TMO Progress Report 42-136 February 15, 1999

Mars Rover Antenna for Solar-Array Integration

J. Huang[1]

A low-gain crossed-slot microstrip patch antenna integrated with the solar-array panel has been successfully developed for the Mars rover application at the frequency of 400 MHz. It achieved a very low mass of 0.5 kg and occupied very small real estate (6.5 percent) of the solar panel. The electrical and mechanical characteristics of several other omni-directional low-gain antennas also are discussed in this article.

I. Introduction

The overall objective of this task was to develop low-mass, compact, omni-directional, low-gain, ultra-high frequency (UHF) antennas for future Mars rovers, landers, and orbiters in support of in situ communications. In particular, a low-mass and compact antenna needs to be developed for the 2001 rover vehicle. This antenna is required to have a wide beamwidth, preferably wider than ± 60 deg from the antenna's broadside, so that, as the orbiter flies by from horizon to horizon in any orbital track, a communications link can be established. The antenna should be a single unit operational over both the downlink (401 MHz) and the uplink (437 MHz) frequencies (8.5 percent bandwidth) with circular polarization and a minimum gain of -2 dBi over the above-specified hemispherical coverage region. It should have a mass less than 1 kg and a size compact enough so as not to significantly obscure or reduce the area allocated for the solar panel (60 cm $\times$ 90 cm).

From the above requirements, it is clear that this antenna task is quite a challenging one. A broad angular coverage with circular polarization generally calls for a physically tall antenna so that it has adequate aperture size to provide close-to-the-horizon coverage. However, such a tall antenna would shadow the solar cells. When one single solar cell is badly shadowed, a complete string of cells could cease to function. On the other hand, a low-profile antenna at 400 MHz would have a large physical aperture (half free-space wavelength is about 35 cm), which may take significant area away from that allocated for the solar cells. In addition, the antenna requires a relatively large bandwidth, which implies that the electrical size of the antenna could be difficult to miniaturize.

To meet the above challenge, several candidate antennas have been studied: (1) the conventional microstrip patch, (2) crossed-drooping dipoles, (3) the quadrifilar helix, (4) the monopole, and (5) the crossed-slot microstrip patch. Although only the crossed-slot patch has been selected for the 2001 rover program, the characteristics of the other antennas and their applicability to future rovers, landers, and orbiters are discussed in the following section. Due to its ability to radiate a relatively broad beam, to integrate with the solar array, and to achieve very low mass, the crossed-slot patch has been selected for breadboard development. Its characteristics and performance results are presented in a separate section.

[1] Spacecraft Telecommunications Equipment Section.

II. Candidate Low-Gain Antennas

The following are several candidate UHF low-gain antennas [1] that may be suitable for use on future Mars rovers, landers, or orbiters. Their performances, masses, and sizes are estimated, and their suitability for use on a rover, lander, or orbiter is discussed. This is only a brief study effort. Once the antenna-mounting configuration is more accurately determined, a more detailed study must be carried out.

A. Conventional Microstrip Patch

A circularly polarized (CP) microstrip patch antenna [2] for 400-MHz operation is shown in Fig. 1. The antenna consists of a 32-cm × 32-cm square conducting patch separated 2.5 cm above a 38-cm × 38-cm square conducting ground plane. The square patch can be supported above the ground plane by either a honeycomb substrate or several small dielectric posts. To achieve CP, the square patch is fed at two orthogonal points by a thin (0.32-cm) power-dividing circuit below the ground plane. This power-dividing circuit is fed by a single TNC connector at the input–output port of the antenna. The overall thickness of the antenna is 2.5 cm, and the total antenna mass is approximately 0.5 kg. The calculated radiation pattern of this patch antenna is given in Fig. 2, which shows a 3-dB beamwidth of 60 deg (±30 deg) with a peak gain of 7 dB. Since the antenna is a broadside radiator, it may be suitable for use by either lander or rover to communicate with the orbiter. It also is suitable as a downward-looking orbiter antenna. It is not suitable, however, for direct linkage between the lander and the rover, where near-horizon communication is needed.

Since the antenna is basically a panel construction and radiates only from the four edges of the patch, it can be integrated with the solar-array panel for rover application, as depicted in Fig. 3. The thin solar cells can be placed above the radiating patch and everywhere around the patch except for a 2.5-cm gap along the four edges of the patch. In other words, looking from the top, the complete solar panel would have a 32-cm × 32-cm square loop of 2.5-cm width where there are no solar cells. The solar cells inside the loop and those outside the loop can be connected together via dc wires at a few locations, as shown in Fig. 3. These dc wires also can be connected below the ground plane of the patch.

The beamwidth of 60 deg is not very broad. To achieve a broader beamwidth, the substrate material could be changed from honeycomb to a high dielectric-constant material. This dielectric constant can be anywhere from 2.0 to 10. The higher the dielectric constant, the smaller the patch and, hence, the broader the beamwidth. However, generally, as the dielectric constant increases, the material mass increases also. In addition, the bandwidth performance of the antenna degrades as the dielectric constant increases. As an example, for a dielectric constant of 2.5, the patch size can be reduced to 25 cm × 25 cm with a beamwidth of about 80 deg and an antenna mass of 3 kg.

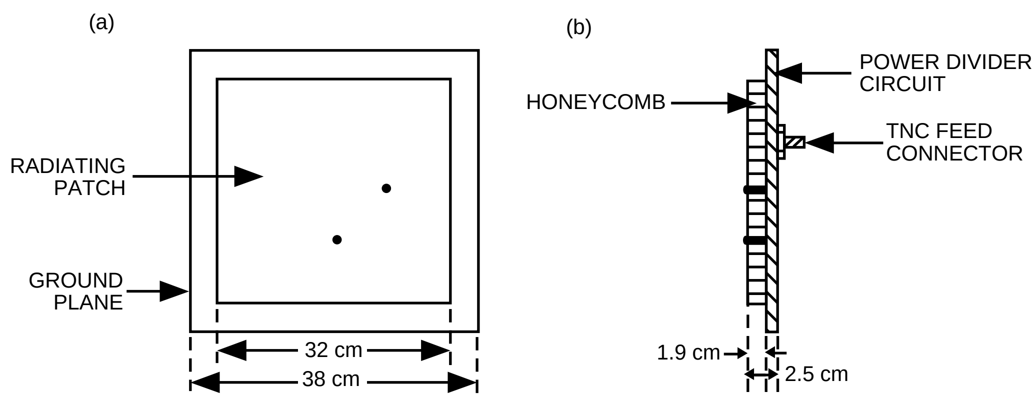

Fig. 1. Circularly polarized microstrip patch antenna at 400 MHz: (a) top view and (b) side view.

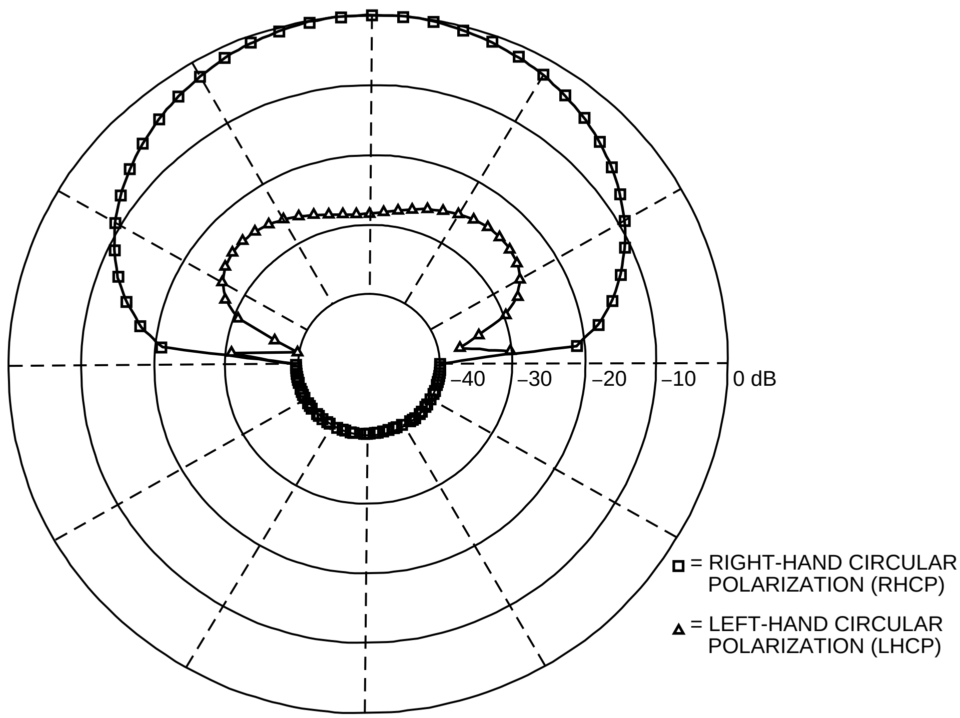

Fig. 2. The calculated elevation pattern of the 400-MHz microstrip antenna.

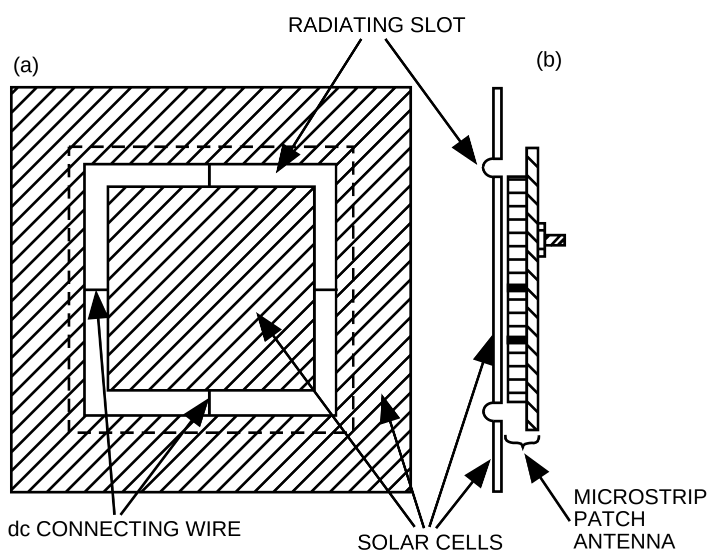

Fig. 3. Integration of the solar-array panel with the UHF microstrip patch: (a) top view and (b) side view.

B. Crossed-Drooping Dipoles

This antenna consists of two crossed dipoles that are drooped downward to provide better coverage and good CP quality toward lower elevation angles,[2] as shown in Fig. 4. The dipoles must be placed at a

[2] J. Huang, "Crossed-Drooping Dipole Antenna," JPL Interoffice Memorandum 3365-87-015 (internal document), Jet Propulsion Laboratory, Pasadena, California, May 1987.

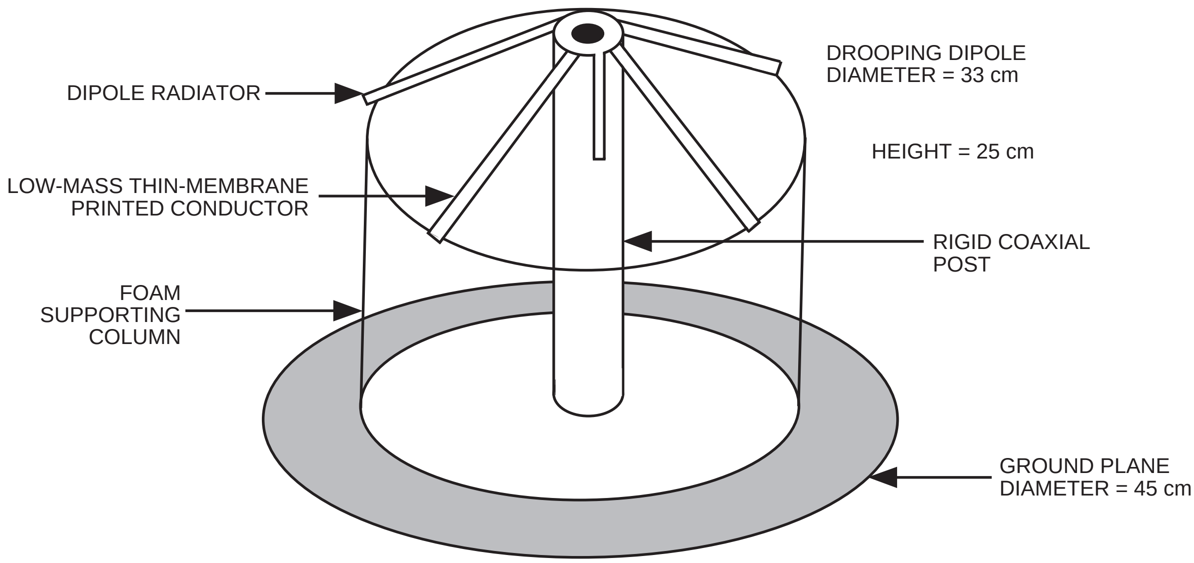

Fig. 4. The crossed-drooping dipole antenna supported on a foam column.

distance between 1/4 and 1/2 wavelength above a metallic ground plane with a diameter of approximately 45 cm. The antenna construction in Fig. 4 shows that a pair of thin-membrane dipole conductors are printed onto a foam supporting column to avoid vibration damage during spacecraft launch. Certainly, without the foam column, the dipoles can be made of heavy metallic rods or lower-mass flexible metal wires. The long dipoles also can be made to be deployable like an umbrella. A mechanical trade-off study should be carried out to determine a more appropriate antenna construction technique for a specific application. The dipoles are fed by a rigid coaxial post, as shown in Fig. 4, where a balanced feed with a pair of 1/4-wavelength-long slits is used to achieve the balanced-dipole radiation. The input–output connection can be either a TNC or a type-N connector located just below the ground plane. The exact spacing between the dipoles and the ground plane is governed by the desired radiation pattern. Various measured patterns versus ground-plane spacings are given in Fig. 5 for an 850-MHz antenna. At 400 MHz, the antenna dimensions would be slightly more than twice those given in Fig. 5. At 1/4-wavelength spacing between the dipoles and the ground plane, the radiation basically is broadside directed, while at 1/2-wavelength spacing, the radiation is more toward the low elevation angles. The total mass of the antenna is estimated to be 1.0 kg for the foam-column configuration.

The crossed-dipole antenna may be used on an orbiter for downward communication to Mars or on a lander or rover for upward communication to the orbiter. It is not suitable for the antenna to be used on both lander and rover for direct linkage between the two, since at very low elevation angles (approach horizon direction), the antenna has very low-gain radiation (-10 dB or lower) regardless of the ground plane spacing.

C. Quadrifilar Helix

This antenna [1] consists of four wire radiators curved symmetrically around the antenna axis. The antenna can be designed for two different operation modes: the axial mode and the normal mode. The axial mode has its radiation peaked along its axis and can be made relatively small, as depicted in Fig. 6. A circular ground plane with a diameter of approximately 25 cm is needed for the axial-mode antenna. The total height of the antenna above the ground plane is about 40 cm. The four curved wires can be printed on a cylindrical foam column or on a hollow dielectric cylinder with a diameter of 20 cm and a total mass of approximately 1.5 kg. The axial mode can provide a relatively broad beam with good CP radiation. It can be designed to achieve approximately 140 deg ($\pm$70 deg) of beamwidth. The normal-mode antenna has its radiation peaked at the normal to its axis, as shown in Fig. 7. To avoid the

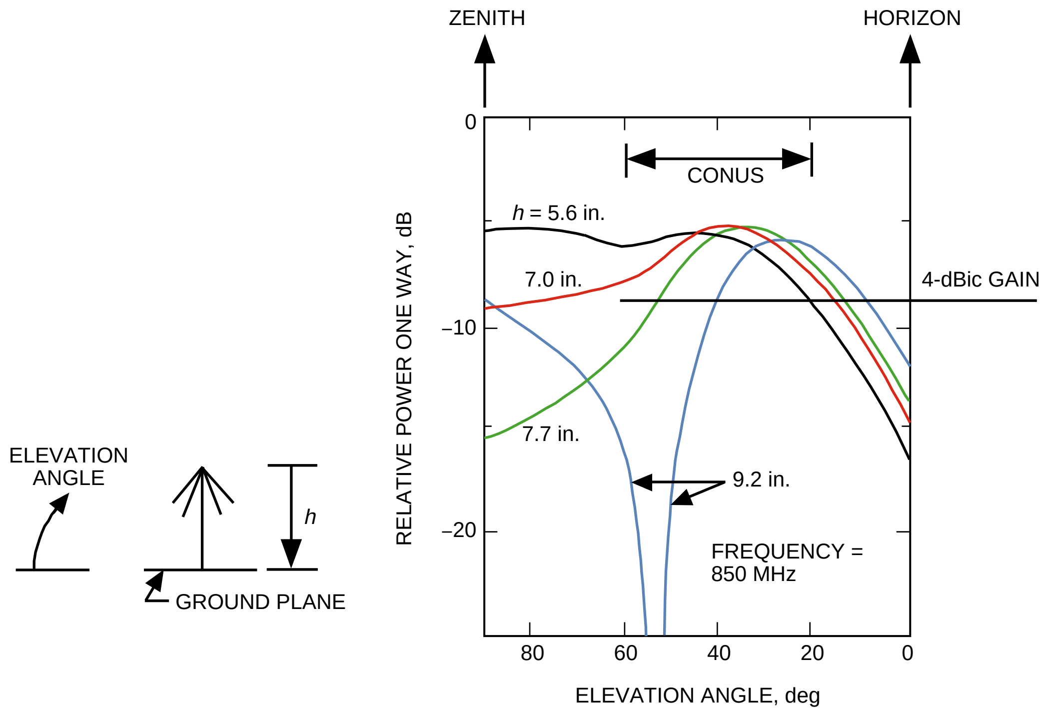

Fig. 5. The radiation patterns of an 850-MHz crossed-drooping dipole versus the ground-plane spacing.

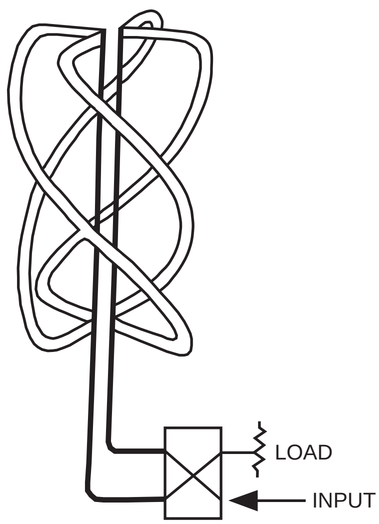

Fig. 6. The axial-mode quadrifilar helix.

multipath scattering effect of a horizontally pointed broad beam, the antenna must be designed with a significantly increased height to yield a narrow elevation beamwidth. This antenna would have a diameter of 8 cm and a height of 2 m or more. Its mass would be greater than 3 kg. The advantage of this normal-mode helix is its ability to provide good CP and adequate gain at low elevation angles. However, it would be physically very long and massive.

The axial-mode helix antenna is suitable for orbiter downward communication to the surface of Mars and for lander or rover upward communication to the orbiter. The normal-mode antenna is suitable only for mounting on the lander for horizontal communication to a rover.

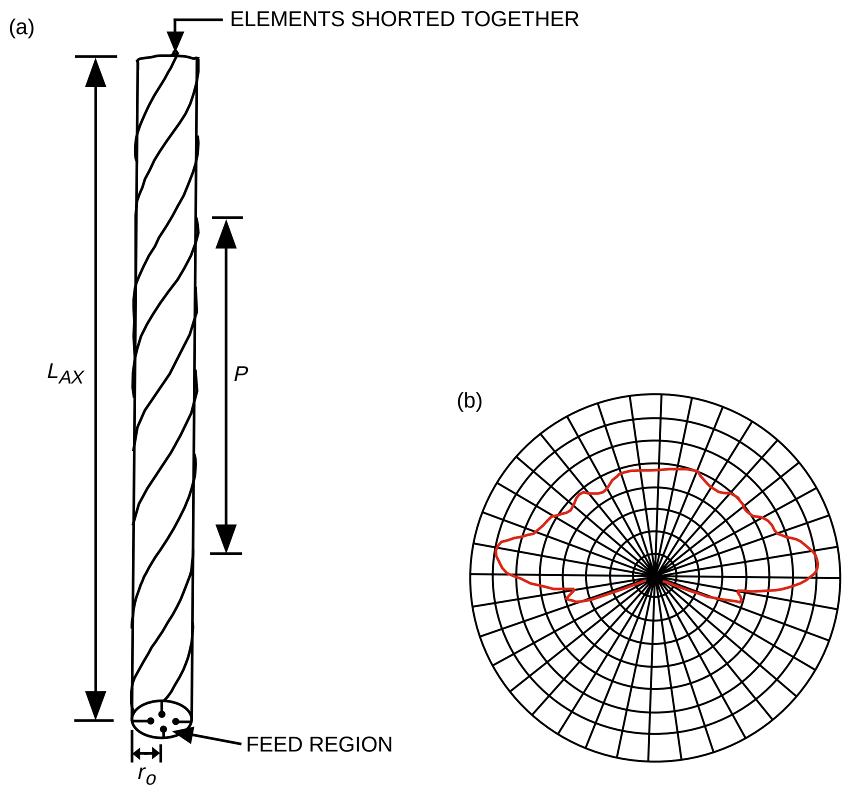

Fig. 7. The normal-mode (a) quadrifilar helix and (b) its radiation pattern.

D. Monopole Antenna

The simplest antenna would be the monopole whip antenna with a height of approximately 1/4 wavelength or 25 cm at 400 MHz. If the antenna is vertically positioned, it will radiate a vertically polarized field with a broad null in its axial direction (zenith direction) and its peak radiation pointed at approximately 35 deg above the horizon. Because it is linearly polarized, it suffers a 3-dB reduction in communication linkage if the antenna at the opposite end of the link is circularly polarized. When the monopole is mounted close to the Martian surface, a null will be formed in the horizontal direction due to its field reaction with the Martian soil at a small grazing incident angle, as shown in Fig. 8. For short-distance communication between the lander and the rover with plenty of transmit RF power, such as that for the Mars Pathfinder, this null behavior in the horizontal direction may be ignored. For long-distance communication when the link margin is small, the monopole may not be used for communication between the lander and the rover. The mass of the monopole is estimated to be less than 0.25 kg.

The monopole is suitable for use on a lander or a rover only when the communication link margin is large.

III. Crossed-Slot Patch for Solar-Array Integration

A. Description

A crossed-slot patch [2] is a microstrip antenna element that consists of four 1/4-wavelength-long sub-patches, as shown in Fig. 9. Each sub-patch has a square or slightly rectangular shape with one edge electrically shorted to the common ground plane. This electrical shorting can be accomplished by connecting the sub-patch and the ground plane either by a small, continuous, thin metallic sheet or by many metallic shorting pins (8 to 10 per edge). The four sub-patches are shorted at four sequentially

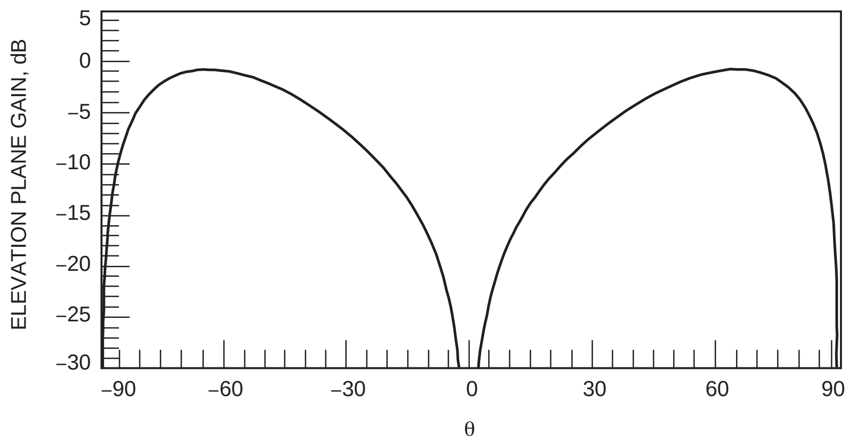

Fig. 8. The pattern of the monopole antenna mounted close to the Martian surface.

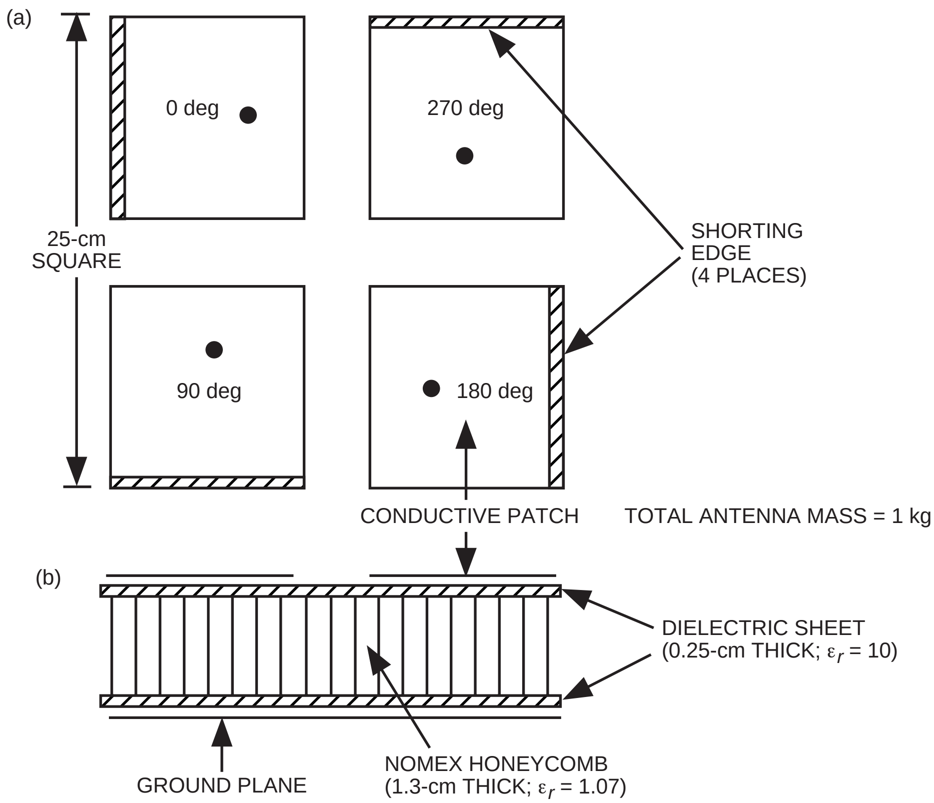

Fig. 9. The crossed-slot microstrip patch antenna with a honeycomb substrate and relatively thick and high-dielectric-constant face sheet: (a) top view and (b) side view.

located edges. The four sub-patches also are excited at four sequentially located 50-ohm input impedance points by four coaxial probes. These four feed probes then are combined behind the ground plane by a hybrid circuit that provides the needed 0-, 90-, 180-, and 270-deg electrical phases. The four sub-patches are separated from and supported above the ground plane by a one-inch-thick nonconducting honeycomb panel. Since a sub-patch radiates only from its three open edges, foreign low-profile objects (metallic or nonmetallic) can be placed on top of each sub-patch without significantly disturbing the radiation characteristics of the antenna. Consequently, solar cells can be placed on top of the four sub-patches of the crossed-slot patch antenna, as shown in Fig. 10. Although all open edges of the four sub-patches radiate, the major portions of the radiated fields originate at the central crossed slots. Since each slot radiates with a cosinusoidal amplitude distribution with the maximum field located at the slot center, the crossed-slot patch has a very small effective radiating aperture, which leads to a relatively broad far-field beam.

B. Antenna Fabrication and Test

Two differently designed crossed-slot patch antennas were fabricated and tested. One, shown in Fig. 9, uses a substrate with a higher average dielectric constant. The substrate consists of two relatively thick (0.25-cm) dielectric sheets with very high dielectric constant ($\varepsilon_r = 10$) and a 1.3-cm-thick honeycomb with a low dielectric constant ($\varepsilon_r = 1.07$). Each sub-patch has a square dimension of 11.4 cm, and the overall antenna has a dimension of 25-cm square. The second antenna, shown in Fig. 11, uses a 2.5-cm-thick substrate with a very low average dielectric constant of 1.07. The two dielectric sheets are very thin (0.05 mm) with a moderate dielectric constant of 3.5. The overall antenna has a square dimension of 33 cm with each of its sub-patches having a square dimension of 15.2 cm. It is clear that antenna unit one, due to its higher average substrate dielectric constant, has the desired smaller dimension but an undesirable larger mass (1.3 kg) as compared with antenna unit two, which has a total mass of 0.5 kg. Both antennas were tested on a Hewlett Packard (HP)8510 network analyzer for input-impedance matching and on an outdoor far-field range for antenna gains and radiation patterns. The measured input-impedance matches for both antennas are very similar, and only measured impedance of antenna unit two is shown in Fig. 12. It indicates that the antenna achieved a 2:1 voltage standing wave ratio (VSWR) bandwidth (a -10 dB return loss) of 40 MHz to accommodate the transmit frequency of 401 MHz and the receive frequency of 437 MHz.

The measured radiation patterns of the smaller crossed-slot patch with a heavier dielectric-constant substrate are given in Figs. 13(a) and 13(b). The antenna, which achieved a peak gain of 4.5 dB, is mounted at the center of an aluminum ground plane (0.3-cm thick) with dimensions of 50 cm $\times$ 80 cm, as shown in Fig. 10. This ground plane simulates the effect of the solar-cell panel on top of the rover. Portions of the ground plane are on top of the crossed-slot sub-patches to demonstrate that solar cells can indeed be placed on top of the radiating patch antenna. Figure 13(a) gives the pattern along the narrow dimension of the ground plane, and Fig. 13(b) gives the pattern along the broad dimension.

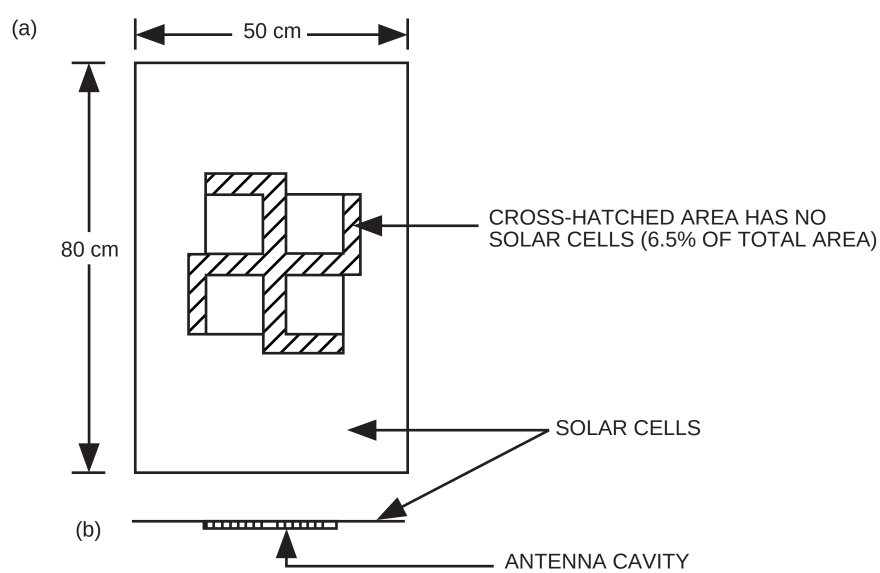

Fig. 10. The integrated solar-array panel with a crossed-slot microstrip patch: (a) top view and (b) side view.

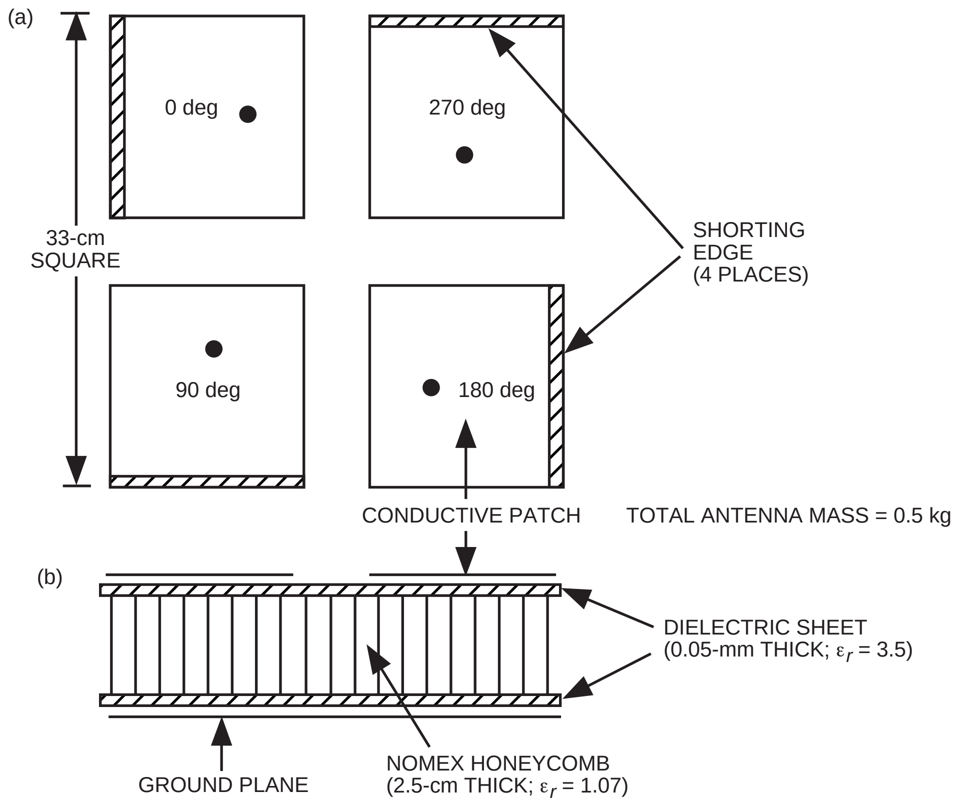

Fig. 11. The crossed-slot microstrip patch antenna with a honeycomb substrate and relatively thin and moderate-dielectric-constant face sheet: (a) top view and (b) side view.

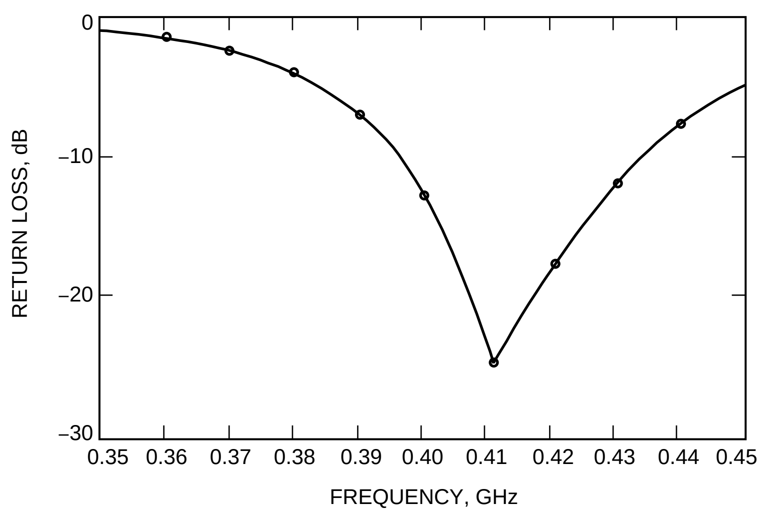

Fig. 12. The measured input return loss of the antenna in Fig. 11.

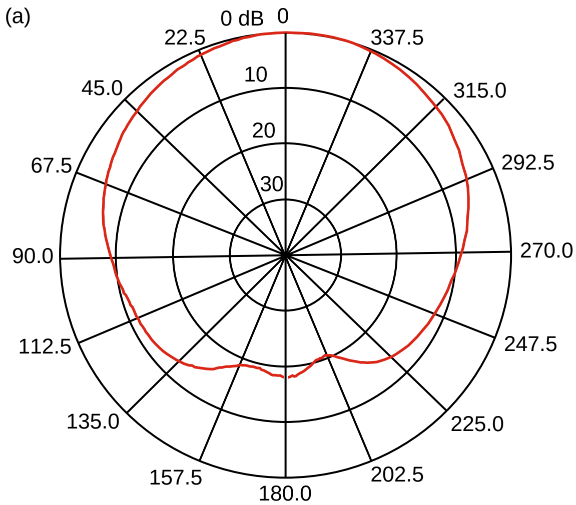

Fig. 13. The measured principal-plane patterns of the antenna in Fig. 9 mounted on a 50-cm×50-cm simulated solar-panel ground plane across: (a) the narrow dimension of the panel and (b) the broad dimension of the panel.

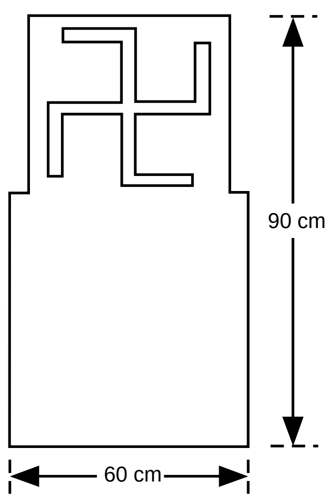

Fig. 14. The simulated solar-panel ground plane with a size of 60 cm×90 cm.

The antenna, measured at a representative frequency of 410 MHz, has a peak gain of 4.5 dB. From these patterns, it is clear that the low-profile crossed-slot patch antenna does radiate a relatively broad beam and is capable of integrating with the solar array. The radiation patterns of the larger crossed-slot patch antenna with a lower dielectric-constant substrate also are measured. This time the antenna is mounted on the front portion of a slightly larger aluminum ground plane (60 cm × 90 cm), as depicted in Fig. 14. Again, portions of the ground plane are placed on top of the four sub-patches to simulate the solar panel. The measured radiation patterns along four different directions ($\phi = 0$, 45, 60, and 90 deg) of the ground plane are given in Figs. 15(a) through (d). The $\phi = 0$-deg cut is along the narrow dimension of the ground plane, while the $\phi = 90$-deg cut is along the broad dimension. Again, a relatively broad beam radiation is achieved from the crossed-slot patch with a peak gain of 5.0 dB. Some asymmetry in the pattern shape is observed, which is due to the asymmetric mounting of the radiator at the front portion of the ground plane instead of at the center.

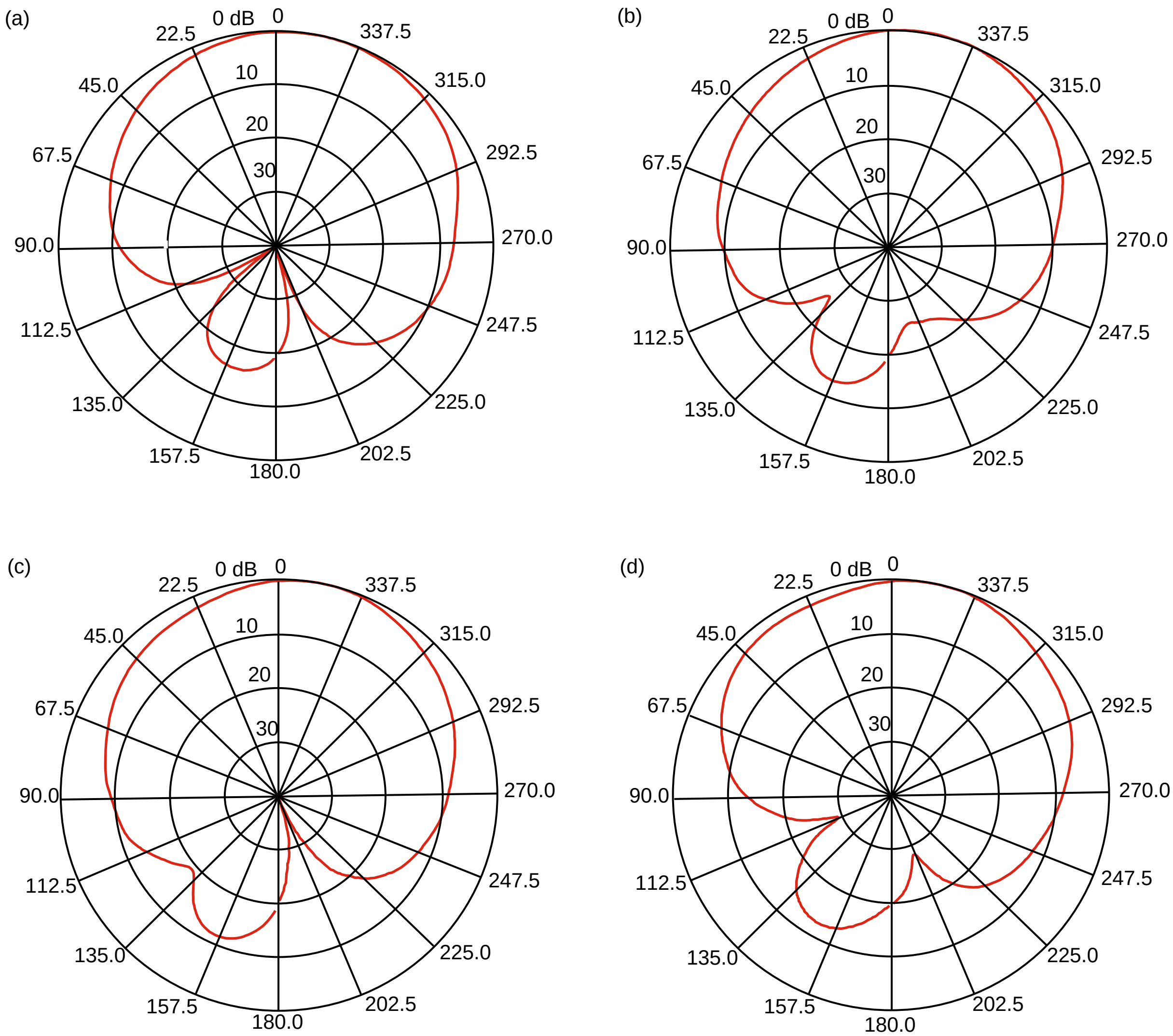

Fig. 15. The measured patterns of the crossed-slot patch in Fig. 11 mounted on the simulated solar panel in Fig. 14: (a) ϕ= 0-deg cut, (b) ϕ= 45-deg cut, (c) ϕ= 60-deg cut, and (d) ϕ= 90-deg cut.

A feature of the rover system that is undesirable to the antenna system requires a tall mast to be deployed above the solar panel to support a video camera and other electronic devices. This tall mast will obstruct the field-of-view of the antenna. The effect of this mast obstruction was measured at the antenna range. The mast was simulated by an aluminum tube 7.5 cm in diameter and 0.9 m in height and was mounted at one corner of the ground plane away from the crossed-slot patch antenna. The measured radiation patterns with the effect of this mast are given in Figs. 16(a) through (d). Again, four different pattern cuts along the four different ground plane directions are made. The effect of the mast is obvious in these patterns, where pattern asymmetry and gain reduction clearly are shown, especially in the low elevation direction of the ϕ = 60-deg cut. However, the effect of this tall mast does not seem to be detrimental to the overall telecommunications system. A certain amount of sacrifice of the telecommunications system must be accepted to accommodate other important systems on the physically small rover.

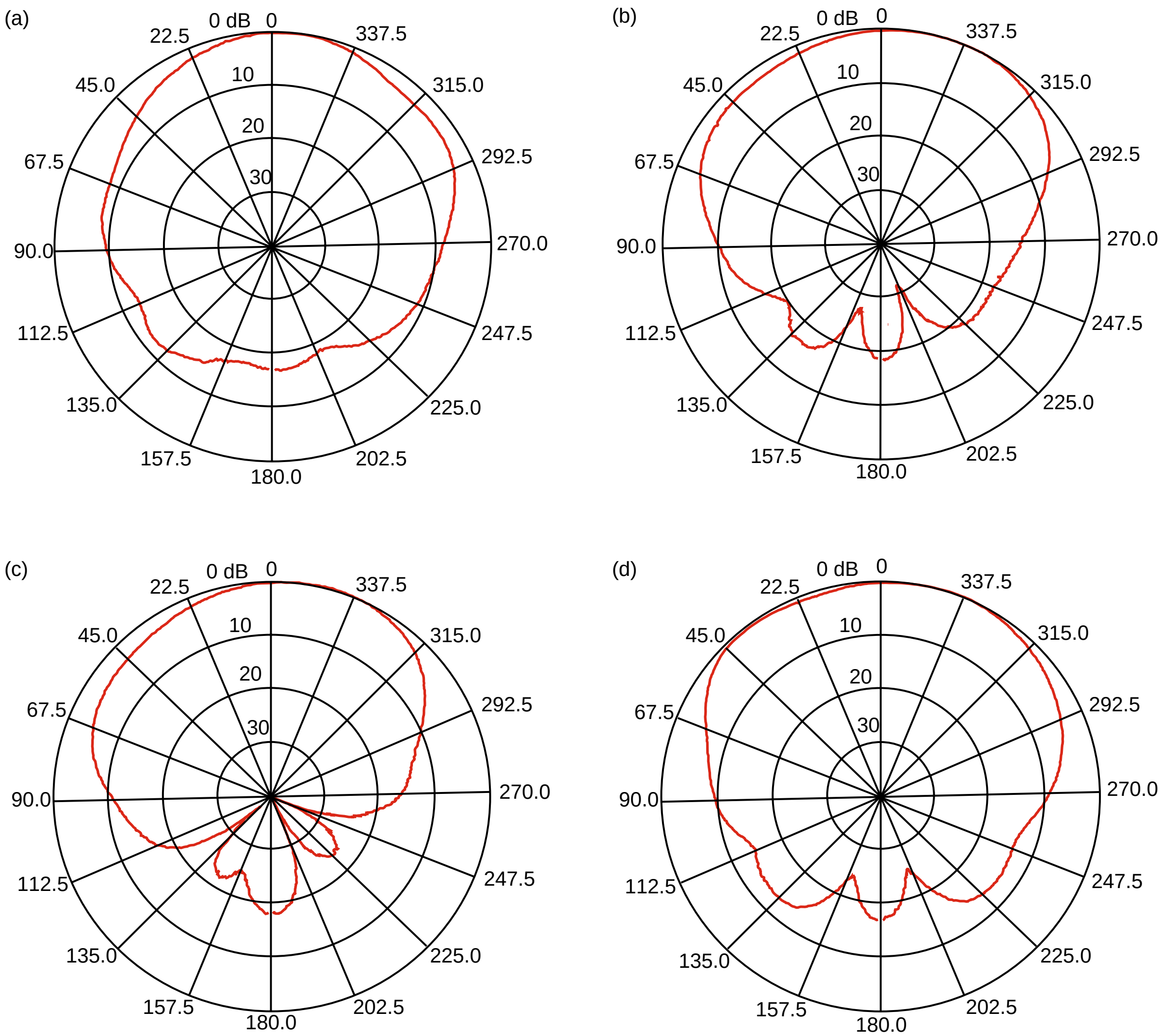

Fig. 16. The same measured patterns as in Fig. 15 except with a tall cylindrical mast mounted at one corner of the simulated solar panel: (a) ϕ= 0-deg cut, (b) ϕ= 45-deg cut, (c) ϕ= 60-deg cut, and (d) ϕ= 90-deg cut.

IV. Conclusion

Several UHF omni-directional low-gain antennas have been studied for possible installation on the 2001 Mars rover for communication with a Mars orbiter. A crossed-slot patch antenna has been selected for more extensive study due to its low profile, small mass, and ability to be integrated with the rover solar panel. With this antenna, the premium real estate of the small rover can be more effectively utilized. Two different designs of the crossed-slot patch were fabricated and tested. A simulated solar panel was integrated with the antenna. The needed broad omni-directional patterns with sufficient gain were achieved for both antennas. This type of patch antenna may be an attractive option for future rover telecommunications systems.

References

[1] A. Kumar, *Fixed and Mobile Terminal Antennas*, Boston, Massachusetts: Artech House, pp. 164–215, 1991.

[2] J. R. James and P. S. Hall, *Handbook of Microstrip Antennas*, London, England: Peter Peregrinus Ltd., 1989.