ALLAN R. JABLON and ROBERT K. STILWELL

SPACECRAFT REFLECTOR ANTENNA DEVELOPMENT: CHALLENGES AND NOVEL SOLUTIONS

Spacecraft microwave systems, such as radar altimeters, high-data-rate communications systems, and angle-tracking systems, often require high-gain narrow-beamwidth antennas. In many cases, these antennas must be able to accommodate multiple frequencies and polarizations simultaneously, as well as meet stringent thermal and mechanical constraints. The parabolic reflector antenna has the potential to meet these special demands efficiently and cost-effectively, but adapting it to satisfy spacecraft antenna requirements poses unique challenges. In recent years, the APL Space Department has developed several innovative designs for spacecraft reflector antennas, along with novel numerical analysis methods for characterizing their performance.

INTRODUCTION

Antennas for radar altimeter and angle-tracking microwave spacecraft systems must have high gain and narrow beamwidth so that their energy output is confined to a limited angular region in space. Often, the beam must be circularly symmetric. High-data-rate communication systems require high-gain antennas to meet link requirements.

A primary function of these antennas is to control the distribution of the radiated energy in space, which is described by the antenna power gain. Gain in a particular direction is defined as

$$G(\theta,\phi)=\frac{4\pi U(\theta,\phi)}{P_{\text{in}}} \quad (1)$$

where $U(\theta,\phi)$ is the radiation intensity (power radiated per unit solid angle), and P_{in} is the power delivered to the antenna. For circular aperture symmetry, the antenna beamwidth, BW, is inversely proportional to the square root of the maximum power gain, G (also called simply "gain"):

$$BW \propto \frac{1}{\sqrt{G}}\,. \quad (2)$$

High antenna gain implies a large antenna aperture or surface area. Such an aperture could be achieved via a relatively complex and expensive array antenna or even a long and bulky horn or helix antenna, but the simplest, most cost-effective solution is the parabolic reflector antenna, a quasi-optical device that collimates the energy from a feed placed at the reflector focal point. Despite the relative maturity of the art of reflector design, the stringent constraints imposed by spacecraft create unique design and analysis challenges for spacecraft reflector antenna development.

THE PARABOLIC REFLECTOR ANTENNA

Figure 1 depicts the behavior of geometric optics rays in the presence of parabolic reflectors with a focal feed (Fig. 1A) and in a folded-optics configuration with a subreflector (Fig. 1B). The paraboloid, which is the three-dimensional counterpart of the parabola, is useful in electromagnetics because (1) the paraboloid reflects an electromagnetic ray emanating from the focus in a direction parallel to the paraboloid axis, and (2) the distance traveled by any ray from the focus to the paraboloid and then to a plane perpendicular to the paraboloid axis is independent of the path. Therefore, the wave propagating from a parabolic reflector is approximately a plane wave.

A more accurate picture of parabolic reflector operation can be obtained from diffraction theory; however, the geometric optics approximation is sufficient for a basic understanding.

The geometry of a parabolic reflector (i.e., the shape of the surface) is completely described by its diameter and its focal length. In operation, a feed antenna located at the paraboloid focal point launches electromagnetic waves. The feed beamwidth must be wide enough to efficiently illuminate the reflector, yet narrow enough to

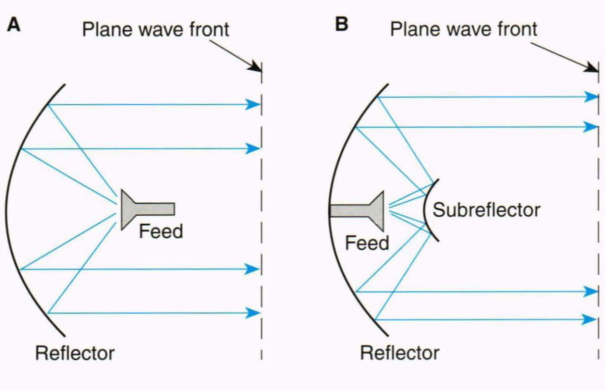


Figure 1. A parabolic reflector returns geometric optics rays emitted from the focus in a direction parallel to the paraboloid axis. All waves travel the same distance, independent of path. **A.** Focal-feed configuration. **B.** Folded-optics configuration.

avert significant loss of energy beyond the reflector edge. The most widely used feed antennas are waveguide horns, helices, and dipoles.

SPACECRAFT REFLECTOR ANTENNA DESIGN

Feed design is the most complicated part of reflector antenna design. Feed design for spacecraft reflector antennas is especially challenging because the antenna must often perform several functions simultaneously to meet spacecraft space constraints. For example, feeds may have to provide for multiple polarizations, multiple frequencies, or both. The feed radiation pattern, commonly referred to as the "primary pattern," must provide an illumination function that produces either maximum gain or reduced sidelobe levels in the reflector radiation pattern, known as the "secondary pattern."

Other feed design considerations include polarization, input impedance, beam circularity, and physical size. For a circularly polarized antenna, the degree of polarization purity is usually described by the axial ratio, which is the ratio of the major and minor axes of the polarization ellipse. The polarization purity for either linear or circular polarization can be described by the polarization ratio, which is the ratio of the cross-polarized and co-polarized components of the electric field. Antenna input impedance must be designed to minimize input signal reflections, which are described by the input voltage standing-wave ratio (VSWR). A circularly symmetric primary pattern is desirable because it produces a secondary pattern with high efficiency and beam symmetry. Feed size is limited by restrictions on feed and feed support aperture blockages, which can affect gain and sidelobe levels.

Random and non-random surface shape errors in reflector antenna design are also important because they can affect gain, sidelobes, and beam pointing. In spacecraft reflector antennas, thermal gradients leading to surface shape irregularities can affect antenna performance adversely.

In addition to electrical aspects, the reflector, feed, and feed support structure must be mechanically designed to withstand launch stresses. Materials must also meet requirements for electrical conductivity, weight, structural integrity, thermal properties, and outgassing.

Another significant issue for spacecraft reflector antennas is boresight alignment. The narrow beamwidth of the reflector antenna, as well as the uncertainty of determining exact spacecraft attitude, imposes particularly stringent boresight alignment requirements on spacecraft reflector antennas. Optical and mechanical methods must be developed to determine boresight alignment errors accurately.

Given the many factors that enter into antenna design, it is clear that design engineers must have adequate analytical methods for predicting antenna performance. For example, techniques for structural and electromagnetic analysis are needed to characterize reflector distortions and associated electrical effects caused by thermal gradients, as well as feed motion induced by thermal effects.

REFLECTOR ANTENNAS FOR RADAR ALTIMETERS

The APL Space Department has been a leader in the field of satellite radar altimetry for ocean surface measurements since the NASA Seasat program in 1978. These systems accurately measure the distance between the satellite orbit and a subsatellite point on the ocean surface with a precision of a few centimeters, providing data on the Earth's gravitational field and mesoscale oceanographic features. The antenna for the radar altimeter must have high gain and a narrow, circularly symmetric beam so that the instrument can operate in a pulse-limited mode (where the measurement area on the ocean surface is small with respect to the extent of the antenna beam).

Seasat-A Radar Altimeter Antenna

The National Aeronautics and Space Administration (NASA) Seasat-A was the first Earth satellite designed specifically for oceanographic observations. Among the complement of instruments on board was an APL radar altimeter, a third-generation design built on the experience gained from the Skylab and Geodynamic Experimental Ocean Satellite (GEOS-C) programs. Its function was to measure precisely both the altitude of the satellite above the ocean surface and the significant wave height at the subsatellite point. These measurements were used along with the results of APL's Precision Orbit Determination (POD) experiment to characterize the topography of the sea surface. (The POD experiment determined satellite position using data from a Doppler beacon and a laser reflector array onboard the satellite.)

The radar altimeter operated at a center frequency of 13.5 GHz and generated a linear FM waveform with a peak power of 2.4 kW at a pulse repetition frequency of 1 kHz. The antenna was specified to be nadir-directed and linearly polarized, with a gain of at least 40 dBi (decibels above isotropic). The pencil beam had to be symmetrical (have the same shape in all planes through the beam) with a 3-dB beamwidth greater than 1.5°. No scanning was required.

To meet the antenna requirements, we used a 1-m-dia. parabolic reflector fed by a small flared waveguide horn at the focus. The primary radiation pattern had to illuminate the reflector efficiently without excessive energy "spill" over the edge. In addition, the beamwidths of the E-plane (plane parallel to the electric field) and H-plane (plane parallel to the magnetic field) had to be equal so that the secondary pattern was symmetrical. A simple flared horn fed from a rectangular waveguide supporting only the dominant transverse electric mode TE_{10} will naturally radiate with linear polarization. To avoid a high VSWR, the horn had to be sized so that the reflections from the beginning of the flare and the aperture canceled at the desired frequency.

Horns made with a flare in just one plane, known as sectoral horns, are amenable to analysis, and their radiation patterns can be calculated rather accurately. However, the Seasat-A feed horn had to be flared in both planes simultaneously. The analysis of such a compound horn is more difficult because aperture dimensions and flare length interact to influence E- and H-plane patterns, as well as impedance match. For the analysis, APL drew on the work of the M.I.T. Radiation Laboratory, which studied the design of small compound horns extensively during World War II. Coupling approximate theory with the results of experimental studies, M.I.T. devised a design procedure for obtaining desired E- and H-plane beamwidths while maintaining a good match to waveguide with arbitrary dimensions.[1] APL used this procedure in the Seasat-A design to create a reflector pattern whose power density was 20 dB lower at the edge than at the center.

The mechanical design of the Seasat-A antenna had to include provisions for (1) positioning the electrical phase center of the horn axially to coincide with the focus of the paraboloid, and (2) aligning the beam peak normal to the antenna mounting plate and, eventually, with the spacecraft axis. We focused the horn axially by maximizing the depth of the first nulls off the main lobe in the radiation pattern, and located the beam peak by splitting the −6-dB angles.

The Seasat-A radar altimeter antenna operated over a frequency band of 13.32 to 13.68 GHz and delivered a minimum boresight gain of 40.5 dBi, a maximum sidelobe level of −27 dB, a 1.52° minimum −3-dB beamwidth, and a maximum deviation from beam circularity of 3%. A photograph of the electrical model antenna is shown in Figure 2.

Launched into orbit aboard Seasat-A on 27 June 1978, the APL radar altimeter operated successfully; the GEOS-C satellite and surface measurements verified its waveheight observations. The altimeter achieved a measurement precision of 10 cm, compared with precisions greater than 50 cm for earlier instruments. Unfortunately, a malfunction in the spacecraft power system caused the failure of the entire satellite after sixty-nine days of operation.

Geosat-A Radar Altimeter Antenna

The few data collected by Seasat-A proved so useful for research in geodesy and oceanography that a new dedicated radar altimeter satellite was clearly needed. Thus, the U.S. Navy and APL made plans to fly a Seasat-type altimeter on the Geosat-A satellite but with an improved traveling wave tube and instrumentation and a modified antenna.

The antenna modifications were necessary because the attitude control system of the Geosat-A spacecraft was less accurate than that of the much larger and complex Seasat spacecraft. Specifically, the design −3-dB beamwidth was increased to 2.1° so that the subsatellite point would always be effectively illuminated by the radar altimeter. Gain was expected to be reduced to 37.6 dBi.

The most straightforward way of modifying the electrical characteristics would have been to use a slightly smaller reflector than on the Seasat with a similar or identical feed horn. However, since the Geosat altimeter was supposed to be as nearly identical to the Seasat instrument as possible, APL wanted to maintain the same reflector size and mechanical design. The APL designers therefore increased the secondary beamwidth by decreasing the beamwidth of the feed horn so that the outer portion of the reflector received negligible illumination.

However, we encountered other difficulties. When we tried to determine the secondary radiation pattern using the aperture integration method and the pattern from an open-ended waveguide to approximate the primary pattern, we found that the horn aperture dimensions would have to be increased by nearly 50% to increase the secondary beamwidth to 2.1°. The M.I.T. Radiation Laboratory design technique[1] for determining the flare lengths needed to impedance match such a horn showed that the final design was too large for the Seasat-A system of feed struts; thus, some mechanical redesign was required after all.

The electrical characteristics of the Geosat-A radar altimeter antenna demonstrated some of the problems encountered in the underillumination of a parabolic reflector. The actual −3-dB beamwidth was somewhat less than the 2.1° initially sought, possibly because we used open-ended waveguide patterns were used to represent a compound horn in the numerical modeling. Simply equalizing the E- and H-plane primary pattern beamwidths does not ensure good beam symmetry as the feed horn grows: the 45° and 135° planes narrow, resulting in a "square" secondary beam. Reflections from the vertex back into the feed also become problematic as the horn gain increases, causing a higher VSWR.

Geosat-A was launched on 12 March 1985 and successfully completed its five-year mission. The instrument

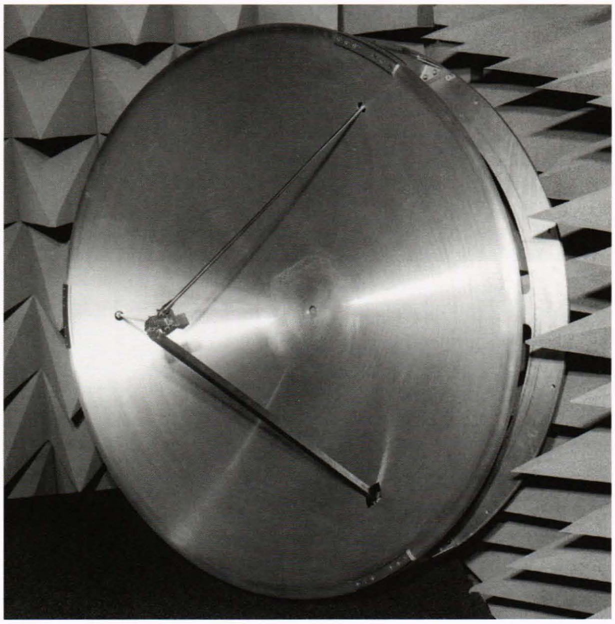


Figure 2. Electrical model of the antenna for NASA's Seasat-A radar altimeter, the first satellite designed for studying oceanography. This antenna is a 1-m-dia. parabolic reflector with a compound rectangular horn feed. The Laboratory used techniques developed by the M.I.T. Radiation Laboratory to design the flared compound feed horn.

achieved a measurement precision of 3.5 cm. Its radar altimeter antenna as launched operated over the 13.32- to 13.68-GHz frequency band with a minimum boresight gain of 38.1 dBi, a maximum sidelobe level better than −20 dB, a minimum −3-dB beamwidth of 1.85°, and a maximum deviation from beam circularity of 8.8%. Since the Geosat-A spacecraft attitude system proved to be more accurate than was originally presumed, the narrowing of the antenna beam did not affect the system adversely. The beam symmetry was not as true as that of Seasat-A, but it was within the specified 10%. The increase in VSWR was also acceptable. A photograph of the flight altimeter is shown in Figure 3.

TOPEX Radar Altimeter Antenna

The Ocean Topography Experiment (TOPEX)/Poseidon satellite is a joint U.S.-France—NASA-CNES (French national space agency)—spacecraft launched in August 1992 to collect ocean surface data. The spacecraft carries the TOPEX and Poseidon radar altimeters, which are being used to map the global circulation of the oceans.

The TOPEX radar altimeter, designed and built by APL, is the highest precision satellite radar altimeter orbited to date, measuring the ocean surface to a precision of less than 2 cm. It is a dual-frequency instrument, operating at center frequencies of 5.3 GHz (C-band) and 13.6 GHz (Ku-band), with a peak power of 20 W. The use of two frequency bands allows corrections for ionospheric effects. The French-built Poseidon radar altimeter operates at Ku-band. A common antenna is used for the two altimeters.

The antenna, shown in Figure 4, is a focal-feed 1.5-m-dia. parabolic reflector antenna with capabilities for handling two frequencies and three separate signals (linearly polarized).[2] To accommodate the two separate Ku-band signals (one for TOPEX, one for Poseidon) with sufficient isolation, the signals were launched with orthogonal polarization via an orthomode transducer, a device that accepts two signals from separate rectangular waveguide ports and outputs them orthogonally polarized in a common circular waveguide (Fig. 5).

The complex feed requirements imposed several stringent criteria on the antenna feed horn. First, it had to be a dual-band feed horn with a common phase center at the two frequency bands. Second, horn geometry had to be circularly symmetric to accommodate the dual polarizations and three separate signals. Finally, the feed horn had to produce a circularly symmetric primary pattern to ensure secondary pattern circularity and low cross polarization. To meet these requirements, APL designed a dual-

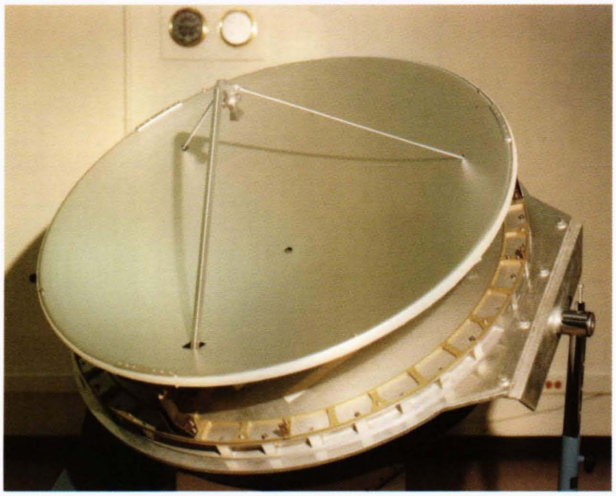


Figure 3. Flight radar altimeter for the Geosat-A oceanography satellite. The antenna consists of a 1-m-dia. parabolic reflector with a compound rectangular horn feed. The antenna is approximately the same size and design as that for the Seasat-A, but has a larger 3-dB beamwidth to compensate for lower accuracy in the spacecraft attitude system.

Figure 4. The radar altimeter flight antenna for the Ocean Topography Experiment (TOPEX)/Poseidon satellite. The antenna consists of a 1.5-m-dia. reflector with a dual-frequency, three-port feed. Dual orthogonally polarized signals are launched via an orthomode transducer (see Fig. 5).

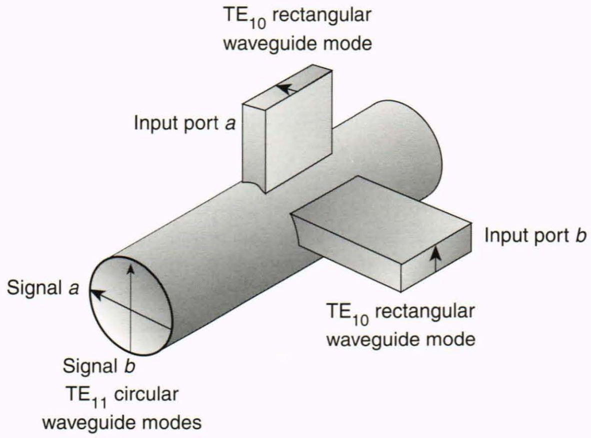
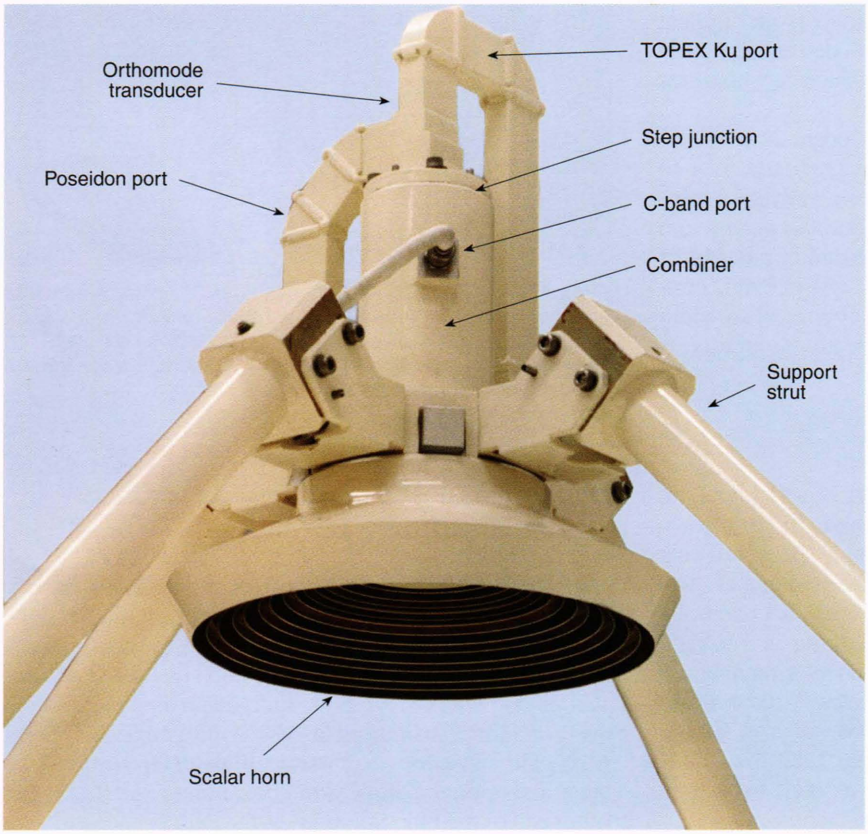


Figure 5. The orthomode transducer used in the Ocean Topography Experiment (TOPEX)/Poseidon satellite radar altimeter antenna. The transducer launches two Ku-band signals with orthogonal linear polarizations in circular waveguide, one for each instrument.

depth, corrugated, conical scalar (wide-flare) horn.[3-5] Corrugations on the walls create infinite surface impedance, resulting in equal E- and H-plane beamwidths. The horn propagates the HE_{11} mode (hybrid mode, transverse electric predominant), which is a combination of transverse electric TE_{11} and transverse magnetic TM_{11} circular waveguide modes propagating at the same phase velocity. The wide-flare geometry provides a fixed-phase center over a broad frequency band. The feed is shown in Figure 6A.

A major design challenge was devising a means of inputting the Ku- and C-band signals through a common waveguide (combining section) to the feed horn. Since Ku-band waveguide is smaller than C-band waveguide, the combining section waveguide diameter had to be large enough for the C-band signal. Initially, we fed the C-band signal by coaxial cable into the combining section waveguide in the dominant TE_{11} circular waveguide mode while the Ku-band signals were fed from behind using the dominant TE_{11} mode. A tapered waveguide provided the transition between the Ku-band circular waveguide and the combining section waveguide. To increase Ku-band signal coupling to the horn and to broaden the beamwidth, we replaced the tapered waveguide transition with a step junction mode transducer, which introduces the TE_{11} and TM_{11} circular waveguide modes in the combining section waveguide at Ku-band (Fig. 6B).[6] The length of the combining section

A



B

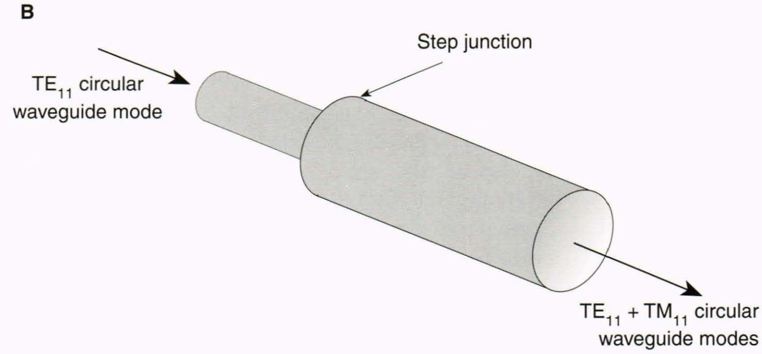


Figure 6. The Ocean Topography Experiment (TOPEX)/Poseidon radar altimeter flight antenna feed. **A.** The feed consists of a dual-depth conical corrugated (scalar) horn, a common waveguide for both C- and Ku-band signals (combiner), and an orthomode transducer (Fig. 5). **B.** Step junction mode transducer used to convert a Ku-band signal in the smaller waveguide from the dominant transverse electric TE_{11} waveguide mode to a combination of TE_{11} and transverse magnetic TM_{11} modes in the larger waveguide. The length of the larger waveguide is adjusted to ensure that the two modes are in phase at the waveguide–horn junction.

waveguide was adjusted to ensure that the two modes were in phase at the horn throat. For maximum isolation between the C-band probe and the Ku-band inputs, the probe was physically situated at a 45° angle from the electric fields of the two Ku-band signals.

To achieve VSWR requirements at C-band, we designed a vertex matching plate and placed it at the vertex of the reflector.[7] The plate changes the phase of the feed reflections from a small circular region in the reflector center so that they cancel feed reflections from the rest of the reflector, thereby improving the feed VSWR. Using a vertex matching plate incurs a slight increase in secondary pattern sidelobe and cross-polarization levels.

The 1.5-m-dia. reflector was fabricated with lightweight honeycomb-core aluminum to save weight. The resulting reflector weighed only 20 lb versus 40 lb for the more conventional spun aluminum material.

The antenna boresight alignment accuracy requirement was 0.05°. To meet this stringent standard, we developed a boresight alignment method using transits and optical surfaces. This method was successful in delivering highly accurate boresight alignments and has since been used for several reflector antennas.

The TOPEX radar altimeter antenna operates over frequency bands of 13.44 to 13.76 GHz (Ku) and 5.14 to 5.46 GHz (C). At Ku-band, the antenna delivers a minimum boresight gain of 43.3 dBi, a minimum beamwidth of 1.0°, a maximum deviation from beam circularity of 7.2%, and a maximum VSWR of 1.3:1. At C-band, minimum boresight gain is 35.0 dBi, minimum beamwidth is 2.7°, maximum deviation from beam circularity is 4.8%, and maximum VSWR is 1.25:1.

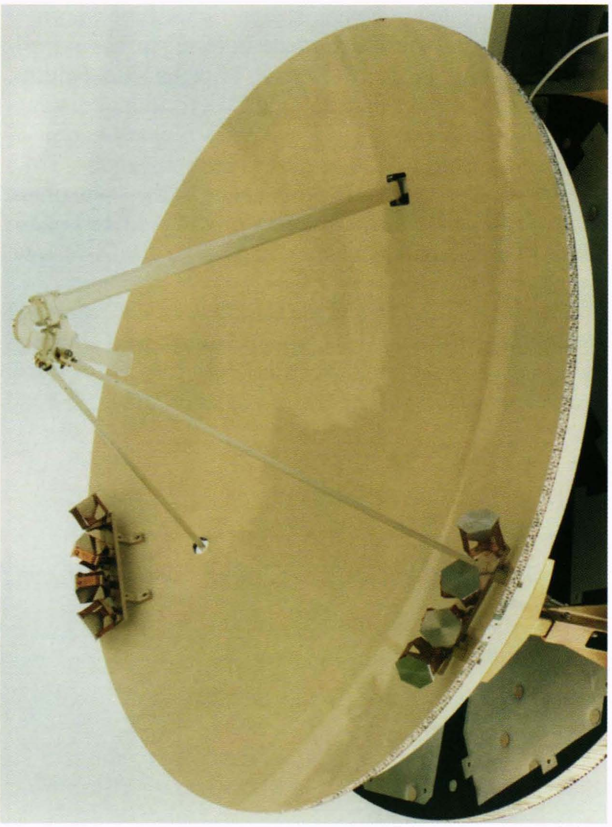


Figure 7. The Spinsat Radar Altimeter (SALT) flight antenna. The antenna consists of a 36-in.-dia. parabolic reflector with a compound rectangular horn feed. A laser reflector array is installed on the reflector to save space; the resulting aperture blockage decreases antenna gain only slightly.

Spinsat Radar Altimeter Antenna

The Spinsat Radar Altimeter (SALT) is a lightweight, high-performance instrument designed to be flown aboard a lightsat (i.e., a relatively small spacecraft that generally carries only one scientific instrument). The SALT antenna, shown in Figure 7, is a 36-in.-dia. parabolic reflector with a focal point feed operating at Ku-band (13.6-GHz center frequency). The feed is a rectangular horn similar to the one used on the Seasat-A radar altimeter antenna; the feed design procedure was also similar to that used for the Seasat-A antenna. Like the TOPEX antenna, the SALT antenna reflector was built from low-mass, honeycomb-core aluminum.

Intended to fly aboard the relatively small Scout launch vehicle, the SALT design included a laser reflector array (LRA) to aid in the orbital location of the spacecraft. Since both the LRA and the maximum antenna aperture size could not fit in the limited space available inside the launch-vehicle fairing, the LRA was placed on the reflector surface. The Laboratory's analysis of the configuration showed acceptable antenna gain despite the resulting aperture blockage. The SALT antenna operated over the frequency band 13.44 to 13.76 GHz, and achieved a minimum boresight gain of 40.0 dBi, a minimum −3-dB beamwidth of 1.71°, a maximum sidelobe level of −26.0 dB, a maximum VSWR of 1.22:1, and a maximum deviation from beam circularity of 2.5%.

COMMUNICATIONS ANTENNAS

High-gain antennas are often required to satisfy link requirements for high-data-rate communications systems. For these antennas, high gain is the most important requirement; the beam shape and sidelobe levels are secondary. Unlike low-gain, wide-beam antennas, which are used for transmitting over a wide geographic area, high-gain spacecraft communications antennas must be accurately pointed at the ground station or satellite at the other end of the link. Sometimes, the entire spacecraft can be maneuvered to achieve the proper orientation. In other cases, the antenna must be pointed by a one- or two-axis positioner.

Delta 181 Test Object Antenna

The Delta 181 spacecraft mission had multiple objectives: (1) to investigate the characteristics of rocket motor plumes in the space environment, (2) to generate a multispectral database of test object observations, (3) to characterize the background environment in low-Earth orbit, and (4) to allow evaluation of state-of-the-art sensors operating in orbit.

The design called for commands to be sent to the test objects in the Delta 181 sensor module at C-band (5690 MHz) via an RF system, and for telemetry to be received at S-band (2374.5 MHz). A very-high-gain antenna was needed to support these links, but packaging constraints limited the available aperture to only 13 in. The Delta 181 antenna also had to be circularly polarized so that the orientation of the linearly polarized test object antennas would not be a problem.

The challenge was therefore to design a circularly polarized, dual-frequency, 13-in.-dia. parabolic reflector antenna. A number of techniques allow dual-frequency use from a single reflector. For example, frequency-selective surfaces used as subreflectors allow both focal feeding and Cassegrainian operation.[8] Multiple-frequency feeds such as coaxial horns are also possible.[9] However, our initial investigation indicated that the Delta 181 reflector diameter was too small a multiple of wavelengths to make these techniques practical. A first cut at the design of a coaxial S-band/C-band horn as a focal feed indicated that it would block an unacceptably high percentage of the 13-in.-dia. aperture.

One possibility was to use a backfire bifilar helix as a feed. These antennas are attractive for several reasons: they have been used as broad-beam telemetry antennas in the past,[10] they are simple in construction, they produce good circular polarization, and they are fairly small in diameter. Good reflector performance was obtained at both S- and C-band with a bifilar helix feed in a 13-in.-dia. dish, although combining the two was a problem. Mounting a C-band helix in front of an S-band helix resulted in excessive separation between the electrical phase centers at the two frequencies, preventing simultaneous focusing and reducing performance.

The solution to the problem was to modify another type of antenna, known as a short backfire antenna.[11] This kind of antenna uses a flat main reflector with a shallow rim, fed by crossed dipoles one-quarter wavelength above the reflector. A small, half-wavelength-diameter disk, located one-half wavelength above the main reflector, acts as a subreflector. A two-wavelength-diameter main reflector produces gains on the order of 15 dBi. Since the Delta 181 13-in.-dia. dish was not much more than two wavelengths in diameter at S-band, we tested a short backfire feed installed at the vertex of the dish. The feed operated well at S-band, but the subreflector severely degraded the performance of a C-band bifilar helix at the focus. We eliminated the problem by replacing the solid disk subreflector with tuned parasitic crossed-dipole reflectors. The final configuration is shown in Figure 8, a photograph of the flight antenna.

At S-band, the boresight gain of the Delta 181 dual-frequency reflector antenna was 15 dBic (decibels above isotropic circular). Other performance parameters were a −3-dB beamwidth of 27°, a VSWR of 1.26:1, and a cross-polarization ratio over the 3-dB beamwidth of 11.5 dB. At C-band, maximum gain was 24 dBic. Other parameters were a −3-dB beamwidth of 9.5°, a VSWR of 1.26:1, and a cross-polarization ratio over the 3-dB beamwidth of 18.0 dB.

The Delta 181 spacecraft was launched from Cape Canaveral on 8 February 1988. Two groups of test objects were deployed and observed during the mission. All primary mission objectives were fully met.

X-Band Science Data Link Antennas for the Midcourse Space Experiment

The Midcourse Space Experiment (MSX) spacecraft, currently under development at APL, will carry out sensor, targeting, and surveillance experiments for the Ballistic Missile Defense Organization. The primary science data link is an X-band system with two (redundant) 8-in.-dia. parabolic reflector antennas (Fig. 9) pointed at the

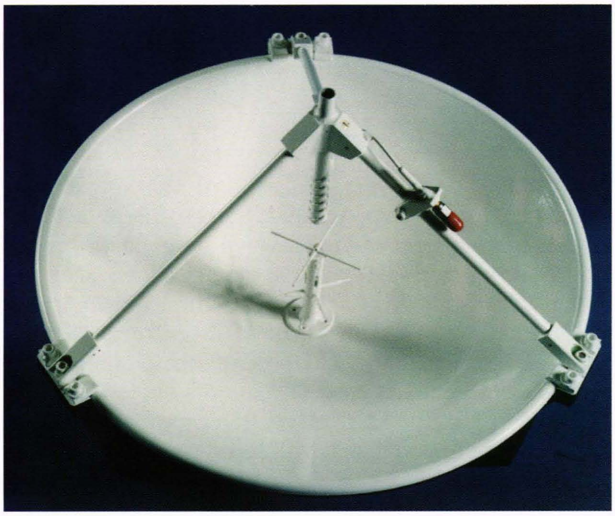


Figure 8. The Delta 181 test object flight antenna. The antenna incorporates a backfire bifilar helix feed for C-band operation and a short backfire antenna for S-band operation. For minimum impact on C-band operation, APL designers replaced the solid disk subreflector with tuned parasitic crossed-dipole reflectors.

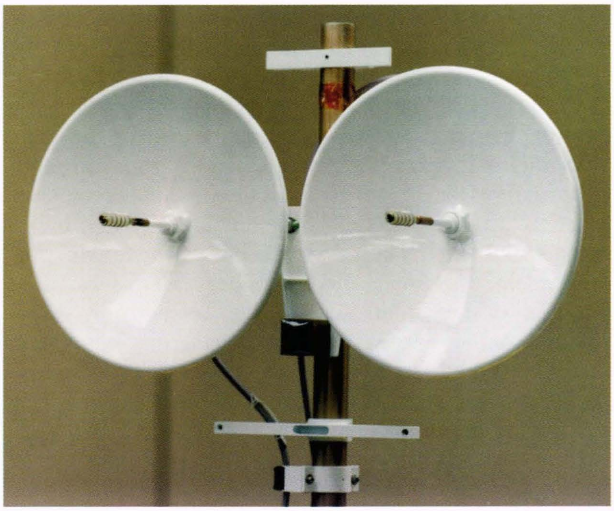


Figure 9. Each of the two Midcourse Space Experiment (MSX) spacecraft X-band flight antennas consists of an 8-in.-dia. parabolic reflector with a monofilar backfire helix. This type of feed is small enough to avert aperture blockage.

receiving groundstation by a two-axis gimballed positioner. The feed for this antenna has to be small enough to avoid unacceptable blockage of the relatively small antenna aperture, a requirement that precludes horn or open-ended waveguide feeds. The solution is a monofilar backfire helix feed consisting of an input coaxial section, a quarter-wave transformer built into the coaxial feed section, a coaxial-to-two-wire (unequal diameter) balun, and a monofilar backfire helix antenna.[12] The feed is supported from the vertex of the reflector, thereby eliminating the need for support struts, which would significantly increase aperture blockage. To survive the stresses of launch, the supporting feed tube is constructed of hardened beryllium-copper, and the helix is supported by a cylinder made of Lexan. The antennas achieve a minimum boresight gain of 22.1 dBic, an axial ratio less than 2.9 dB in the −1-dB beamwidth, and a maximum input VSWR of 1.28:1.

BEACON ANTENNAS

As part of its mission, the MSX will observe various targets via a number of sensors. Some of these sensors have a narrow field-of-view, which complicates open-loop or program tracking of the targets. The beacon receiver onboard the MSX will provide for acquisition and closed-loop angle tracking of cooperative targets using an array of four antennas and passive phase-comparison monopulse techniques to determine the angle of arrival of S-band (2200 to 2270 MHz) transmissions from the targets.[13] The four antennas will be on a square grid with center-to-center spacing of 24 in. on a side. Field-of-view considerations dictate a 3-dB beamwidth for each antenna of approximately 20°. Further, the antennas have to be circularly polarized because the target beacons will be nominally linearly polarized but oriented randomly.

After considering a variety of antenna types, including modified short backfires and helicones, we decided on an 18-in.-dia. parabolic reflector antenna with backfire bifilar helix feeds. This choice was based on the success of the Delta 181 test object antenna, which showed the effectiveness of a bifilar helix feed with a small reflector. In the MSX antenna design, the helical feed was again supported by a tripod mounted to the rim of the dish. Since multipath (stray reflected radiation) from surrounding structures can create errors in the beacon receiver, we tested an electrical model of the antenna to see if cylindrical metal shields could significantly reduce the spillover sidelobes. Only a modest improvement was noted (because of the small size of the antennas in wavelengths), but no degradation was detected in main beam performance, and the shields proved to be advantageous to the thermal control system of the instrument. They were therefore incorporated into the design. The apertures of the antennas are covered by 0.03-in.-thick epoxy glass radomes, but they reduce gain by only 0.3 dB.

During operation of the beacon receiver system, a pilot tone signal will be injected into each of the four channels so that the four-channel receiver can be continuously phase aligned. Since temperature differences among the antennas and connecting cables can create unacceptably high channel-to-channel phase errors, they too must be included in the calibration path of the pilot tone. A simple dipole is often used to inject a calibration signal into the vertex of a parabolic antenna, but half-wave dipoles mounted to the vertices of the small beacon receiver antennas perturb the antenna's radiation performance significantly.

Consequently, we proposed to use a simple quarter-wave monopole mounted at each vertex. If we kept the feed in the null of its radiation pattern by directing the wire of the monopole along the axis of symmetry of the dish, dish performance was not degraded. However, the pilot tone also did not couple into the receiver channels adequately. Our solution was to bend the top portion of the monopole to fill in the null of the monopole's radiation pattern, which increases coupling without significantly affecting performance. The monopole can also be tuned to present a reasonable VSWR to the pilot tone signal.

This simple approach to vertex injection of the pilot tone signal had to be modified because of an unexpected phenomenon: the coupling to the feed helix varied rapidly with frequency and was very sensitive to small changes in orientation and geometry of the bent monopole. To study these effects, we transformed coupling data taken in the frequency domain to the time domain and noted components with very long time delays relative to the dimensions of the antenna. It appeared that the antenna–monople arrangement was acting like a high Q circuit that was "ringing." That is, the antenna was acting like a filter and storing most of its energy rather than radiating it. Concave conducting surfaces, such as the reflector and the cylindrical metal shield, can support the propagation of electromagnetic surface waves that are polarized with the electric field normal to the surface. These waves are analogous to the so-called "whispering gallery modes" of acoustics.[14] Evidently, the vertical portion of the vertex monopole was exciting such waves, which, in turn, caused the frequency and orientation sensitivities. Bending the monople down still closer to the reflector surface to minimize its vertical extent solved the problem without impairing the coupling to the feed, but made the VSWR of the monopole excessive. To compensate, we increased the signal level and added 10-dB attenuators to the inputs of the pilot tone injection ports.

An engineering model of the MSX beacon receiver antennas was assembled, tuned, electrically tested, and evaluated for vibration and thermal-vacuum environmental effects. The flight antennas (Fig. 10) have also been assembled, tuned, electrically tested, and integrated onto the beacon receiver bench, which is undergoing calibration at the APL Space Department's antenna range.

NUMERICAL ANALYSIS AND DESIGN

We use several computer-aided engineering packages to aid in the design and analysis of spacecraft reflector antennas. The primary program is the Ohio State University Numerical Electromagnetic Code-Reflector Antenna Code (NEC-REF), which uses aperture integration and the

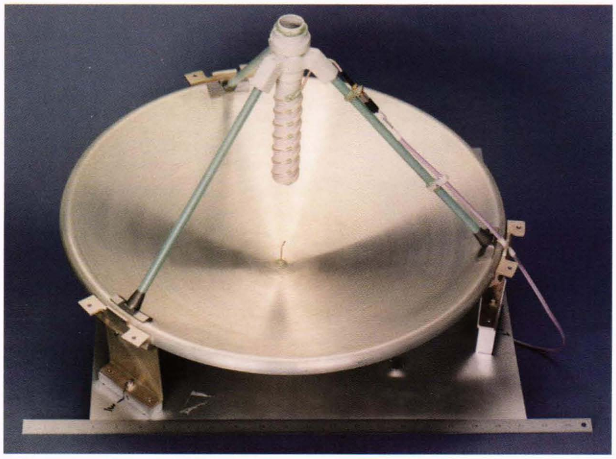


Figure 10. Engineering model antenna for the Midcourse Space Experiment (MSX) spacecraft. The antenna array consists of four 18-in.-dia. parabolic reflectors with backfire bifilar helix feeds in a square geometry. A quarter-wave monopole, mounted at each vertex and bent to fill the monopole null, produces an acceptable compromise between degree of signal coupling and dish performance.

geometrical theory of diffraction to predict the antenna patterns of reflector antennas.[15] The program accurately calculates gain, beamwidth, and sidelobes and can account for aperture blockage due to the feed and feed support struts. Measured feed pattern data, including phase errors, can be used to simulate the feed. The model also calculates farfield and nearfield patterns, plus the effects of a limited number of nearby objects. Radiation hazards can also be assessed. Other software packages used in reflector antenna design include horn and wire antenna analysis programs.

We have used the NEC-REF code to evaluate the effects of feed and feed support aperture blockage for the TOPEX, SALT, and MSX antennas, as well as radiation hazard effects for the MSX antennas. In addition, by manipulating the primary pattern phase distribution, we were able to determine the secondary patterns due to a shaped reflector for the NASA Advanced Composition Explorer program.

An important issue in spacecraft reflector antenna development is the effect of variations in the thermal environment on-orbit. Thermal gradients can cause reflector distortions and feed displacement, resulting in beam steering and phase changes. Since NEC-REF can analyze perfect reflector surfaces only, we developed a method to incorporate the effects of the reflector distortions and feed displacements into the primary pattern phase distribution.[16] This method employs ray tracing to determine path length changes due to reflector distortions at specified points on the reflector surface. These distortion data are developed by a stress engineer using thermal data and finite-element software such as NASTRAN, the NASA structural analysis program.

Thermal distortion analyses for the TOPEX and SALT radar altimeter antennas determined the magnitude of beam steering due to thermal gradients across the dish surface. For the MSX beacon receiver array, the analysis indicated the relative phase differences between adjacent elements due to thermal distortion.

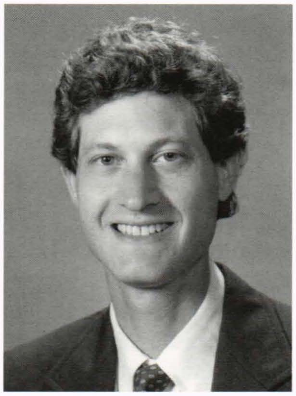
CONCLUSION

Satellite reflector antenna design is a challenging discipline. Depending on the application, antennas may have to provide high gain and narrow beamwidth while accommodating complex, dual-frequency, multifunctional operation; size and mechanical constraints; and special electrical, thermal, and environmental requirements, among others. Designers must anticipate and account for the effects of all these factors and their interactions on antenna performance. The most critical element in the design is the antenna feed. The APL Space Department has developed a combination of innovative design and analysis methods to produce high-gain, narrow-beamwidth, parabolic reflector antennas for spacecraft radar altimetry, angle tracking, and high-data-rate communications. These designs have contributed greatly to the success of such spacecraft missions as Seasat-A, Geosat-A, TOPEX, SALT, Delta 181, and the upcoming MSX.

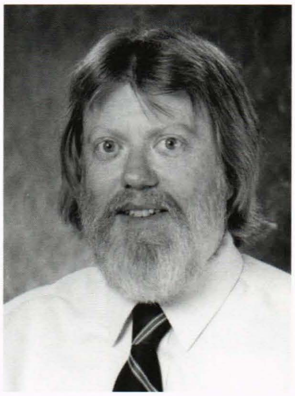
REFERENCES

1. Risser, J. R., *Characteristics of Horn Feeds on Rectangular Waveguide*, MIT Radiation Laboratory Report 656, Cambridge, Mass. (Dec 1945).
2. Jablon, A. R., "TOPEX Spacecraft Dual-Frequency Radar Altimeter Antenna," in *Proc. 1991 Antenna Applications Symp.*, Session IV, Univ. Ill., Robert Allerton Park, Ill. (Sep 1991).
3. Kay, A. F., *The Scalar Feed*, Air Force Cambridge Research Labs Report, AFCRL Rep. 65-347, AD60169 (Mar 1964).
4. Ghosh, S., Atatia, N., and Watson, B. K., "Hybrid Mode Feed for Multiband Applications Having a Dual-Depth Corrugation Boundary," *Electron. Lett.* **18** (20), 860–862 (1982).
5. Thomas, B., "Design of Corrugated Horns," *IEEE Trans. Antennas Propag.* **AP-26**(2), 367–372 (1978).
6. Potter, P. D., "A New Horn Antenna with Suppressed Sidelobes and Equal Beamwidths," *Microwave J.* **1**, 71–78 (1963).
7. Silver, S., *Microwave Antenna Theory and Design*, McGraw-Hill, New York, pp. 443–447 (1949).
8. Agrawal, V. D., and Imbriale, W. A. "Design of a Dichroic Subreflector," *IEEE Trans. Antennas Propag.* **AP-27**, 466–473 (1979).
9. Schennum, G. H., "A Dual-Frequency Coaxial Feed for a Prime Focus Antenna," in *IEEE Antennas Propag. Symp. Dig.*, pp. 236–238 (1973).
10. Stilwell, R. K., "Satellite Applications of the Bifilar Helix Antenna," *Johns Hopkins APL Tech. Dig.* **12**(1), 75–80 (1991).
11. Ehrenspeck, H. W., "The Short Backfire Antenna," *Proc. IEEE* **53**(8), 1161–1162 (1965).
12. Johnson, R. C., and Cotton, R. B., "A Backfire Helical Feed," *IEEE Trans. Antennas Propag.* **AP-32**, 1126–1127 (Oct 1984).
13. Valverde, C. R., Stilwell, R. K., Russo, A. A., Daniels, J., and McKnight, T. R., "Space-Based Angle-Tracking Radar System Design," in *Proc. RF EXPO WEST*, San Diego, Cal., pp. 87–108 (Mar 1992).
14. Walker, J., *The Flying Circus of Physics*, John Wiley & Sons, p. 9 (1975).
15. Chang, Y. C., and Rudduck, R. C., *Numerical Electromagnetic Code–Reflector Antenna Code, NEC-REF (Version 2), Part II: Code Manual*, Report 712242-17, The Ohio State University Electro-Science Laboratory, Columbus, Ohio (1982).
16. Jablon, A. R., and Persons, D. F., "Spacecraft Reflector Antenna Thermal Distortion Analysis," in *Proc. RF EXPO WEST*, San Diego, Cal., pp. 161–172 (Mar 1992).

THE AUTHORS



ALLAN R. JABLON is an engineer in the Microwave and RF Systems Group in the APL Space Department and a member of the APL Senior Professional Staff. He received a B.S.E.E. from Virginia Polytechnic Institute and State University in 1986 and an M.S. degree in electrical engineering from The Johns Hopkins University G.W.C. Whiting School of Engineering in 1990. Since joining APL in 1986, he has worked on antenna design, development, and testing, as well as RF systems and microwave circuit design. He has designed and developed antennas for several spacecraft programs.



ROBERT K. STILWELL is currently the Supervisor of the Antenna Systems Section of the Microwave and RF Systems Group. He received a B.S.E.E. degree from Kansas State University in 1973 and an M.S. degree in electrical engineering from The Johns Hopkins University in 1976. Since joining APL in 1973, he has been responsible for the design, development, and test of various types of antennas for more than twenty satellites. He has also worked on ground-based antennas, and has contributed to numerous Space Department studies.