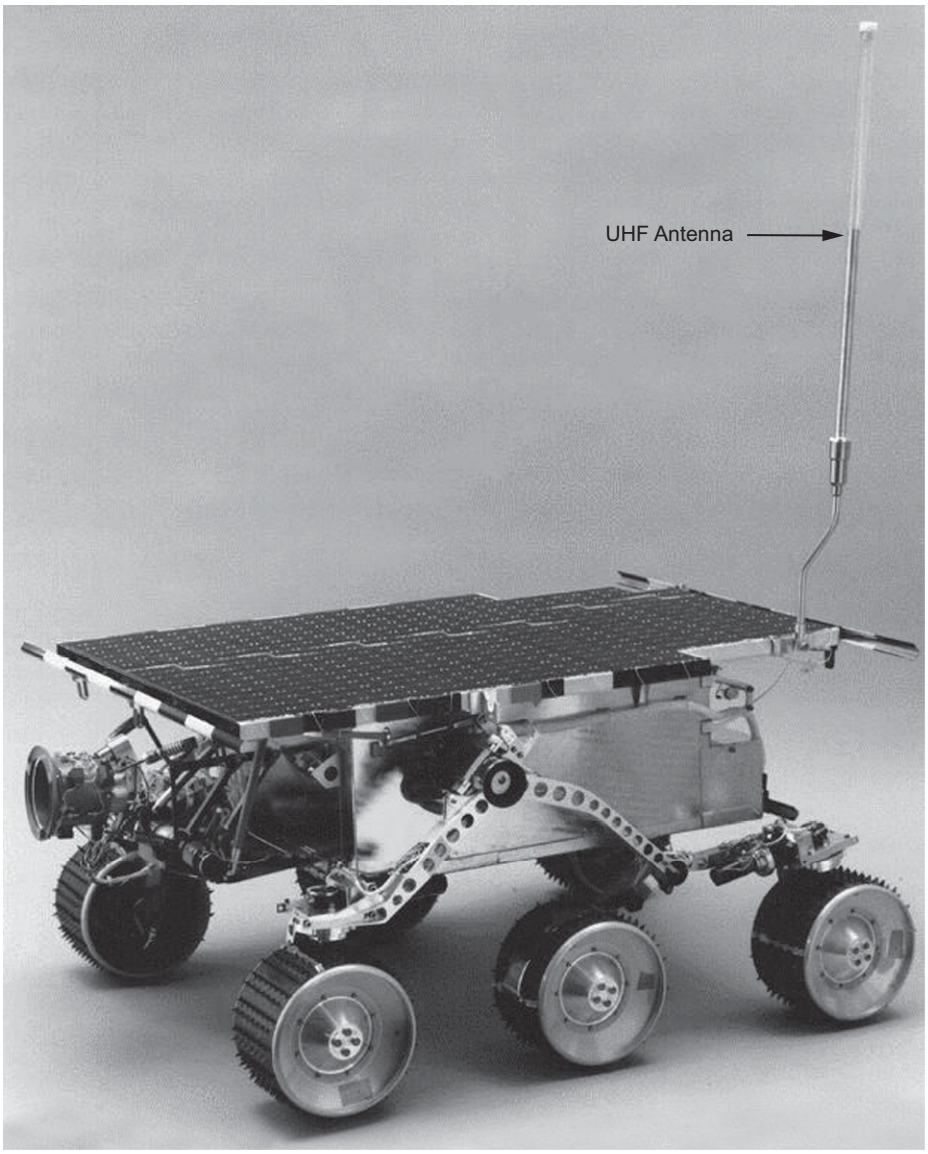


Fig. 4-23. Mars Pathfinder rover (Sojourner) with its UHF antenna deployed.

used as a handy test port. Placing a short over the antenna aperture reflected the incident left hand polarized signal back to the polarizer. The then right-hand polarized reflected signal was routed to the right-hand-circular-polarized test port on the polarizer.

This antenna was mounted near the outer diameter of the cruise stage through a hole in the cruise-stage solar array. The fact that this spacecraft was a

Table 4-3. Pathfinder Rover antenna specifications.

Parameter	Value
Overall length	45.0 cm (includes support tube)
RF: connector type	Coaxial SMA
RF center frequency	459.7 MHz
RF bandwidth	700 KHz for < 2:1 VSWR
RF gain	1.4 dBi-vertical polarization
Free space match	1.09:1 VSWR at center frequency
Materials	Fiberglass tube, aluminum tube, Teflon supports, coaxial cable

spinner meant that the MGA signals had a phase "wow." This phase modulation was factored into the telecommunications link design and was handled through ground processing. Antenna patterns of the MGA while mounted to a cruise-stage mockup are provided in Fig. 4-26. In this instance, care was taken to assure that the cruise-stage mock-up agreed with the final flight cruise-stage design. In-flight measurements show that the link performed as expected.

The cruise-stage LGA employed the choked circular waveguide design concept employed by the LGAs on Pathfinder and used in the antenna stack on this spacecraft. There were some subtle variations in the choke rings and the use of internal matching irises to maximize antenna performance, but the basic design was the same. In series with this antenna was a hybrid septum polarizer of the same design as that used with the MGA to achieve the required RHCP. Notice that the MGA used LHCP while the LGA used RHCP, this was done to provide some polarization isolation between the two antennas. Patterns for the cruise LGA while mounted to the cruise stage mock-up are provided in Fig. 4-27.

Whereas the Mars Pathfinder cruise-stage antenna was directly connected to the antenna stack, the MER assembly used an intermediate connection point, a hybrid septum polarizer, to split the signal into two oppositely polarized signals (See Fig. 4-28). The two polarized signals could then use the same circular waveguide that made up the antenna stack. There was another septum polarizer At the bottom of the stack. This polarizer sent the two signals to their proper locations in accordance with their polarization.

4.3.2.2 Entry, Descent, and Landing Antennas. As with the Pathfinder mission, there was a design requirement to maintain communications with the lander throughout all phases of entry, descent, and landing (EDL). This was especially emphasized after the loss of the Mars Polar Lander in which there

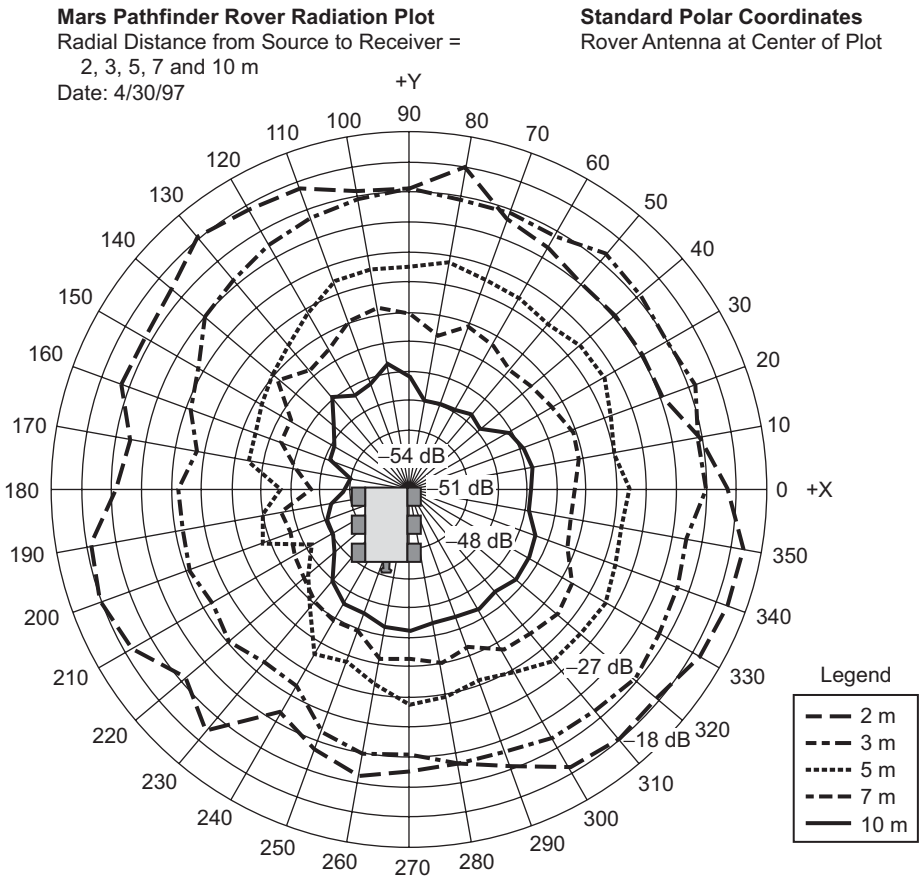


Fig. 4-24. Mars Pathfinder rover UHF antenna measurements [33].

was no link back to Earth during EDL. Receiving telemetry during descent may have provided better clues as to what caused the mission failure.

In order to facilitate the EDL requirements, the antenna stack concept from the Pathfinder mission was reused (see Fig. 4-17). Once again the backshell LGA was used as the link antenna during entry.

For the parachute descent, a slightly different concept was used. The Pathfinder spacecraft used a direct-to-Earth X-band link via the disc-cone antenna. The two MERs used the lander LGA, peering over the top of the lander for the X-band direct-to-Earth link. In addition, a new, UHF monopole antenna was implemented.

The MER lander design allowed the top of the rover LGA to protrude above the lander petals. This provided just enough clearance to facilitate a reasonable (albeit noisy) antenna pattern (see Figs. 4-29 and 4-30). Since the lander swayed back and forth during descent and the Earth was close to the

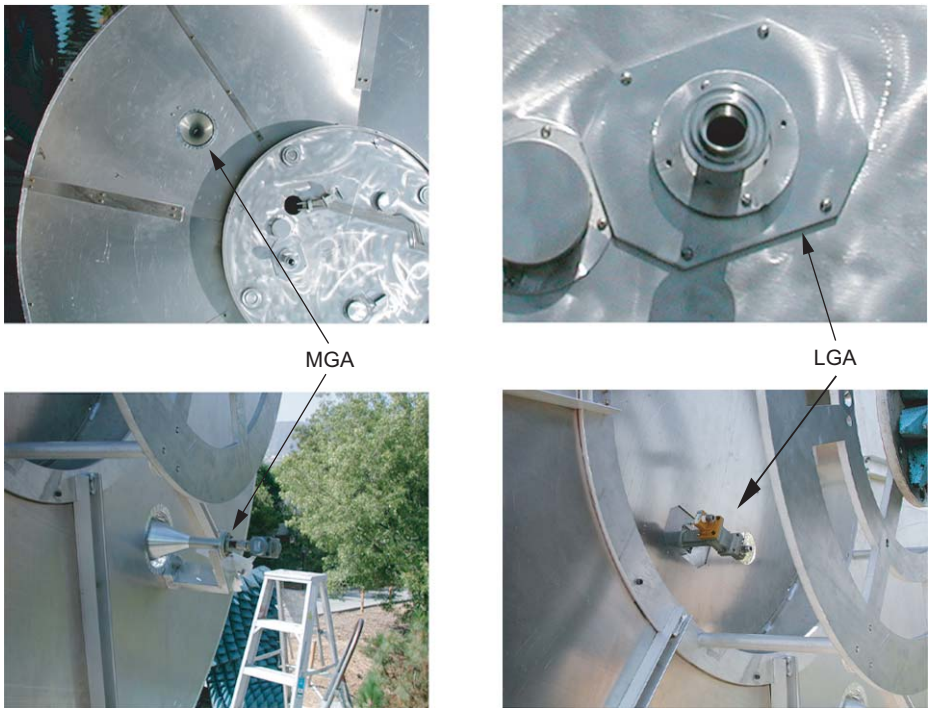


Fig. 4-25. Mars Exploration Rover MGA and LGA mounted on the cruise-stage mock-up.

horizon, this pattern did not provide an ideal angular coverage, but it provided an adequate link back to Earth.

For both MER Spirit and Opportunity, the descent UHF antenna was the primary link for descent. The UHF descent antenna communicated in a one-way (transmit only) mode of operation with MGS. The UHF monopole was mounted to the top of one of the lander petals as was done with the Mars Pathfinder X-band EDL antenna. This spring-loaded monopole popped up into action after lander separation from the aeroshell/backshell. The simple design consisted of a coaxial cable with an extended center conductor radiator. A solid Vespel radome was used to provide support and some measure of tuning. (see Fig. 4-31) The use of the Vespel replaced an earlier design that used a hollow fiberglass radome with a small metallic ball on the end to support the center conductor wire. This earlier design was found to be highly susceptible to ionization/corona at the operational powers of 15 W at 401 MHz. The new Vespel radome provided some relief from this problem, as is discussed in more detail in Section 4.3.2.4. Patterns were taken of this antenna mounted to a full-scale mock-up of the lander. The performance of this monopole was highly influenced by the lander. This less-than-ideal pattern due to the close proximity

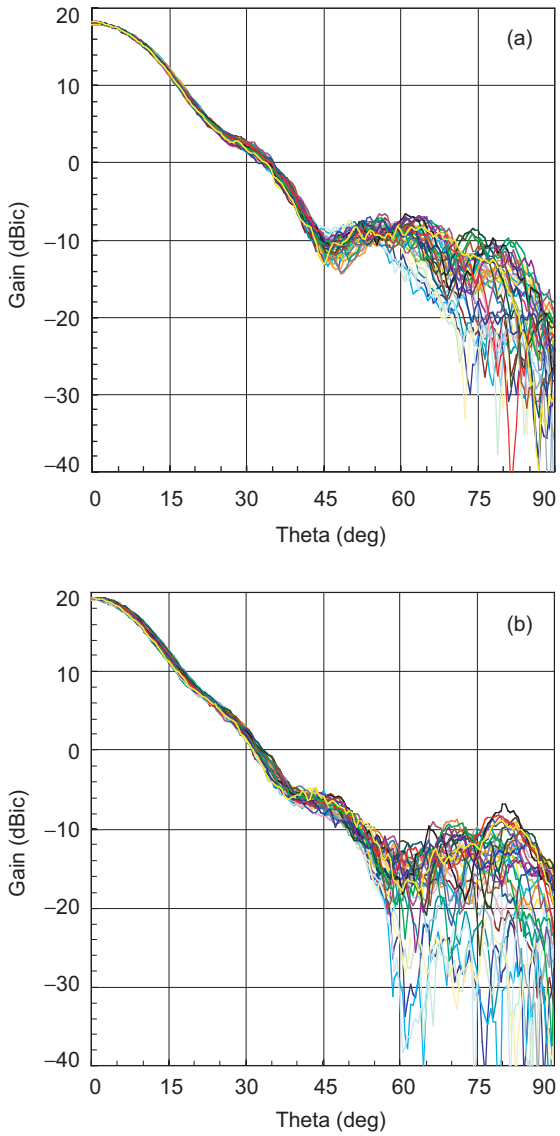


Fig. 4-26. Mars Exploration Rover measured radiation patterns from the MGA mounted on a cruise-stage mock-up: (a) 7.1 GHz, boresight gain = 18.1 dBiC and (b) 8.4 GHz, boresight gain = 19.3 dBiC.

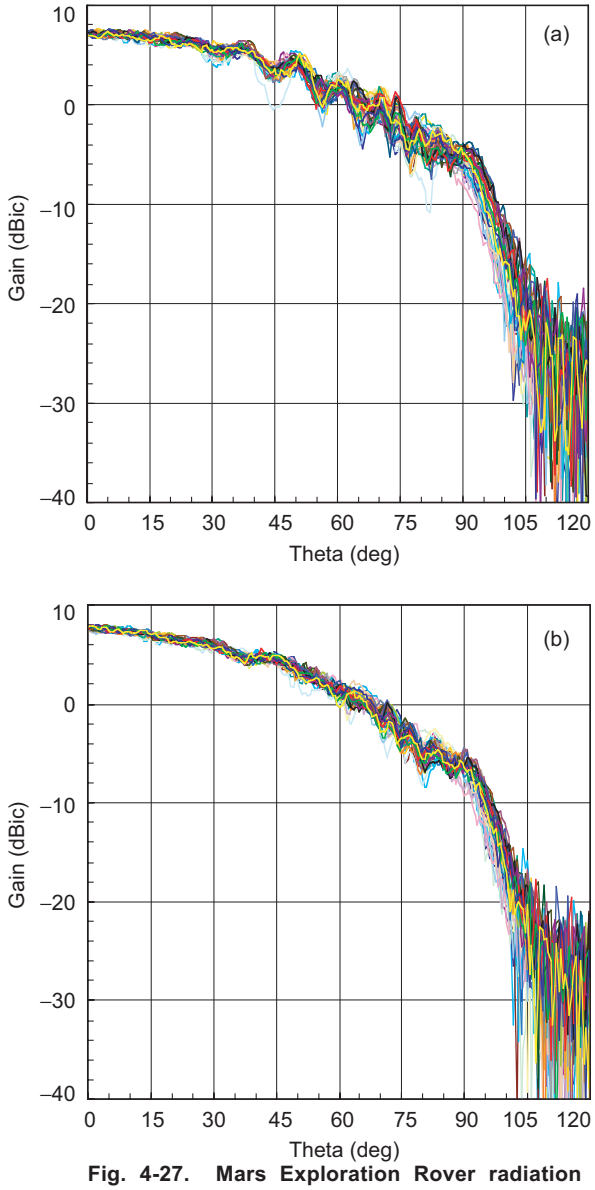


Fig. 4-27. Mars Exploration Rover radiation patterns for the LGA on a cruise-stage mock-up: (a) 7.1 GHz, boresight gain = 7.1 dBiC and (b) 8.4 GHz, boresight gain = 7.8 dBiC.

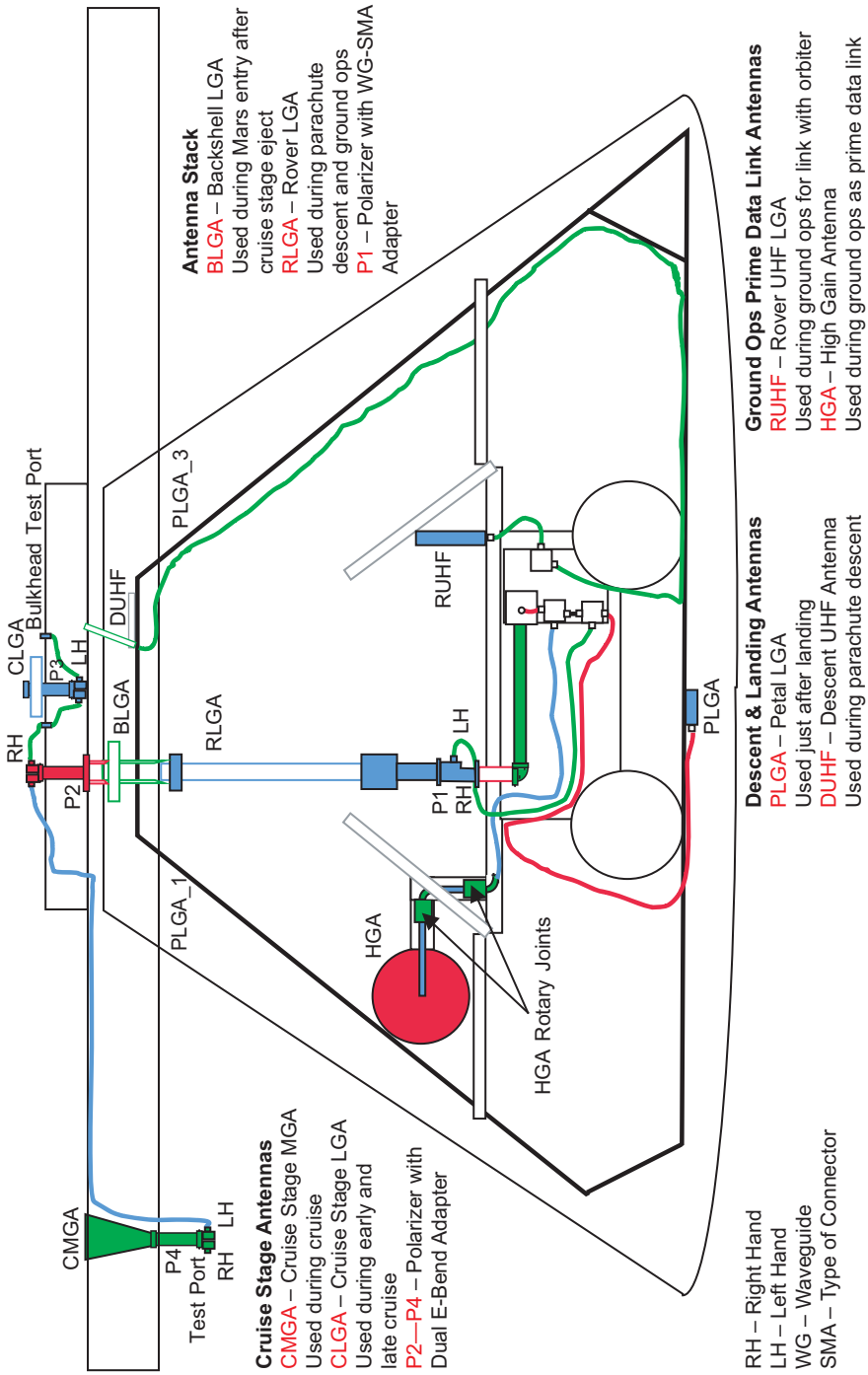


Fig. 4-28. Configuration of Mars Exploration Rover antennas during cruise stage.

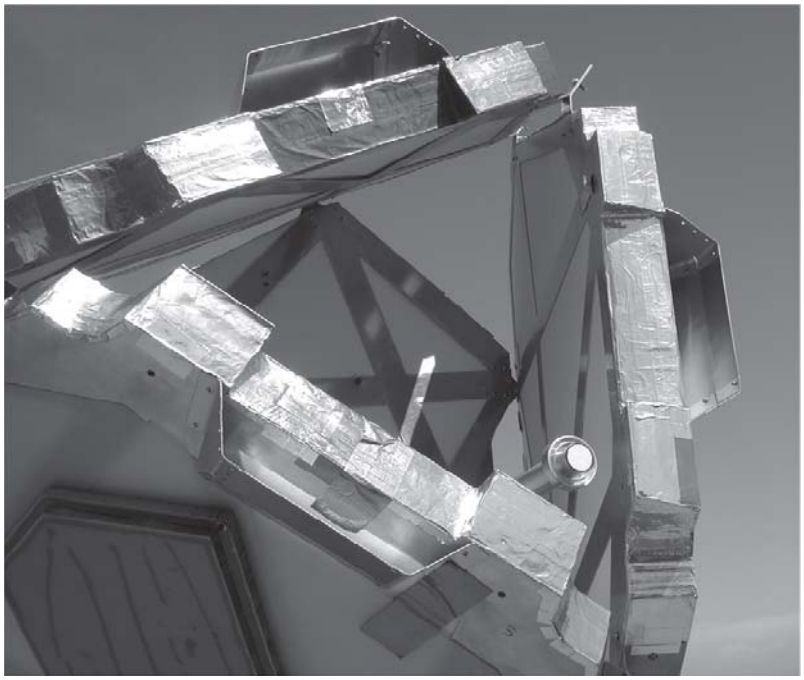


Fig. 4-29. Mars Exploration Rover lander LGA mounted inside a full-scale lander mock-up. This antenna is used as a direct-to-Earth link during descent.

to the lander was a compromise that had to be made. The lander geometry was highly constrained and did not leave room to implement other more elaborate concepts. Of course, cost and schedule played in the compromise space as well.

4.3.2.3 Direct-to-Earth Rover Communications Antennas for Landed Operations. The rover deck was populated with two X-band direct-to-Earth antennas. Both of these mirrored the design used for the Mars Pathfinder mission. A rover LGA was used periodically for sending telemetry and receiving commands. The two-axis gimbaled HGA was used to send science data and telemetry as well as receive commands. The HGA design used is identical to that used for the Pathfinder mission. The LGA used the same design principals and varied only in that it incorporated a few matching irises and an RF choke near the interface between the two circular waveguides that form the spring-loaded strut-like configuration used to take up loads incurred during landing. Radiation patterns for the rover LGA while mounted to a full-scale mock-up of the rover are provided in Fig. 4-32.

In addition to the rover-mounted antennas, there was also one other direct-to-Earth link antenna that was mounted to the base petal of the lander. This antenna was to provide one of three possible data links from the time right after

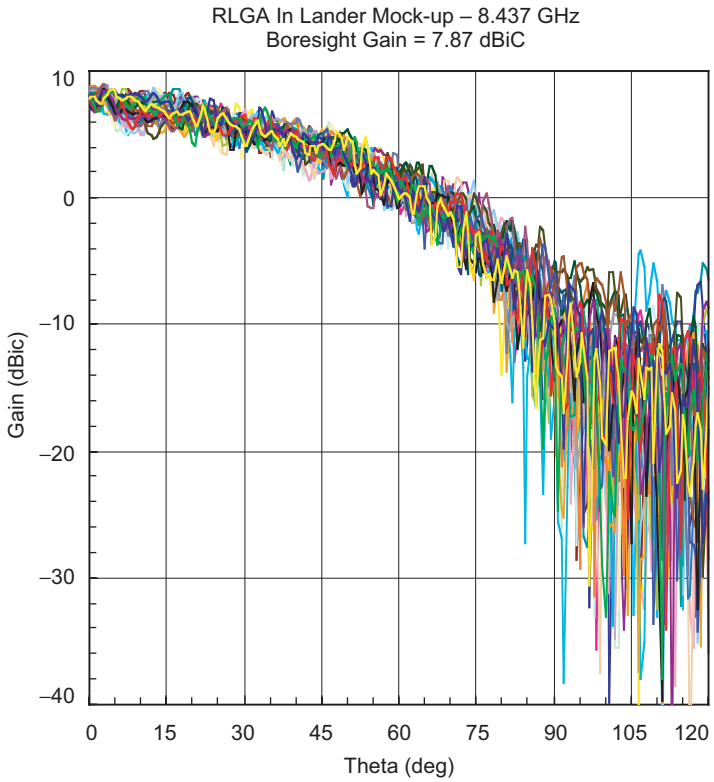


Fig. 4-30. Radiation pattern of Mars Exploration Rover LGA mounted inside a full-scale lander mock-up.

the lander came to a roll-stop after descent through the time just before opening the lander petals. This antenna would be necessary in the event the lander came to rest on one of the side petals. With the rover LGA providing coverage in the region above the base petal, this antenna would provide coverage behind the base petal. In addition, the descent UHF antenna might have provided link, depending on its orientation after landing.

The base petal LGA (PLGA) is a X-band microstrip patch tuned to the transmit frequency of 8.437 GHz (Fig. 4-33). The antenna employs a thin Last-A-Foam radome for protection and as a spacer to prevent contact with the airbag hardware. Like the descent UHF antenna, this antenna was forced into a non-ideal location. Since the lander was surrounded by large inflated air bags at this phase of the mission, there were few places to mount the antenna in order to provide coverage behind the base petal. As a result, the antenna was mounted in the center of the base petal underneath the airbags. All three antennas used for the link at this phase of the mission were subject to some amount of airbag

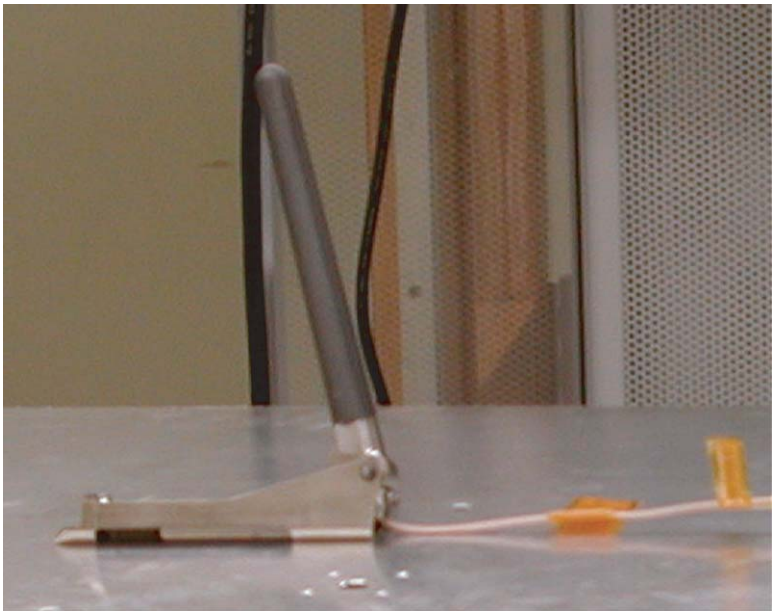


Fig. 4-31. Mars Exploration Rover descent UHF antenna.

blockage. The radiation patterns for the PLGA when mounted on a simulated base petal with a single air bag attached are shown in Fig. 4-34.

4.3.2.4 Rover-to-Orbiting-Asset UHF Relay Link Antenna. In addition to the X-band direct-to-Earth link antennas, the MER rovers use a UHF link for relaying science data back to Earth via one of the orbiting assets, either MGS or Mars Odyssey.

Each rover's deck-mounted UHF antenna consists of a simple one quarter wavelength monopole (see Fig. 4-35). This antenna was not the first choice for this function. Its free space radiation pattern sends it energy out to the sides across the rover deck in a torroidal pattern. This energy interacts with the many vertical structures mounted to the rover deck. In addition, due to configuration constraints, the monopole had to be placed close to the edge of the rover deck, which did not provide an ideal ground plane for the antenna. These effects resulted in patterns that are fairly unrecognizable relative to a classical monopole pattern. As has been mentioned several times in this chapter, any LGA should be installed as far from spacecraft structure as possible, or the user link should have lots of margin (greater than 20 dB). Unfortunately, neither choice was possible in this mission. The highly crowded rover deck could only fit a very small antenna whose volume had to fit within an envelope about the size of the monopole. Alternate designs (such as the turnstile antenna used on Viking) could not be used.

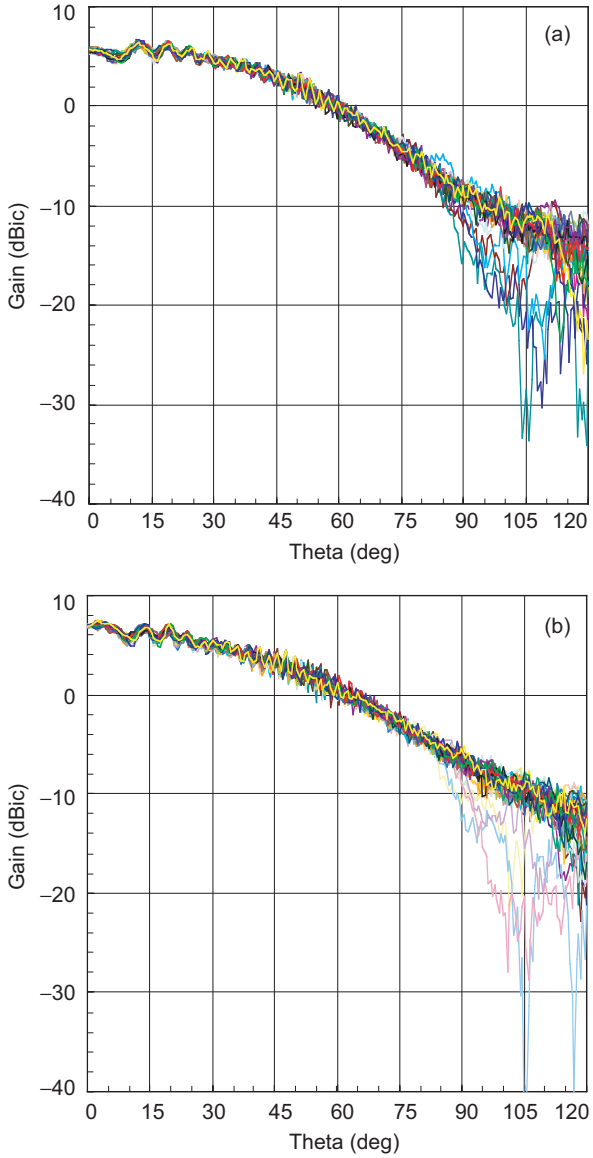


Fig. 4-32. Radiation patterns of the Mars Exploration Rover LGA measured with antenna mounted to a full-scale mock-up of the rover deck and its major instruments: (a) 7.181 GHz, boresight gain = 5.73 dBiC and (b) 8.437 GHz, boresight gain = 6.85 dBiC.

(a)

(b)

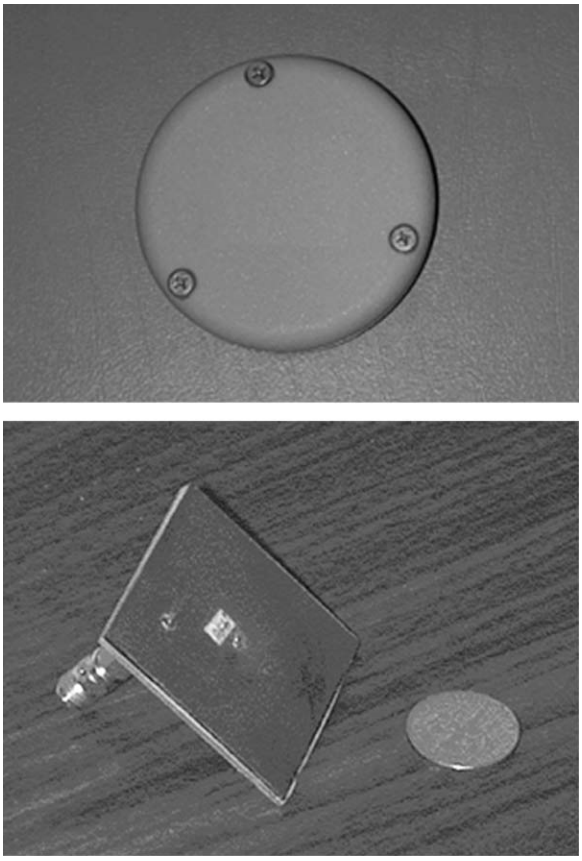


Fig. 4-33. Mars Exploration Rover (a) breadboard petal LGA patch antenna and (b) its flight unit Last-A-Foam radome (note dime for size).

Another design consideration that was particularly relevant to the UHF frequency band is ionization/corona effects on the Martian surface. It turns out that the 4- to 12-T (533- to 1600-Pa) Martian atmospheric pressure is just about ideal for corona to occur. This is true for radiation power even as low as 5 W. For this mission, the 15-W UHF transmit power provided ample opportunity for corona. The corona effect occurs when electric fields are strong enough to strip electrons from surrounding gas atoms; these electrons then recombine, giving rise to the corona glow. In addition to optical radiation, accelerated free electrons can radiate broadband noise, and in the case of antennas, the shroud of ionized gas can cause the antenna to electrically look larger than its radiating elements. This causes the antenna to be mismatched, sometimes severely, as is the case with a resonant antenna like a monopole. This problem can usually be

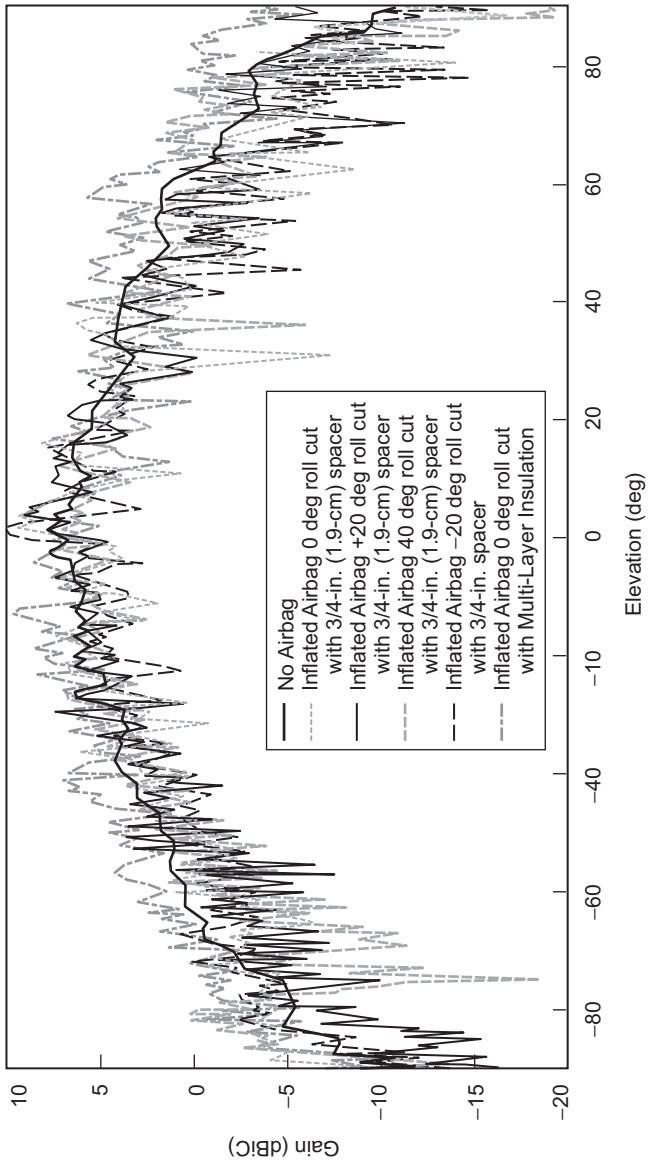


Fig. 4-34. Mars Exploration Rover base petal X-band LGA and its radiation patterns in the presence of the base petal and a single lander airbag. Note: the flight unit low-gain patch antenna uses a Last-A-Foam radome for protection and as a spacer to prevent contact with the airbag.

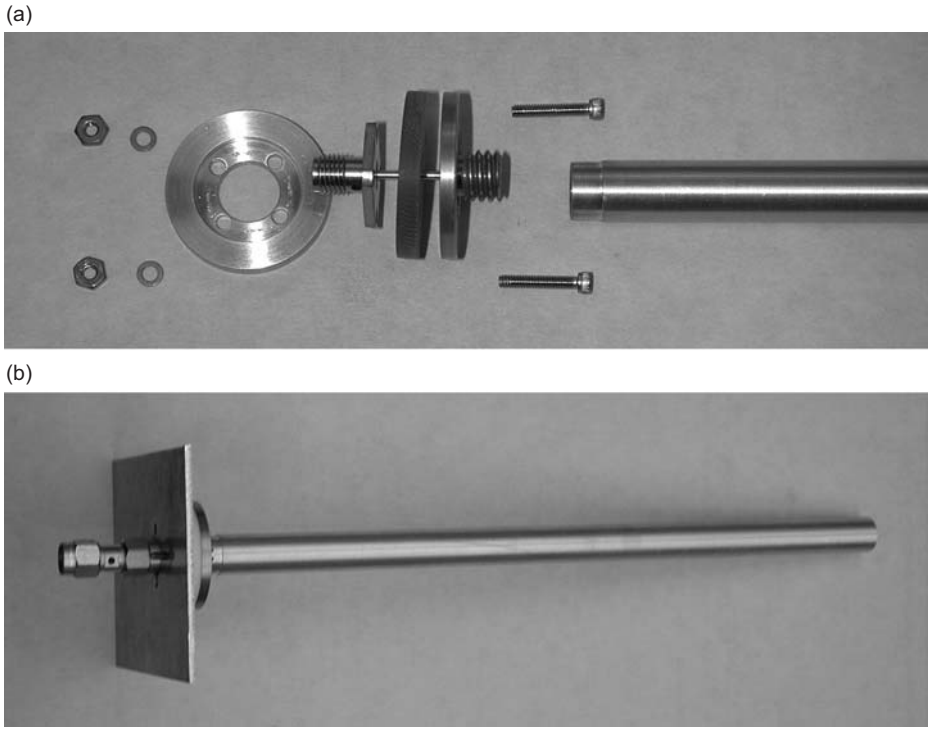


Fig. 4-35. Breadboard version of MER rover UHF antenna: (a) exploded view of breadboard monopole antenna and (b) assembled breadboard monopole antenna.

avoided by using rounded tips on the radiating elements as was done for the Viking antenna (see Fig. 4-13). As is well known, pointed tip (very small radius of curvature) radiating elements have high electric fields in the vicinity of the point, these fields give can facilitate the corona/ionization problem. In the case of a Mars-based antenna, the problem is even more difficult. When the gas pressure is very low, in addition to stripping electrons off of neighboring gas atoms, electrons are emitted from the radiating element metal itself. These electrons have fairly large mean-free paths. In the oscillating fields with long wavelengths, such as at UHF (~0.75-m wavelength), this allows the electron to be accelerated to high velocities before it comes in contact with a gas atom. This is opposed to the higher-pressure case where the electrons emitted from the surface do not get very far before coming in contact with a gas atom or (for higher frequencies with short wavelengths) cannot gather enough momentum. In the low-pressure case when the electron does reach the atom, it has sufficient energy to knock off electrons before it finally recombines. This process can start an avalanche effect. At these lower pressures, rounding the element tips is not sufficient. It has been found that one needs to raise the work-function (the measure of how readily a material will emit electrons) of the element. In the

case of the Viking UHF antenna, this was done by surrounding the element with a foam cap. For the MER program, it was found that wrapping the antenna in black (carbon-loaded) Kapton tape raised the work function enough to prevent corona at our operational power of 15 W.

Figure 4-36 shows the rover UHF antenna operated in a vacuum chamber with a back-fill of simulated Mars gas (mostly CO_2). The pressure of the gas was varied while a fixed excitation power fed the antenna. As this was done, the antenna began to generate corona/ionization. At first the effect was quite local, around the tip of the monopole. As the pressure was lowered, the mean free path increased, increasing the area over which the corona occurred. Finally, when the pressure was so low that there was no longer any gas to ionize, the effect stopped. It should be noted that this type of ionization is rather benign in terms of its ability to damage the RF hardware. In the case where there is extremely high potentials, an ionization event can break down the intervening gas generating a instantaneous arc of electric current which has sufficient heat energy to damage the equipment. This type of ionization is not a problem for the MER rover UHF antenna.

As was mentioned in Section 4.3.2.2, the original descent UHF antenna design was susceptible to the corona effect. This antenna employed an exposed metal ball at the tip of the radiating element. It was found that by encasing the radiating element in Vespel, the work function was raised sufficiently high to eliminate the corona at our operational powers.

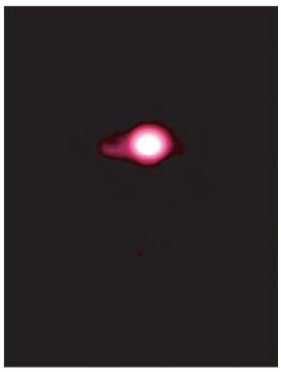
4.4 Continued Mars Exploration

As of the writing of this book chapter, there are several new missions planned for the further exploration of Mars. These include the Mars Reconnaissance Orbiter [29], Mars Science Laboratory (MSL), Mars Scout Missions, and a Mars Sample Return mission [30].

The Mars Reconnaissance Obiter (MRO) mission (launched August 12, 2005) will be the highest data-rate mission ever flown by NASA. Its 3-m HGA and 100-W X-band TWTA will facilitate data rates on the order of 6 megabits per second (Mbps). In addition to the X-band link frequency, the MRO antenna also hosts a Ka-band “experimental” link. As with the MGS, the MRO Ka-band signal is fed to the high-gain dish through a dual-band feed. Once again the X-band is fed coaxially through a corrugated horn, and the Ka-band is fed via a central disc-on-rod antenna (See Fig. 4-37). The optics for the MRO HGA use a derivative of the Gregorian type optics. This so called “displaced-axis” optics design is shown in Fig. 4-38. The advantage of this reflector assembly is that rays are reflected from the subreflector in such a manner as to avoid re-reflection back into the feed, thus minimizing the central blockage of the feed. The as-built reflector is shown in Fig. 4-39. The main reflector and the

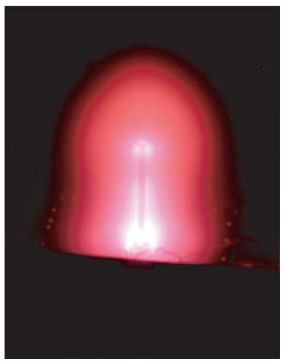
Inside Vacuum Chamber

2 T (267 Pa)
60 W Peak (15 W Avg)



1 T (133 Pa)
60 W Peak (15 W Avg)

0.1 T (13.33 Pa)
60 W Peak (15 W Avg)



0.05 T (6.67 Pa)
60 W Peak (15 W Avg)

Fig. 4-36. Corona effects due to the MER Rover UHF (RUHF) antenna when operated in pulse mode at 60-W peak power (15-W average power) at various pressures of simulated Mars gas (mostly CO_2).

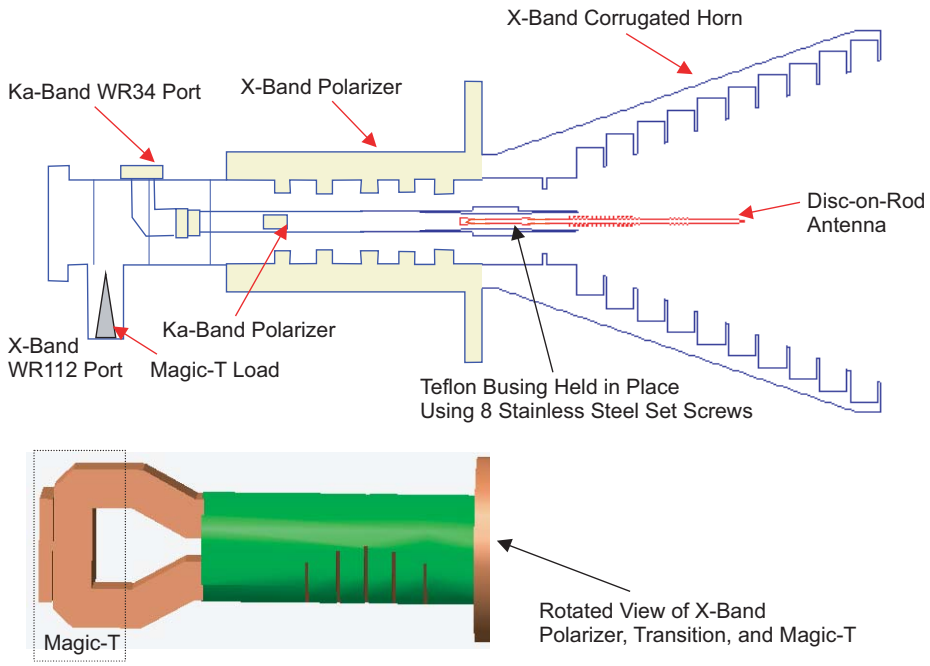


Fig. 4-37. Two views of X-/Ka-band feed assembly (without the long X-band and Ka-band waveguides; this configuration used with MGS and MRO).

subreflectors achieved better than 7 mils (178 µm) root mean square (rms) and 3 mils (76 µm) rms, respectively, manufacturing surface accuracy. The as-measured antenna was found to be 60 percent efficient at X-band and 48 percent efficient at Ka-band. Some of the major loss elements in this system were strut losses, estimated at ~0.5 dB at each frequency; surface reflectivity loss, estimated at ~0.3 dB at both frequencies; and ~1.4 dB of feed losses for the Ka-band frequencies. In addition to the dual-frequency HGA, the MRO spacecraft uses two X-band LGAs mounted as shown in Fig. 4-40. The LGAs were designed to provide as broad of a beam as possible while trying to minimize the interaction with the nearby HGA and spacecraft structure. The LGAs also make use of the septum polarizer produced by Atlantic Microwave, Inc., to achieve the necessary circular polarization. The design, predicted performance, and flight-unit article are shown in Fig. 4-41.

The Mars Science Laboratory mission will utilize the next generation of Mars surface rovers. Planned for the 2009 time frame, this rover will be the size of a small automobile and will host a new generation of scientific instruments to study the surface.

The Mars Scout Missions are a series of lower cost missions selected from proposals from the science community. The first of the scout missions,

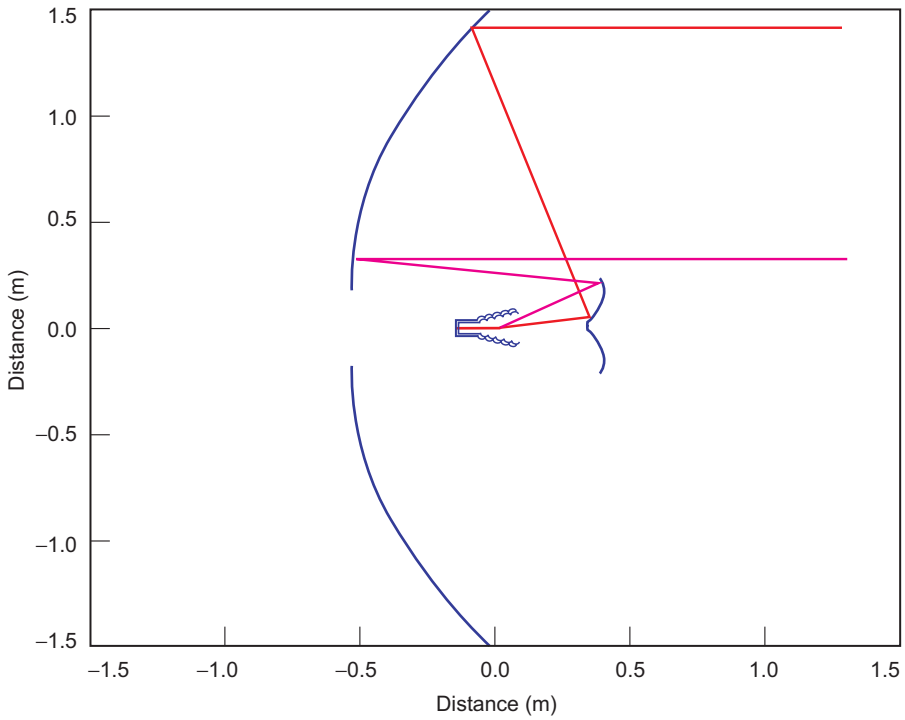


Fig. 4-38. Mars Reconnaissance Orbiter displaced-axis HGA optics.

Phoenix, a refurbished version of the Mars Polar Lander, is anticipated for the year 2007 time frame.

The Mars Sample Return mission is an ambitious endeavor to attempt to return a sample of Mars soil and rock from the surface back to Earth. This mission would involve a lander with a module that can retrieve a sample and launch back into Mars orbit. An orbiter would seek out the sample module and then return back to Earth. This mission is anticipated for some time in the second decade of the 21st Century.

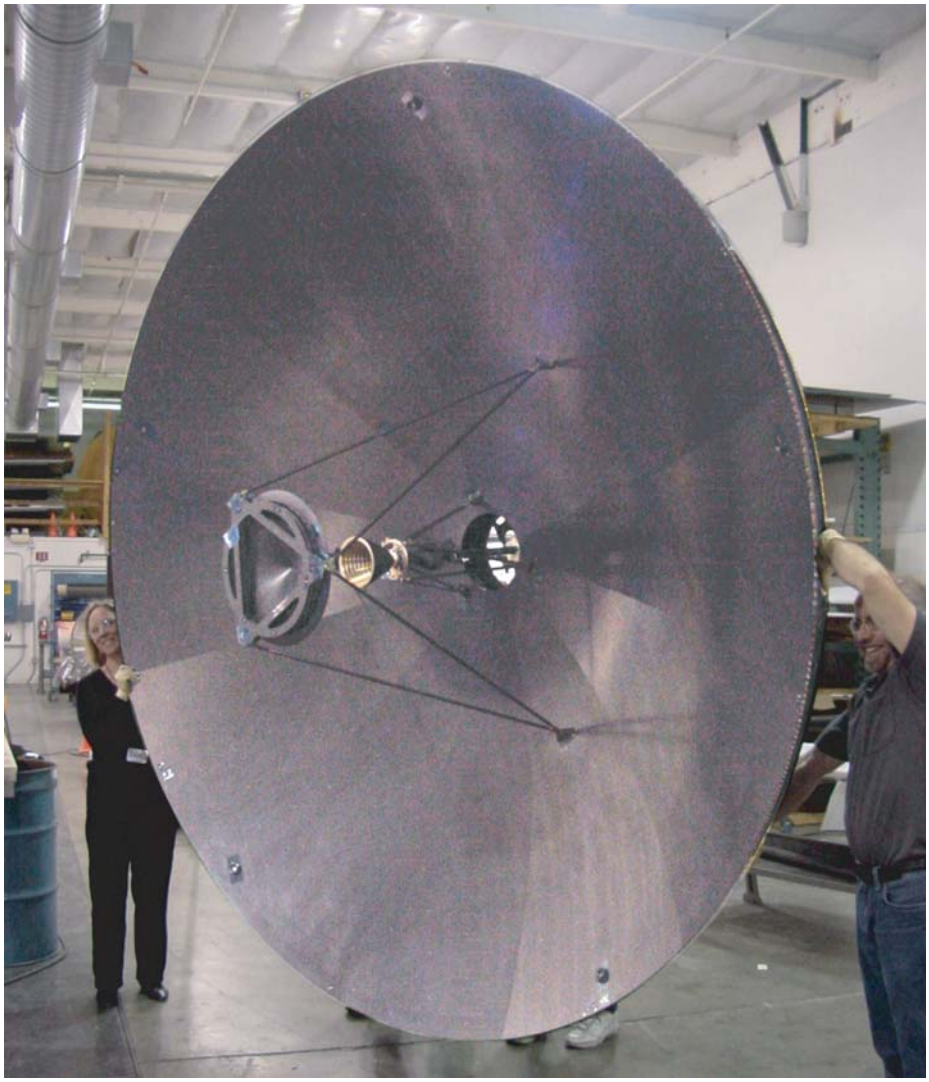


Fig. 4-39. Mars Reconnaissance Orbiter HGA and its X-/Ka-band feed.

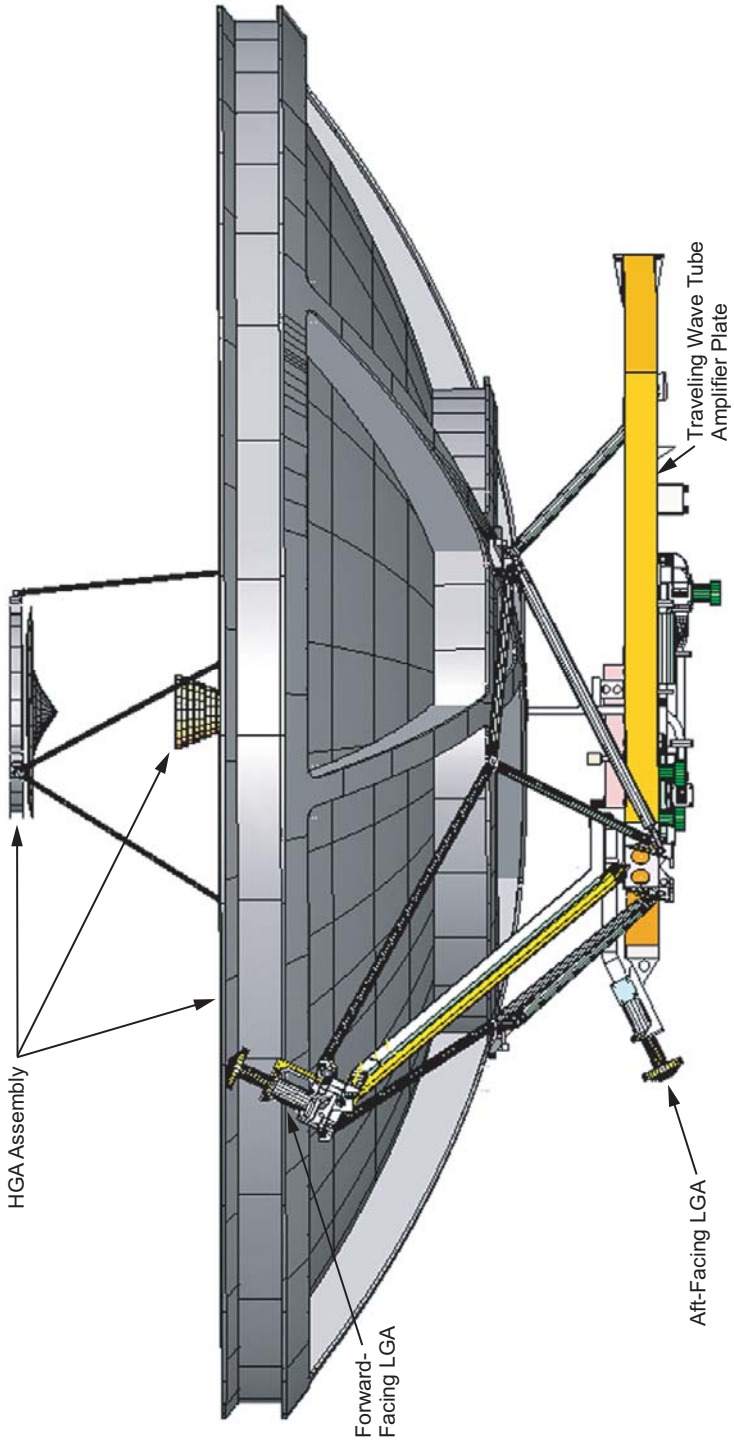


Fig. 4-40. Mars Reconnaissance Orbiter HGA and LGA configuration.

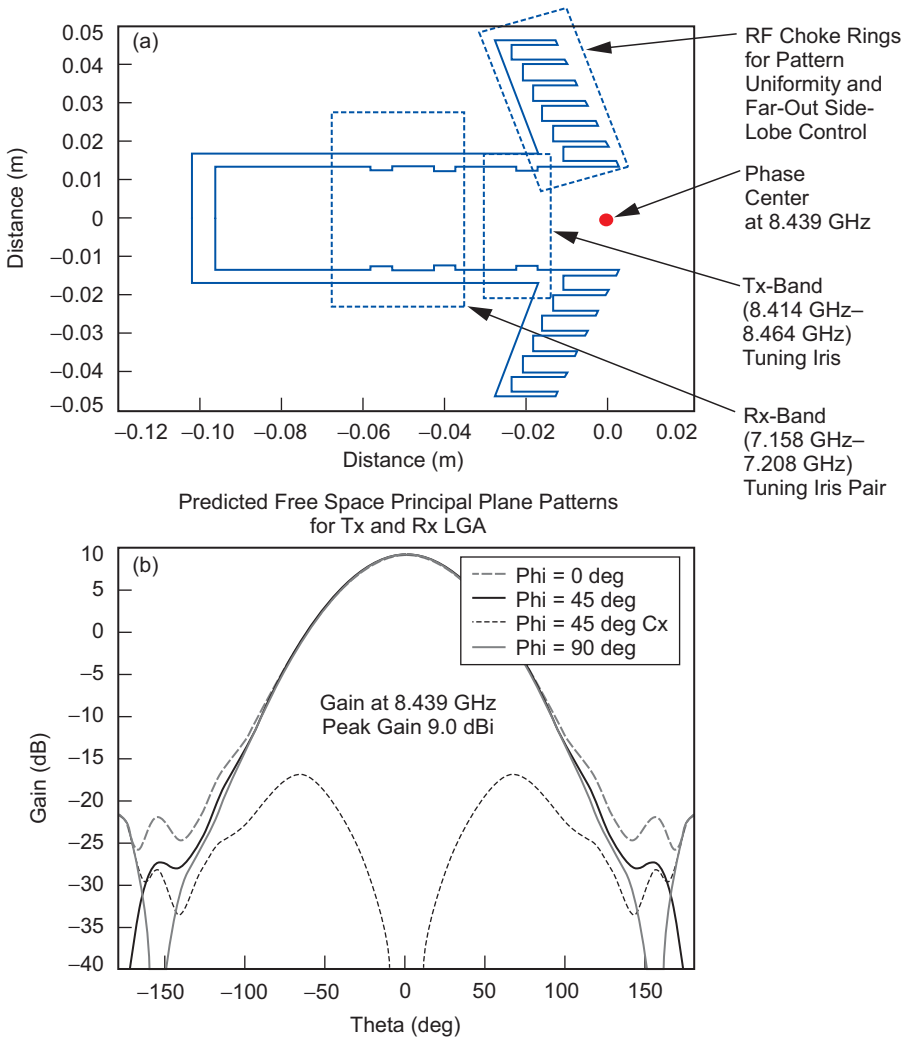
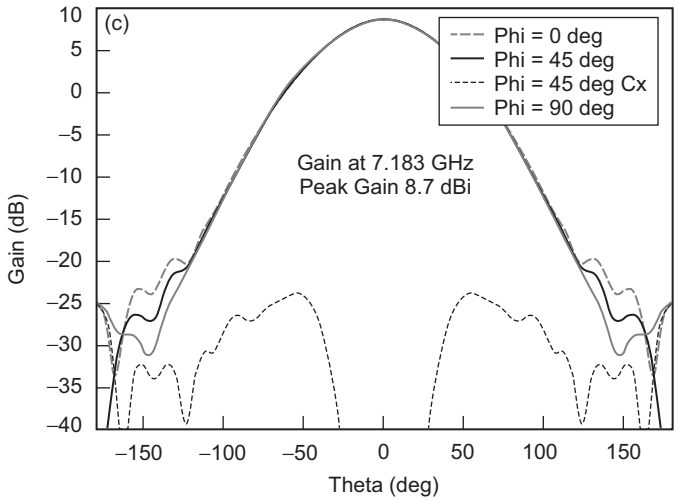


Fig. 4-41. Mars Reconnaissance Orbiter LGA (a) design, (b) predicted performance at transmit frequency, (c) predicted performance at receive frequency, and (d) flight unit.



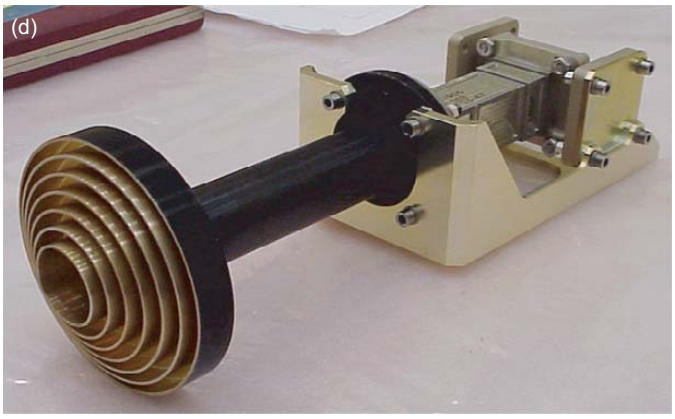


Fig. 4-41. Mars Reconnaissance Orbiter LGA (a) design, (b) predicted performance at transmit frequency, (c) predicted performance at receive frequency, and (d) flight unit (cont'd.).

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