The Development, Variations, and Applications of an EHF Dual-Band Feed

J.C. Lee

A compact, high-performance, EHF dual-band feed has been designed and developed. Subsequent improvements and modifications for a wide range of antenna applications have been made.

This article begins with three working examples of existing dual-band-antenna approaches, and discusses the dual-band feed that was developed for the antenna to be used on the SCOTT ADM, a satellite communications terminal for mobile command posts. Excellent performance for the feed and antenna in both bands has been achieved. Other applications of the feed with appropriate modifications for dielectric-lens antennas, ADE (displaced-axis elliptical) antennas, and compact electronic-lobing antennas are also discussed. These variations of feeds have been used in the FEP spot-beam antenna backup and a military-communications-satellite spot-beam antenna, in satellite-communications terminals on submarines, and in portable terminals (e.g., SCAMP and Advanced SCAMP).

In the modern world, we have all encountered many communications and radar terminals [1, 2] and have therefore glimpsed profiles of big and small antenna dishes. But we rarely have the chance to see any details of the feeds of the antennas. In theory, we can design an antenna feed simply by applying the well-known Maxwell equations with the appropriate boundary conditions. In practice, however, only the simplest antenna feeds operating in a single frequency band can be analyzed this way. Indeed, the development of compact, high-performance, dual-band antenna feeds presents a number of challenges: boundary conditions involving both dielectric and conducting materials, multi-frequency-band operation, and the inclusion of switching diodes in the feed aperture all might need to be considered. Furthermore, the design of such feeds is, at best, an inexact science that requires experience and expertise in electronic circuits, electromagnetics, and antennas.

In this article, we discuss antennas and feeds that operate simultaneously in two well-separated frequency bands—hence the term *dual band.* The following sections describe how we conceived and developed a dual-band feed, and how we subsequently improved and modified the feed for various antenna applications.

Background

Dual-Band Ratio

The dual-frequency-band ratio γ is defined as the quotient obtained by dividing the high-band center frequency by the low-band center frequency. For γ close to 1, we can use a single broadband antenna and feed. The two closely spaced bands can be separated easily by the use of filters or polarization diplexers. For γ much larger than 1, many systems will utilize two antennas, one each for the low and high frequency bands. Generally, the low-frequency-band antenna will dominate in size. Because the high-frequency-band feed and antenna is generally small in comparison, it can easily be located where it does not interfere with the performance of the low-frequency-band antenna. The case we will discuss is one in which γ

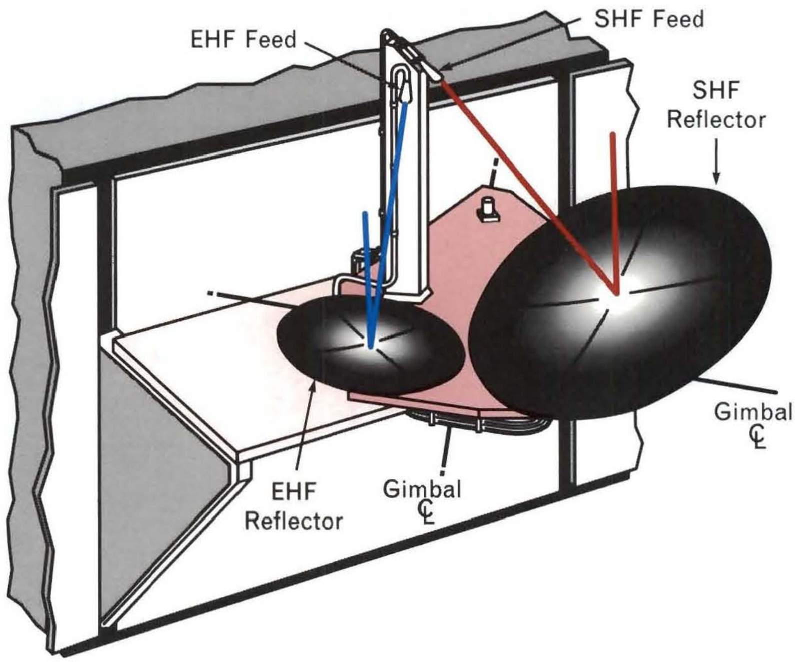


FIGURE 1. Proposed dual-antenna system for satellite spot-beam application. The aperture diameters of the EHF and SHF reflectors are 21" and 32", respectively.

is close to 2 (2.15, to be exact)—a practical value for many military and commercial applications—and in which it is often desirable to achieve good performance in both bands with a single dual-band antenna.

Three Design Examples

For a given antenna requirement, there is usually more than one design approach. Some approaches, however, might result in antennas that are impractical because of size, weight, or other considerations. This subsection will introduce and discuss three relevant examples that illustrate three different approaches to the design of a dual-band antenna. An examination of the deficiencies of these approaches suggests to some extent the possibility of a significantly improved design.

The three approaches are

1. a dual-antenna system,
2. a single main antenna with a dichroic subreflector and two single-band feeds, and
3. a single antenna with a dual-band feed.

The first approach with $\gamma = 2.15$ results in an elementary straightforward system. We can individually optimize the RF design for each band, since the two bands are electrically independent. Because γ is not much

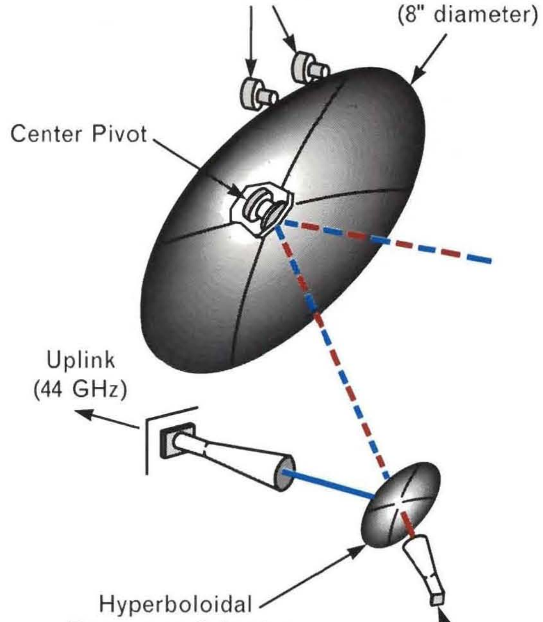


FIGURE 2. Spot-beam antenna system that uses a dichroic subreflector with a separate feed horn for each band.

larger than 1, however, the nature of the mechanical design calls for a cumbersome brute-force approach. Nevertheless, in 1982 such a system was seriously proposed for a steerable spot-beam antenna that was to be used on a communications satellite (Figure 1).

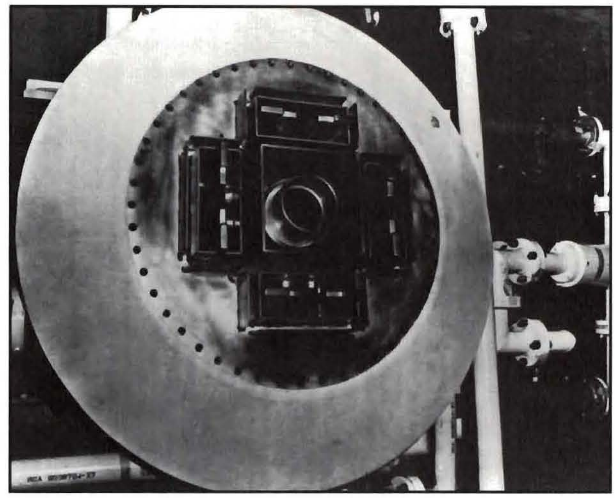
The second approach, again with $\gamma = 2.15$, uses one main reflector for both bands and a separate feed horn for each band. A dichroic frequency-selective subreflector aligns the primary patterns of the two bands. For the low frequency band, the antenna functions as a prime-focus-fed parabolic reflector; for the high frequency band, it functions as a Cassegrain antenna. This concept is currently in use in spot-beam antennas on a communications satellite system (Figure 2). We should note that the dichroic surface consists of an array of numerous resonant elements that are etched by photolithography onto a curved surface. The development and fabrication of such a surface was a complicated and expensive process.

An example of the third approach is the TRADEX (Target Resolution and Discrimination Experiments) antenna, which was developed by RCA and is currently used on Kwajalein Atoll [2]. For TRADEX, γ is equal to 2.23 (Table 1). Figure 3 (top) shows the front view of the feed, in which the opening of the central circular waveguide is the high-frequency-band horn and the space between that horn and the square waveguide opening is the low-frequency-band horn. The rectangular openings on each of the four sides are the tracking horns. Figure 3 (bottom) shows the rear view of the feed without the tracking horns. Note that a turnstile design for the low-frequency-band junction is used. Waveguides and tapered transitions connect the turnstile, orthogonal-mode transducers, hybrid junctions, and couplers. As can be seen in Figure 3 (bottom), the result is a cumbersome mass of RF plumbing.

A study of the three approaches leads to the following conclusion. If a much-simplified dual-band feed can be developed, a design that utilizes some of the concepts demonstrated in the third approach has the best chance of being small and compact.

Design of a Compact Dual-Band Feed

After some effort, we developed a high-performance dual-band feed for the Single Channel Objective Tactical Terminal, Advanced Design Model (SCOTT ADM)—a satellite communications terminal incorporated on a mobile armored personnel carrier to be used as a command post. This application required that the feed be small and compact.



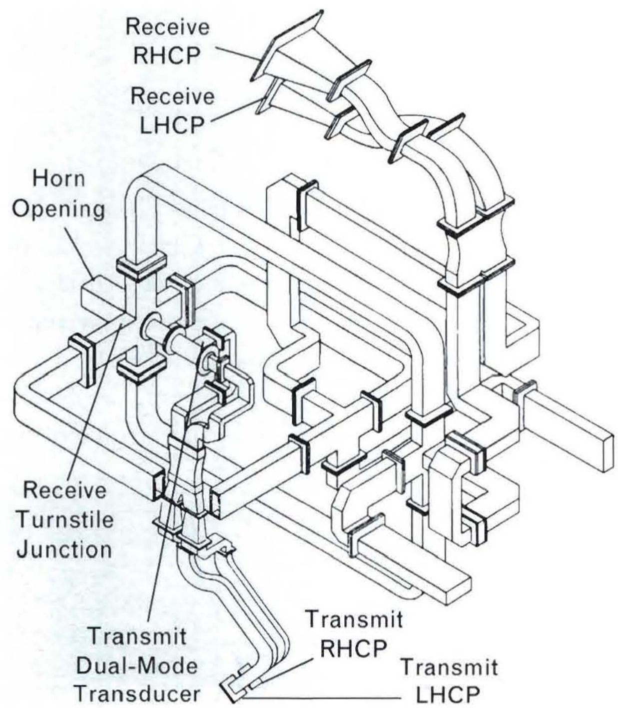


FIGURE 3. Dual-band feed of the TRADEX (Target Resolution and Discrimination Experiments) antenna: (top) front view and (bottom) rear view.

The basic structure of the SCOTT ADM feed consists of two concentric circular cylinders—outer and inner coaxial waveguides used for the low and high frequency bands, respectively. This coaxial structure is compact and effective for γ between 1.5 and 5; indeed, variations of the basic coaxial feed design have been

Table 1. TRADEX Feed Parameters

	TRADEX Dual-Frequency Tracking Feed	Possible Scaled mm-Wave Dual-Frequency Feed
Tracking Frequency	1.32 GHz ± 5%	44.5 GHz ± 2.3%
High Frequency Band	2.95 GHz ± 4%	20.7 GHz ± 1.2%
Dual-Frequency-Band Ratio, γ	2.23	2.15
Center-Square-Horn Size	~6.26" × 6.26"	~0.42" × 0.42"
Six-Horn Overall Size	~13" × 13"	~0.87" × 0.87"
Ground-Plane Size	~30" Diameter	~2" Diameter

useful in many applications. This section describes the feed design and development.

Design Requirements

The two bands of interest are K-band (20.2 to 21.2 GHz) and Q-band (43.5 to 45.5 GHz), which are used for the downlink and uplink, respectively, of EHF military satellite communications systems. General design requirements for the feed are compact size, rugged construction, and low production cost. The RF performance requirements are as follows:

1. for both bands, a symmetric feed radiation amplitude pattern with suitable taper for efficient illumination of the main reflector (subtended angle equal to 85°),
2. coincidental phase centers for the two bands,
3. circular polarization with a small axial ratio for both bands,
4. low transmission losses and a low voltage standing-wave ratio (VSWR), and
5. high isolation between the two frequency bands.

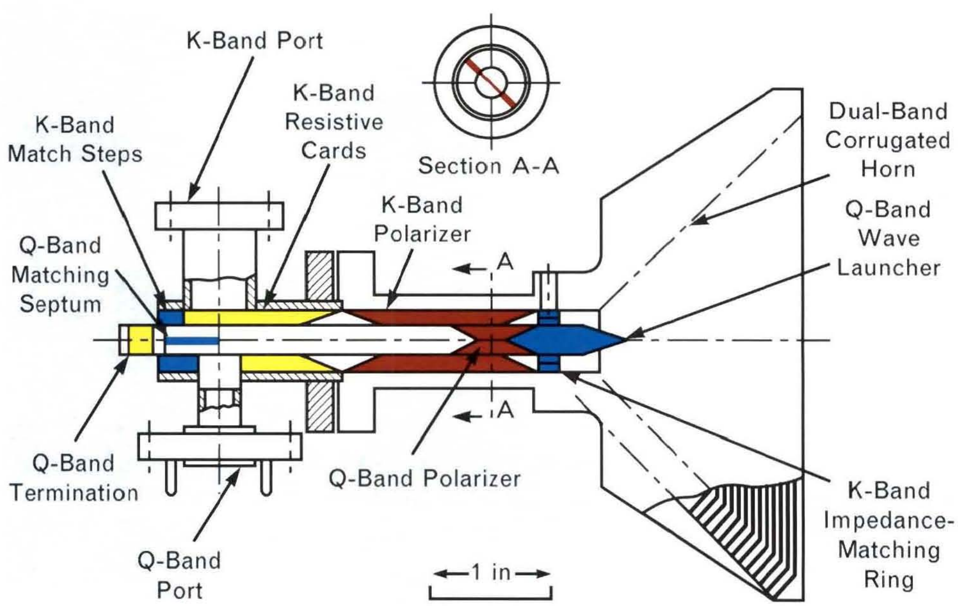


FIGURE 4. Basic dual-band feed design. The components are color coded according to their functions: blue for impedance matching, red for the generation of circular polarization, and yellow for the termination of the cross-polarized field.

Feed Design

Many descriptions of multifrequency feeds have appeared in the open literature. Some of the feeds, e.g., those that utilize coaxial helices [3] or coaxial probe-excited concentric cavities [4], are suitable for lower-frequency microwave applications. Lengthy directional couplers that couple the different frequency-band signals in different waveguides to a common waveguide connected to the radiating aperture have also been developed [5]. More recently, long dielectric rods [6] in the center of a horn have been used to shape the radiation pattern of the high frequency bands while the horn itself is used to control the patterns for the low frequency bands.

Features of all these feeds influenced our present design. In particular, our coaxial-waveguide approach benefited from the concepts embodied in the feeds used at the Goonhilly earth station [7] and the TRADEX radar [8] terminal.

Frequently, a safe and expedient way of designing a feed is to adopt a straightforward procedure—simply to scale and modify an existing feed, such as that used in TRADEX or Goonhilly. For better results, however, a new feed can be designed from scratch with the given requirements in mind. In designing a new feed, we must first identify the basic key components and ensure that the mechanical designs of these components are simple. Additional components such as input/output waveguides, polarizers, and load terminations can then be incorporated through the use of custom-designed matching elements.

The chosen feed design for the SCOTT ADM antenna consists of a single corrugated horn. Optimized for the two separate frequency bands, the horn incorporates two standard-size circular waveguides with concentric openings at the horn throat. The inner and outer circular waveguides are used for the high and low frequency bands, respectively. Rectangular waveguides perpendicular to the feed centerline act as input/output ports to the feed assembly. Instead of using the more conventional straight-out-of-the-rear approach, we have brought the high frequency port out at a right angle to obtain a more compact feed package.

Matching devices have been built near the junctions in the K-band coaxial waveguide and the Q-band circular guide to account for the transition from one geometric form to the other and to account for the 90° bend. Furthermore, in each circular waveguide there are dielectric polarizers, which convert the linearly polarized waves to circularly polarized waves. Both polarizers are located 45° to the incident linear polarization. We can choose the senses of the polarizations independently for the two bands. For the SCOTT application, left-hand polarization is used for both bands. This choice results in a right-hand circularly polarized antenna for both bands after the signal is reflected. Cross-polarized fields are terminated internally to avoid deterioration of the desired polarization.

All of these elements for each frequency band are designed and integrated in a compact and solid fashion. The overall length of the feed is less than 5 in, and the largest cross section of the feed is at the horn opening, which has a diameter of about 4 in. Figure 4 shows the final design of the basic feed [9], in which there are two signal paths: the Q-band 44-GHz uplink and K-band 20-GHz downlink.

The following subsections contain detailed descriptions of each of the main components.

Corrugated Horn

The use of a corrugated horn ensures axially symmetric primary radiation patterns in both bands and results in a much simpler mechanical design than do alternative beam-equalizing designs such as dielectric loading [10] and multimoding [11]. Corrugation also results in a wider bandwidth and is an easier way to control the beam shape and width. To achieve approximately equal beam shapes and phase-center coincidence for both frequency bands, we followed two design principles:

1. A wide horn flare angle [12] was used for wideband operation. In this mode, the beamwidth is determined mainly by the horn flare angle rather than the horn aperture size, and the phase center is near the horn throat.
2. The corrugation depth was chosen between $\frac{3}{4}\lambda$ and λ in the high frequency band and between $\lambda/4$ and $\lambda/2$ in the low frequency band so as to obtain capacitive surface reactances [13] in both frequency bands.

Corrugation ring loading [14], a different approach to achieving wideband operation, complicates the fabrication process, and was thus not used. The approach would have been inappropriate in any event. The performance

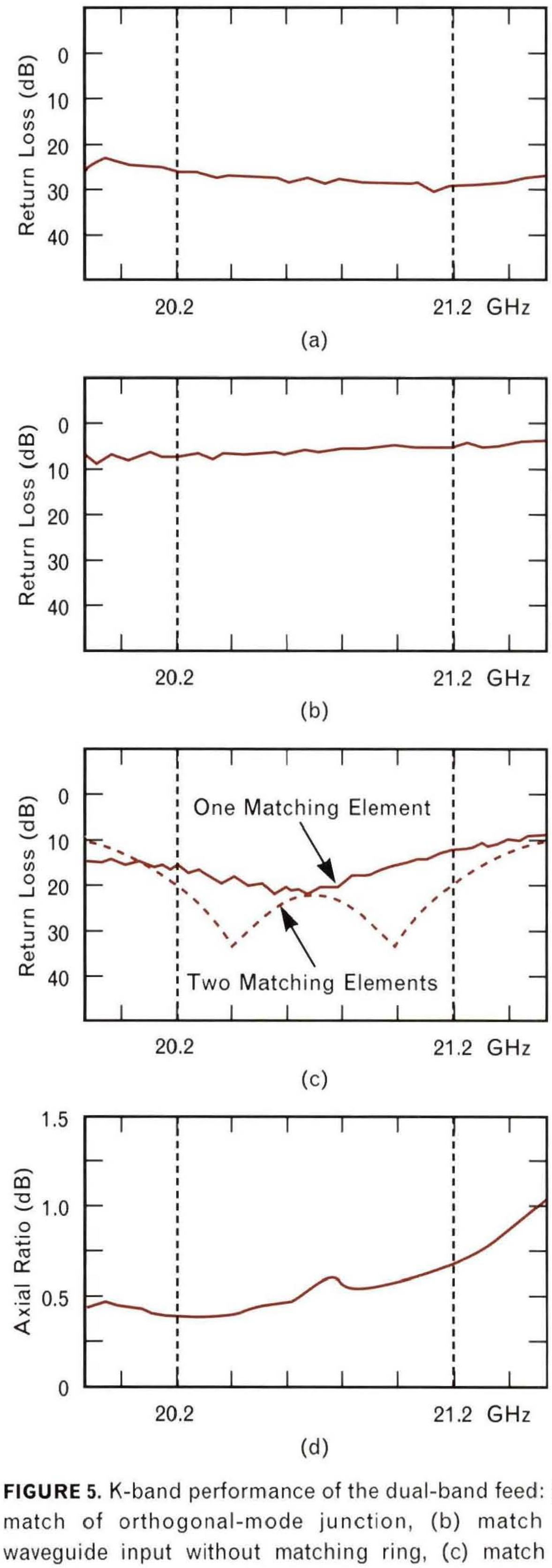


FIGURE 5. K-band performance of the dual-band feed: (a) match of orthogonal-mode junction, (b) match at waveguide input without matching ring, (c) match of coaxial-waveguide opening with one and two matching rings, and (d) axial ratio of polarizer.

improvement gained from corrugation ring loading would be best at the center of the large overall bandwidth. In our case, the two useful bands are widely separated and are located at the edges of the overall band, not at its center.

In a corrugated-horn design, Δ, the difference in wavelengths between the spherical wavefront and plane aperture, is a useful parameter for characterizing the radiation pattern. (Note: $\Delta = [d/(2\lambda)]\tan(\theta_0/2)$, where d is the horn diameter and θ_0 is half the flare angle.) A value of Δ greater than 0.75 ensures wideband operation [13]. Thus, for the design of the corrugated horn, we selected Δ equal to unity at the low-frequency end of the low frequency band. In addition, we chose the semiflare angle to be 46°, and the aperture diameter to be 2.88 in. These dimensions gave the desired beamwidths. In the high frequency band, we chose the width of the corrugations to be less than $\lambda/2$. Fourteen corrugations were used; the corrugation depth was 0.217 in, the pitch 0.120 in, and the tooth thickness 0.013 in. The horn and a portion of the K-band circular waveguide was machined from an aluminum block.

Radome

Because a corrugated horn with a wide flare angle will produce spherical waves at the horn opening, we used a spherical curved surface for the radome design. The radius of the inner surface of the radome was selected to be 2.1 in, and the thickness to be one wavelength at the center frequency of the high frequency band. Because this thickness was close to a half wavelength in the low frequency band, good dual-band transmission characteristics (i.e., losses less than 0.1 dB) could be obtained for radomes made of either Teflon or polyethylene. We chose polyethylene for the present application because of cost considerations, and we fabricated a polyethylene radome with a thickness of 0.176 in. Polyethylene material of a forest-green pigment was also used and tested, and we observed that the pigment had no measurable RF effects. A radome made of Teflon, which has a slightly better water-shedding property, would require a thickness of 0.183 in.

Q-Band Components

We designed the Q-band components with standard-size waveguides: the circular-guide WC-19 and the rectangular-guide WR-22. The orthogonal-mode transducer (OMT) was fabricated with a short section of WR-22 joined at right angles to the WC-19, with the broadside of the WR-22 parallel to the WC-19 axis. A thin conducting septum, 0.10" thick, was positioned at the junction in the WC-19 to match the input impedance and to direct signals from the WR-22 to the open end of the WC-19. We later shaped this septum to obtain a broader bandwidth. Another septum was used at the junction in the WR-22 to improve the match for the orthogonally polarized mode in the circular waveguide. To avoid tight tolerance problems, we did not use any resonant irises at the junction; adequate matching was achieved with the septum alone. A short quarter-wave step load designed for the transmit frequency band was placed in the WC-19 behind the reflecting septum to terminate the orthogonally polarized signals.

A plate polarizer made of Rexolite (a low-loss dielectric material) was located close to the open end of the WC-19. For broadband performance and solid construction, we sandwiched one end of the polarizer plate between the slot of a tapered Teflon rod, and used dielectric pins to secure the rod into the WC-19. The other end of the Teflon rod was also tapered and designed to protrude out of the WC-19 so that a proper wave could be launched in the corrugated horn. We arrived at the dimensions of the rod empirically; the criteria we used were (1) the equalization of the E- and H-plane patterns, (2) the coincidence of the two phase-center locations, and (3) the impedance match at the circular-waveguide opening. Later, the Teflon was replaced by perforated Rexolite for the wave-launcher/polarizer integrated design to simplify the fabrication procedure.

K-Band Components

The K-band components were also designed with standard-size waveguides: the rectangular-guide WR-42 and circular-guide WC-44. The OMT utilized a junction of unique design [15]. We fabricated the component with a short section of WR-42 joined at right angles to the WC-44, with the broad side of the WR-42 parallel to the WC-44 axis. The WC-19 of the Q-band OMT was coaxially located inside the WC-44, and simple stepped conducting blocks were used to support the WC-19 at one end. To shorten the overall length, we utilized the

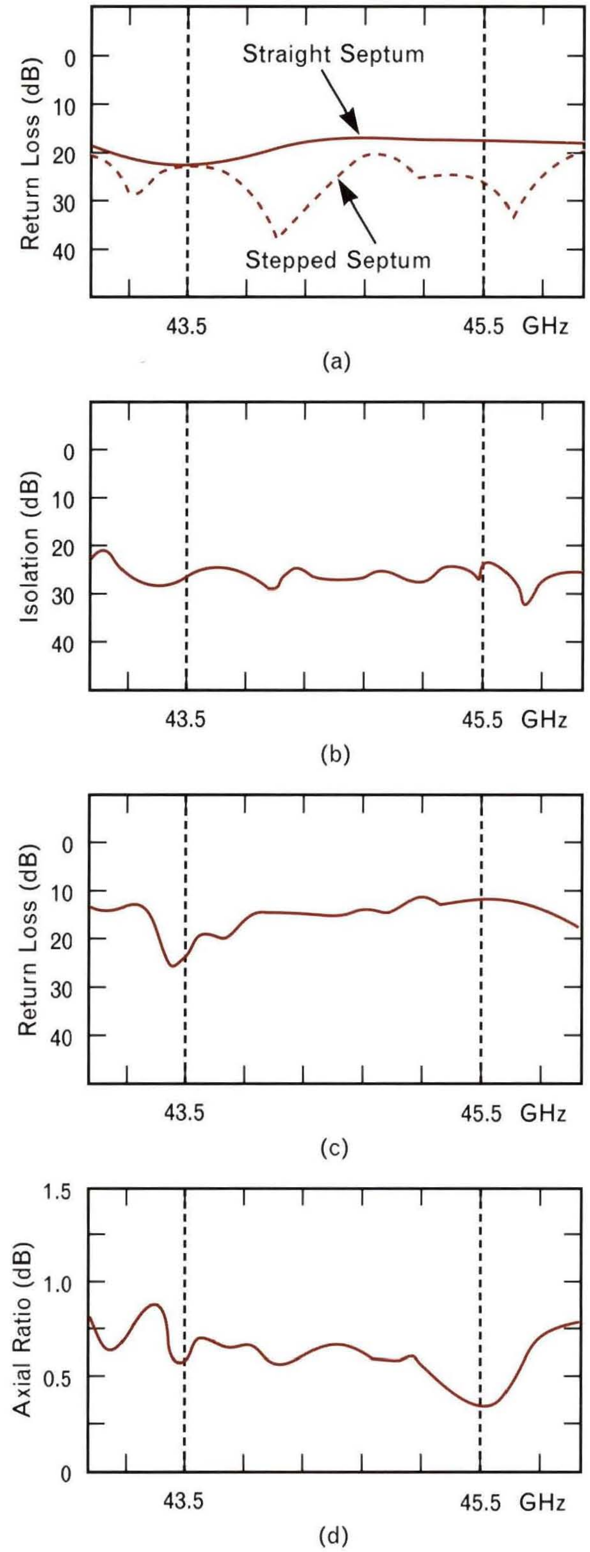


FIGURE 6. Q-band performance of the dual-band feed: (a) match of orthogonal-mode junction, (b) isolation measured between K- and Q-band ports, (c) match of short load, and (d) axial ratio of polarizer.

(a)

(b)

FIGURE 7. Final dual-band feed: (a) disassembled, and (b) assembled.

(a)

(b)

FIGURE 8. Dual-band antenna system mounted on SCOTT ADM (Single Channel Objective Tactical Terminal, Advanced Design Model): (a) on vehicle and (b) off vehicle.

exposed portion of the transmit WR-22 waveguide between the two concentric circular guides (the WC-19 and WC-44) as part of the low-frequency-band matching. We found that the junction had a good match over the whole recommended bandwidth of the WR-42 waveguide. Two thin resistive cards of 150 Ω per square were put in front of the stepped conducting blocks to terminate the orthogonally polarized fields. For a high-power version, the resistive cards can be replaced by two half-wavelength slots to couple the orthogonally polarized fields out of the coaxial waveguide. The fields can then be terminated with a solid load.

The quarter-wave polarizer plate in the low frequency band was made of two pieces of thin Rexolite placed next to the resistive cards in a plane 45° from the plane of the resistive cards. We used two symmetrical pieces of dielectric to maintain field symmetry and to avoid the excitation of higher-order modes. A metal-plate polarizer with air gaps was used in a later version.

The measured value of the normalized impedance at the K-band coaxial-waveguide opening was about $0.7 - j0.8$. This impedance was matched by an impedance transformer made of a Teflon ring over a thin metal ring placed close to the opening. A long metal ring was later added to increase the matching bandwidth. We designed the transformer for matching the junction between the coaxial waveguide and the corrugated horn, and for supporting and concentrically aligning the center and outer circular waveguides.

Component Multifunctionality

To conserve space, we designed the components to be multifunctional whenever possible. Several examples of component multifunctionality follow.

1. The single corrugated horn shapes the primary patterns of both bands,
2. the K-band rectangular-to-circular coaxial waveguide junction plays the dual role of 90° bend and mode/impedance transformer,
3. the counterpart Q-band junction plays a similar dual role,
4. the K-band impedance-matching ring also serves as an alignment spacer, and
5. the Q-band dielectric wave launcher not only matches the fields in the circular guide to that of the horn but also functions as a circular polarizer.

Feed Performance

Figures 5 and 6 respectively show the K- and Q-band performance of the feed. When we used the feed with an offset parabolic reflector that had a 24"-diameter aperture, we obtained an overall antenna efficiency including feed losses of more than 60% (compared to lossless uniform illumination) for both bands.

For other applications, we can change the horn flare angle and opening size; e.g., the antenna can function with a Cassegrain or spot-beam feed. If required, the corrugations of the horn can be modified, reduced, or even eliminated to conserve space. Furthermore, we can increase the matching bandwidth for the K-band coaxial-waveguide opening by adding another matching element, and we can improve the matching bandwidth for the Q-band junction by changing the shape of the septum at the junction. For high-power operation, the resistive cards can be replaced by a solid load, and each polarizer can be mounted in a different direction to change the sense of the circular polarization. We can also take out each polarizer to achieve linear polarization.

Applications

SCOTT ADM Antenna

The feed with radome is shown in Figure 7. Even in the very limited space of an armored personnel carrier (APC) (Figure 8), the operation of the feed was successful:

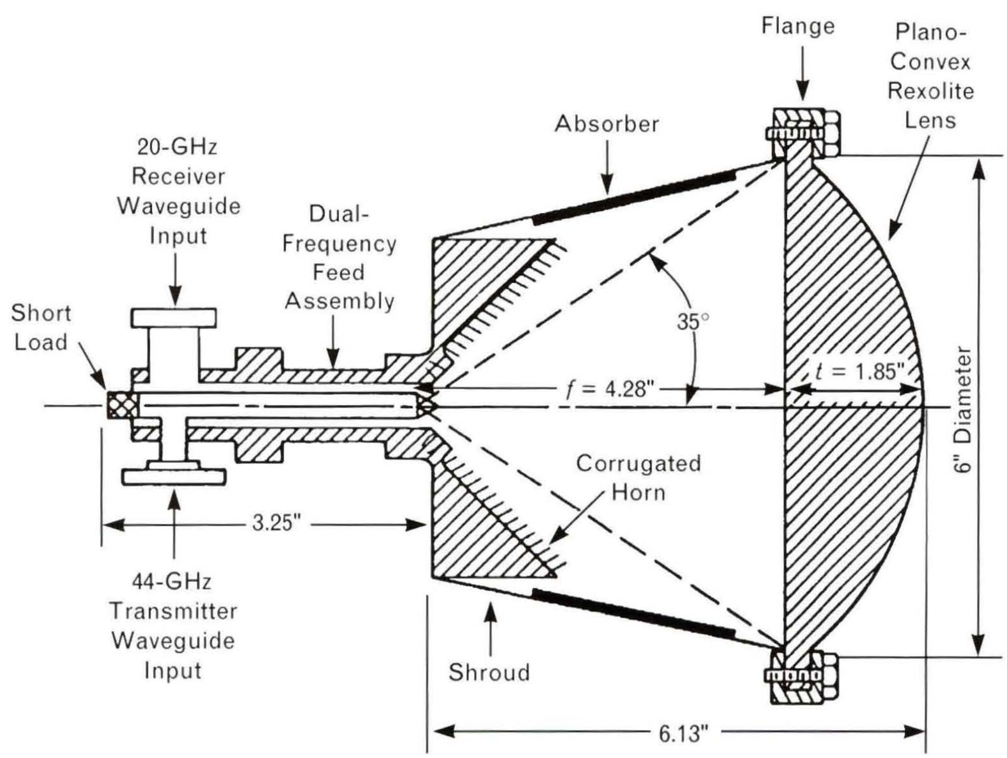


FIGURE 9. Dual-band dielectric-lens antenna.

Table 2. Gain and Directivity of Dielectric-Lens Antenna with Dual-Band Feed

	Uplink Frequency (GHz)			Downlink Frequency (GHz)		
	43.5	44.5	45.5	20.2	20.7	21.2
Directivity of 6" Lens (Uniform Aperture Illumination)	36.8	37.0	37.2	30.2	30.4	30.6
Calculated Directivity of Lens (with Horn Feed)	36.3	36.5	36.7	29.6	29.8	30.0
Measured Gain of Lens (with Horn Feed)	35.3	35.5	35.8	28.8	29.5	29.2
Total Losses of Lens and Feed	1.0	1.0	0.9	0.8	0.3	0.8
Lens Antenna Efficiency	71%	71%	72%	72%	81%	72%
Spillover Losses	0.3	0.3	0.3	0.3	0.3	0.3
Impedance-Mismatch Loss of Feed	0.08	0.05	0.20	0.10	0.03	0.20

Note: All values in dB unless otherwise noted.

good RF performance and mechanical reliability were demonstrated. The basic feed design was used in the final SCOTT terminal. In 1985, the author obtained a patent [15] for the central part of the feed—the K-band rectangular-to-coaxial waveguide junction. The compact dual-band feed has been so popular that a microwave-component company that Lincoln Laboratory, as a technology-transfer demonstration, paid to reproduce two such feeds from our drawings listed the part in its 1987 catalog.

Dielectric-Lens Antenna

The dielectric-lens antenna system consists of a 6"-diameter plano-convex lens that is illuminated by the basic dual-band feed described in the previous section. Figure 9 is a sketch of the dual-band lens, Reference 16 contains details of the antenna system, and Tables 2 and 3 give the measured antenna gain and half-power beamwidth, respectively. The dielectric-lens antenna is suitable for EHF lightweight satellite and airborne terminal applications.

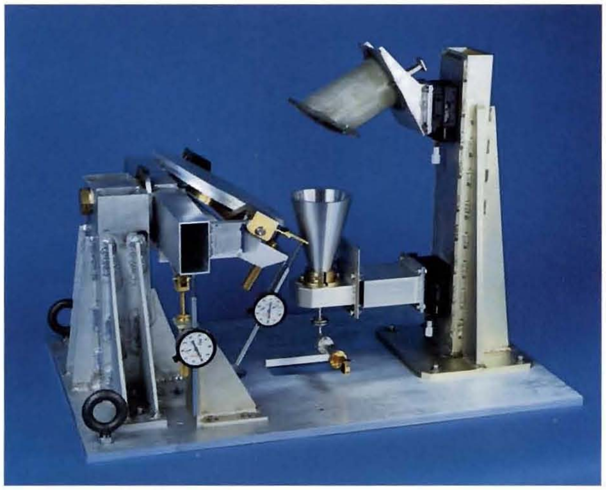
FEP Spot-Beam Antenna Backup

The spot-beam antenna for the FLTSAT EHF Package (FEP) built by Lincoln Laboratory uses an offset reflector common to both the uplink and downlink [17]. (FLTSAT

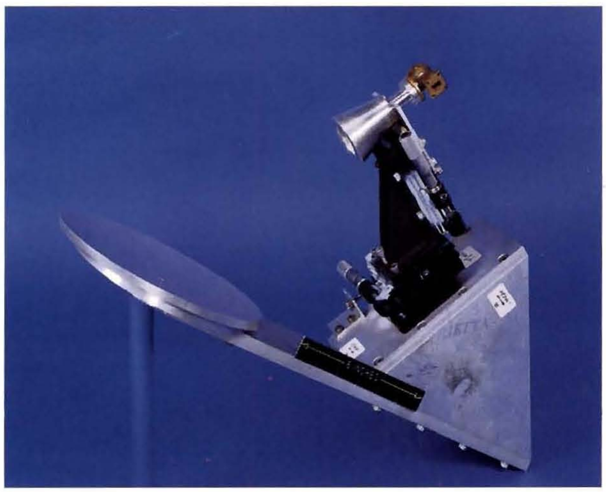
Table 3. Beamwidth Characteristics of a Dielectric-Lens Antenna with Dual-Band Feed

Frequency (GHz)	Polarization Pattern*	Beamwidth 3 dB	Beamwidth 10 dB
20.2	V	6.4°	10.8°
	H	5.9°	9.9°
20.7	V	6.1°	10.4°
	H	5.9°	10.1°
21.2	V	6.0°	10.2°
	H	5.7°	9.5°
43.5	V	2.8°	4.8°
	H	3.0°	5.2°
44.5	V	3.1°	4.9°
	H	3.1°	5.3°
45.5	V	3.0°	4.8°
	H	2.9°	5.0°

*Polarization of incident E field:
V—perpendicular to plane of scan
H—parallel to plane of scan



(a)



(b)

FIGURE 10. FEP (FLTSAT EHF Package) spot-beam antenna: (a) primary design, and (b) backup design.

is a communications satellite built by TRW.) The feed subsystem of the 8"-circular-aperture antenna consists of two separate feed horns and a dichroic subreflector. Figure 10(a) shows the antenna experimental model.

In general, a flat dichroic surface can be readily designed with numerical methods and a computer. The development of a curved dichroic surface, however, requires a trial-and-error procedure.

We used end-loaded crossed-dipole arrays etched from thin copper-clad Mylar sheets to fabricate the dichroic surface. Obtaining the necessary bandwidth required two etched Mylar sheets separated by a phenolic honeycomb structure. Epoxy glue adhered the sheets to the honeycomb. During the course of the dichroic surface development, we uncovered a thermal stability problem: thermal cycling of the subreflector caused a shift in the resonant frequency. In addition, we were concerned that thermal expansion could change the sheet spacing and even cause a loss of mechanical integrity. Thus, as an insurance measure, we undertook an alternative design that utilized the basic dual-band feed described earlier.

For most types of aperture antennas, the radiation beamwidth is inversely proportional to wavelength. For equalization of the beamwidths in the two bands, the illumination for the high frequency band has to be very heavily tapered. Such tapering was accomplished with the proper horn flare angle and the use of a dielectric rod at the end of the high frequency waveguide.

This concept was demonstrated by a makeshift feed that was hastily put together (Figure 10[b]). The measured antenna gain was slightly higher for this feed than for that of the model with the dichroic subreflector. The absence of the extra losses of the dichroic surface and that of the lens in the uplink horn resulted in an improvement in gain of about 1 dB. Weight and size reductions were also significant. Figure 11 compares

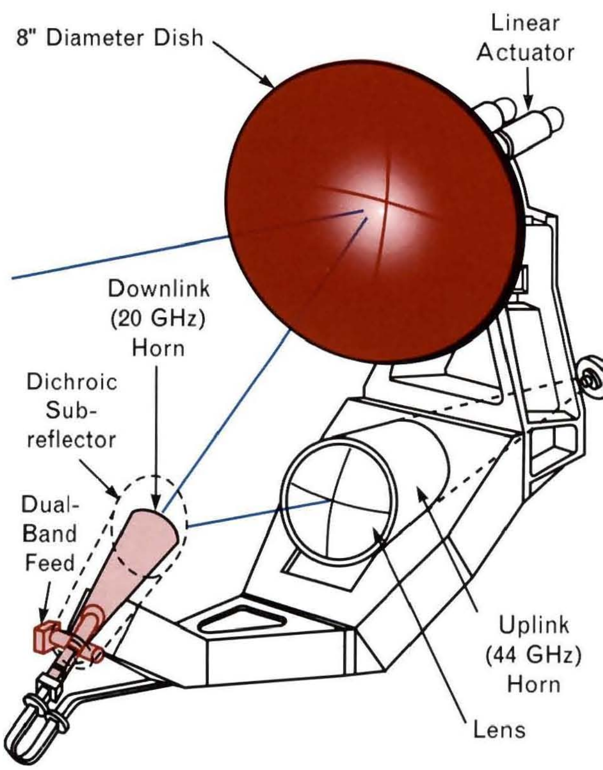


FIGURE 11. Comparison of two spot-beam-antenna designs, one with a dichroic subreflector and the other with a dual-band feed. The components necessary for the dual-band-feed approach are shown shaded in red.

the two approaches directly.

Because the FEP spot-beam antenna was designed for operation on a satellite rather than a ground terminal, the power-handling capabilities for the K-band downlink and Q-band uplink had to be reversed. We made a minor modification of the feed termination load for the K-band cross-polarized field by replacing the resistive cards with an ordinary waveguide load (Figure 12).

Eventually the thermal stability problem mentioned earlier was resolved and the backup dual-band-feed effort discontinued. The results of our work, however, were passed via the Air Force to a military satellite contractor who then dropped its dual-antenna design in favor of our dual-band-feed approach, and significant savings in weight and space were realized.

SCAMP Antenna

For portability, all components of the SCAMP (Single Channel Advanced Man Portable) antenna had to be miniaturized. Although the required system gain dictated the antenna size to a large extent, we made every effort to design a compact antenna.

An offset reflector has the advantages of low sidelobes and no feed-blockage loss. But for circular apertures, an offset reflector needs a paraboloid surface with an elliptical cross section. The major axis of the required elliptical cross section must be larger than the circular aperture diameter by a factor of ~1.2. Thus, for compactness, we instead used a centrally fed, axially symmetric, Casse-

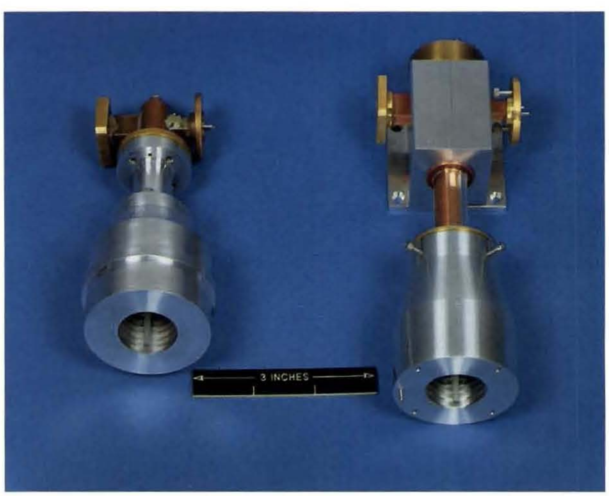


FIGURE 12. Dual-band feed for the FEP spot-beam backup: (left) low-power version with resistive cards and (right) high-power version with solid load.

(a)

(b)

(c)

FIGURE 13. Cassegrain design of the dual-band antenna for SCAMP (Single Channel Advanced Man Portable): (a) overall system, (b) antenna, and (c) feed.

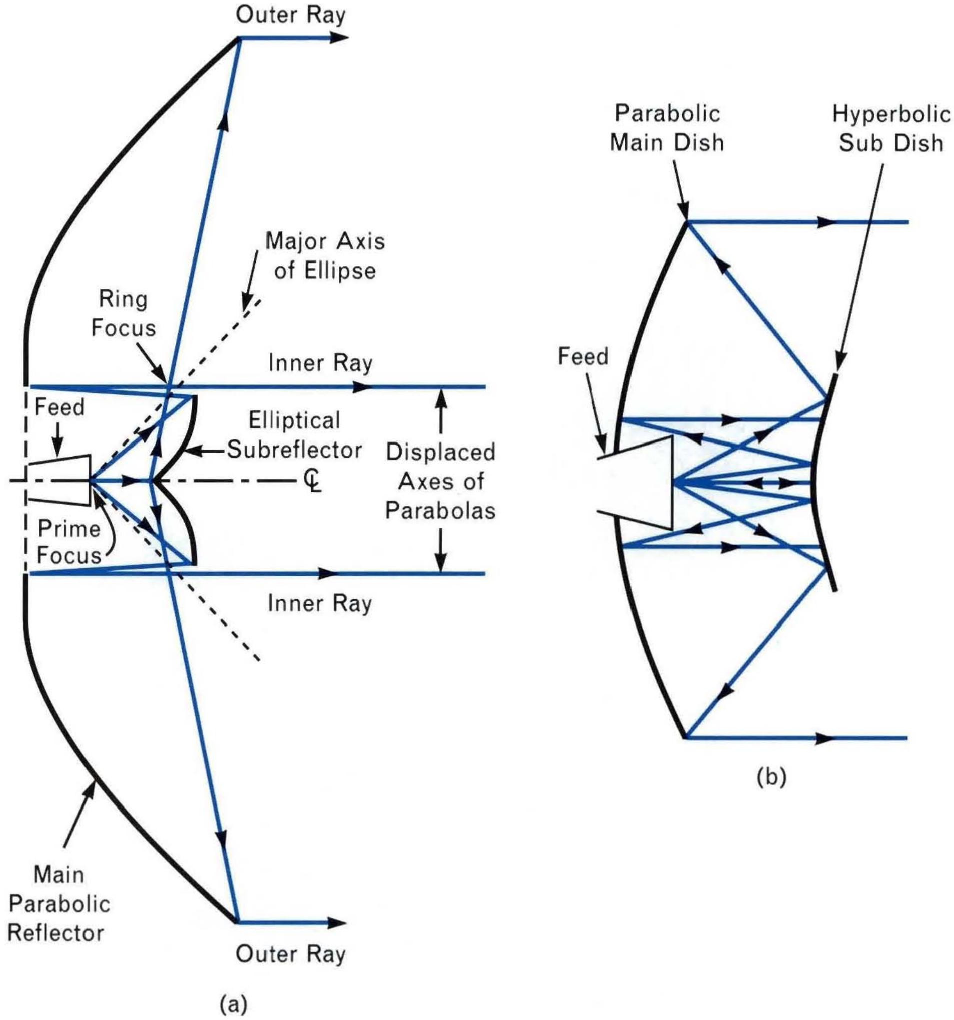


FIGURE 14. Ray-path comparison of (a) ADE design used in Advanced SCAMP with (b) Cassegrain design used in SCAMP.

grain system (Figure 13). The system consists of a 10" parabolic main reflector with a ratio of focal length to diameter equal to 0.25 and a hyperbolic subreflector with eccentricity equal to 1.67. The dual-band feed is a modified SCOTT feed. A metal ridge polarizer attached only to the K-band outer wall of the coaxial waveguide has replaced the original dielectric slab design.

By constructing the Q-band wave-launcher/polarizer from a single piece of Rexolite, we avoided the original design's inexact process of gluing the Teflon wave launcher to the Rexolite polarizer plate. Four longitudinal holes were drilled in the new wave launcher to reduce its effective dielectric constant.

As required by the Cassegrain design, we reduced both the horn flare angle and aperture to narrow the feed pattern. The sense of the horn polarization was changed to accommodate the extra reflection from the subreflector. We chose the feed aperture to optimize the uplink antenna gain—the measured minimum antenna efficiency was 51% for the uplink and 28% for the downlink. Because the SCAMP system was designed with extra margin for the downlink, the relatively low 28%

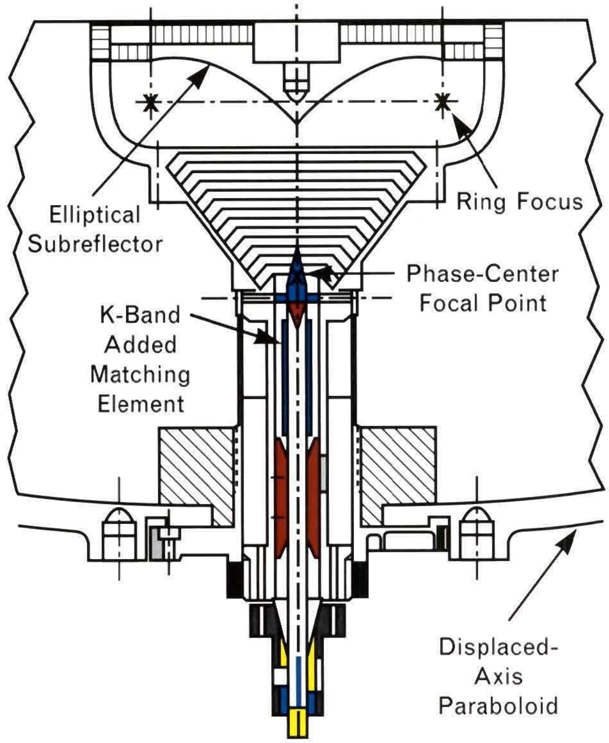


FIGURE 15. ADE (displaced-axis elliptical) design of the Advanced SCAMP antenna. (See Figure 4 for color-coding key.)

efficiency presented no problems. The maximum level of the first sidelobe was about –12 dB.

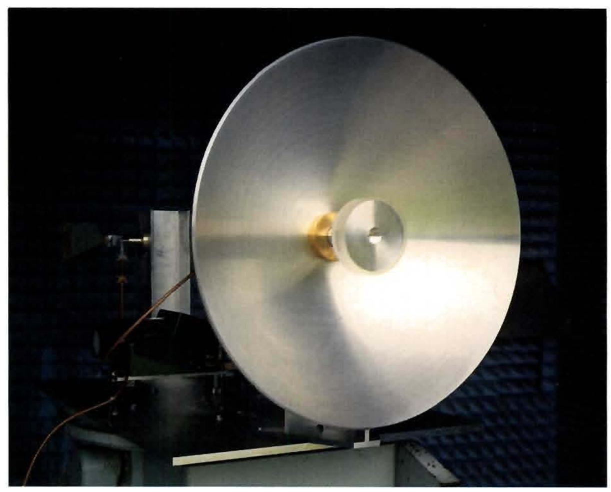
For electrically small (diameter/$\lambda \leq 10$) Cassegrain antennas, conflicting design considerations exist that tend to limit the efficiencies realized. The result is a trade-off between feed-blockage and subreflector-spillover losses. In general, this problem applies to all small satellite communications terminals. For example, two different companies developed small terminals that had antenna efficiencies of about 25% at the low frequency band. To improve the antenna efficiency for such electrically small antennas, a dual-band ADE (displaced-axis elliptical) antenna was developed.

ADE Antenna

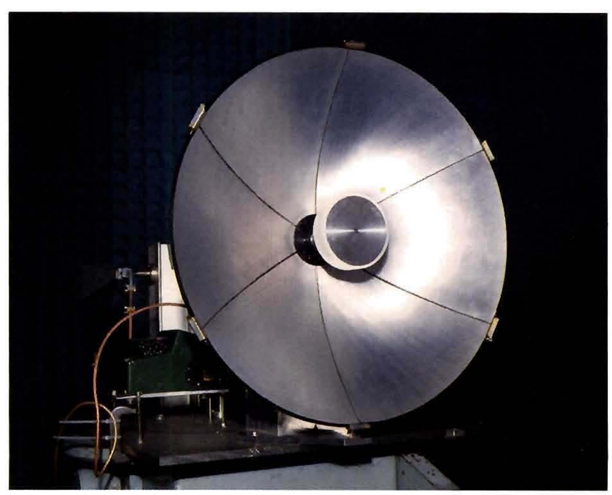
The single-band ADE antenna was invented by J.L. Lee (U.K. patent No. 973583, 1964) and extensively investigated and developed in the Soviet Union [18–20]. ADE antennas have several advantages:

1. relatively high aperture efficiencies for main-reflector diameters as small as 10λ,
2. subreflectors several times smaller than those used in Cassegrain antennas,
3. low reflections in the feeds, and
4. high aperture efficiencies resulting from the subreflector ray-inversion feature, which compensates for the space factor of the main reflector (Figure 14).

We designed and tested dual-band ADE EHF antennas of 6" and 12" diameters. Measured gain data showed good efficiencies of 43% and 52% in the low frequency band for the 6" and 12" antennas, respectively, and 62 to 63% in the high frequency band. This work was published in the *IEEE International Symposium on Antennas and Propagations* [21], and industry immediately showed interest in the development. Under Air Force auspices, four industry representatives visited Lincoln Laboratory



(a)



(b)

FIGURE 16. Advanced SCAMP antenna with (a) solid reflector and (b) petal reflector.

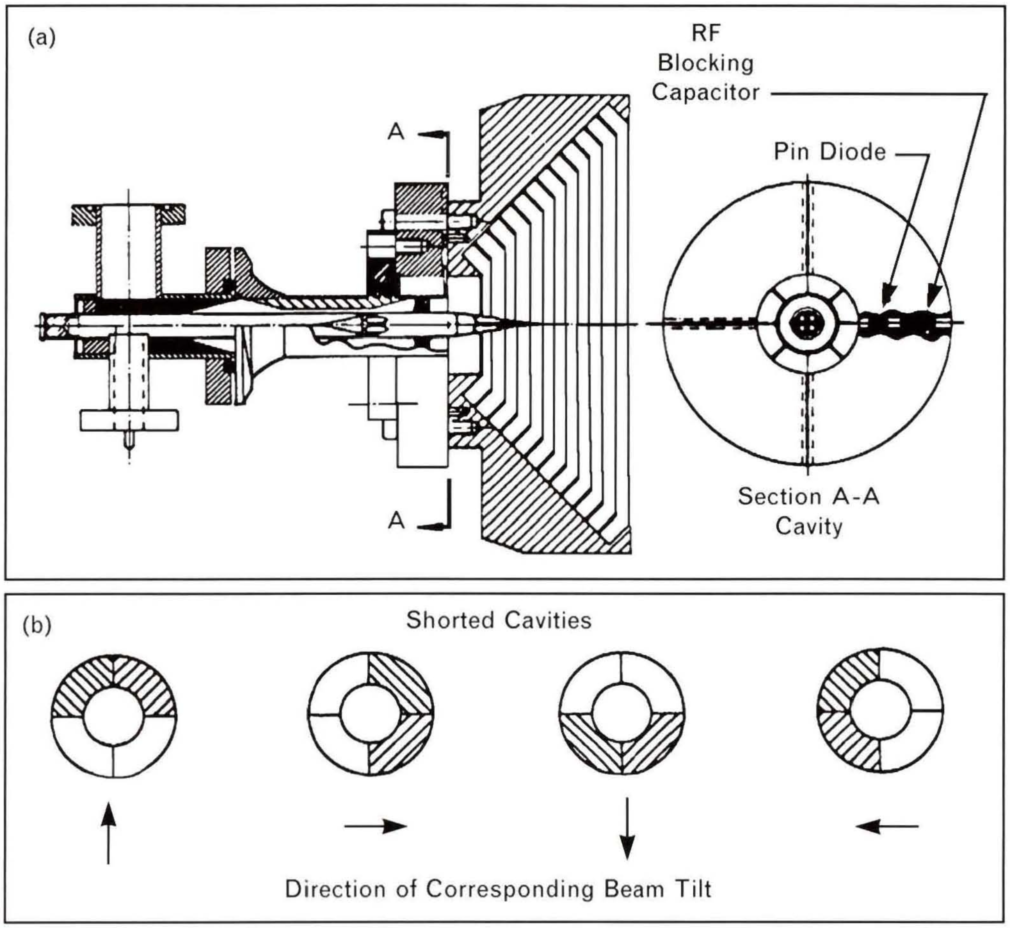


FIGURE 17. Electronic-lobing antenna with diode-switched cavities: (a) sketch of side view and cross section, and (b) diagram showing how switching of the pin diodes displaces the K-band phase center from the reflector focal point. (Note: Shaded areas represent shorted cavities.)

in 1984 and obtained drawings and additional information on the antenna design. Later, an antenna based on the design was successfully used for the first FEP-to-submarine-link experiment [22].

Advanced SCAMP Antenna

Similar to SCAMP, Advanced SCAMP is a portable terminal, but the latter operates at a higher data rate. Another difference is that SCAMP does not require a high-efficiency antenna for the downlink while Advanced SCAMP requires high efficiency for both bands. Thus we adopted the ADE design for Advanced SCAMP [23]. An antenna-aperture diameter of 24" was chosen and, for portability, the reflector was made of six demountable petals.

The larger reflector size somewhat relieved the size restraints on feed and subreflector. For high efficiency, we enlarged and corrugated the feed horn of the antenna (Figure 15). The added length to the feed permitted the use of an additional K-band matching element to improve the impedance match at the coaxial-waveguide opening. In addition, we improved the impedance match by changing the Q-band junction's straight septum into a step shaped septum. The corrugations on the subreflector edge were designed to reduce stray currents at the edge and back of the subreflector.

With a solid aluminum reflector (Figure 16[a]), the measured efficiencies for the uplink and downlink bands are 66% and 55%, respectively. With the petal reflector (Figure 16[b]), the corresponding efficiencies are 56% and 53%. The decrease, which is due to the surface imperfections of the petal assembly, corresponds to a

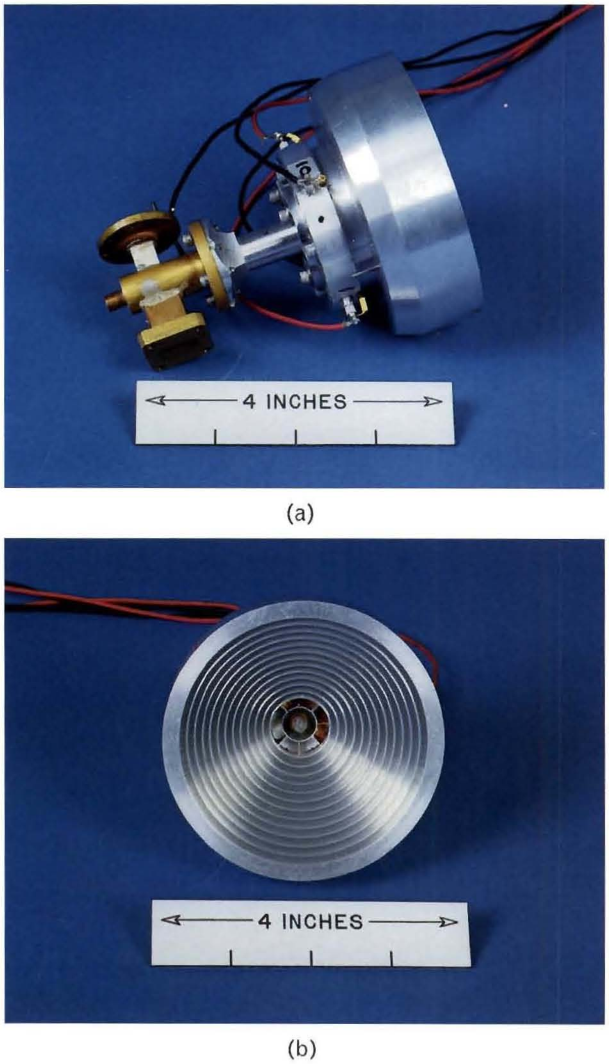


FIGURE 18. Development model of electronic-lobing feed: (a) side view and (b) front view.

reduction of 0.9 and 0.2 dB, respectively. Table 4 lists the efficiencies of the different antennas.

Electronic-Lobing Antenna

All the ground terminal antennas described thus far track satellites by a mechanical stepping of the whole antenna assembly or by a conical scanning of the feed. Current EHF terminals use the following mechanical-tracking procedure: the beam is pointed to one side of the satellite in each of four cardinal positions, the signal amplitude statistics are accumulated at each position, and the pointing offset is computed. The process has three disadvantages:

1. Because of the slow response time due to the mechanical movement of the antenna, passing clouds can confuse tracking.
2. Constant mechanical exercise of the whole an-

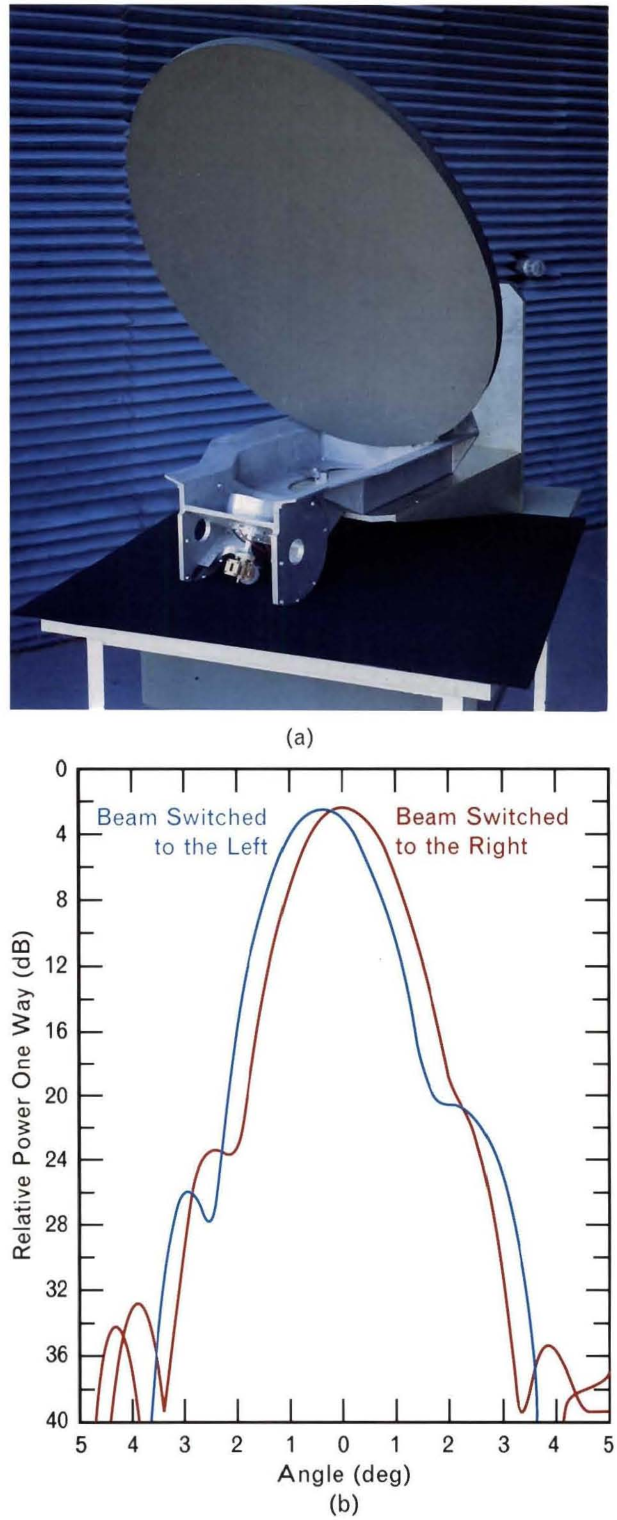


FIGURE 19. SCOTT ADM antenna with electronic-lobing capability: (a) photo and (b) measured antenna patterns at 20.6 GHz.

Table 4. Comparison of Antenna Efficiencies

Antenna	Frequency Band (GHz)	Efficiency
SCOTT	44	60%
	20	60%
ADE 6"	44	63%
	20	43%
SCAMP	44	55%
	20	25%
Advanced SCAMP	44	66%
	20	55%

tenna structure increases the power consumption and reduces the terminal life.

3. The uplink beam is moved, which results in additional pointing losses.

Thus we investigated various ways to add electronic-lobing capability [24] to the basic dual-band feed. Figure 17 shows the design that was selected for further development. In the design, four resonant cavities have been added in circumferential locations at the coaxial-waveguide opening of the dual-band feed. A pin diode located at the open end of each of the four cavities controls the coupling of the cavities to the K-band coaxial-waveguide opening. By switching the diodes in a specific order, we can sequentially displace the K-band phase center from the reflector focal point. This lateral movement of the phase center causes corresponding changes in beam direction.

The design uses miniature, glass-packaged pin diodes with low RF loss and low reactance. The switching time of the diodes is on the order of a few nanoseconds. Figure 18 shows a development model of the feed with the diodes mounted. Details of the throat geometry and nearby structure affect the coupling characteristics of the K-band coaxial waveguide to the side cavity. In the present design, the coupling coefficient is typically about –20 dB. For the feed mounted onto the SCOTT ADM reflector, the average beam squint (i.e., the average rotation of the beam) achieved is about 0.17° (Figure 19), with a standard deviation of 0.06°. The average K-band antenna beamwidth is 1.60°.

Summary

A compact, high-performance, dual-band feed has been designed and developed. We have successfully adapted the feed to numerous different antenna systems such as SCOTT, SCAMP, Advanced SCAMP, and many other smaller terminals, including satellite spot-beam and submarine periscope antennas. Table 5 summarizes the related applications and technology transfers. A possible application for the future is in the lightweight-satellite area.

Acknowledgments

The author acknowledges the support of W.C. Cummings, D.M. Snider, R.F. Bauer, W. Rotman,

Table 5. Summary of Dual-Band-Feed Technology Transfers

Lincoln Laboratory Development	Technology Transfer to
SCOTT ADM 24" Antenna	SCOTT 66" Antenna (Patent in 1985)
FEP Spot-Beam Antenna Backup	Satellite Spot-Beam Antenna
SCAMP	
ADE Antenna	Submarine Antenna
Advanced SCAMP	
Electronic-Lobing Antenna	Technology License

Note: Other possible applications include lightweight satellites.

and A.R. Dion; the measurement assistance of R.J. Burns and J.P. McCrillis; and the fabrication help of G.M. Willman.

REFERENCES

1. W.W. Ward and F.W. Floyd, "Thirty Years of Research and Development in Space Communications at Lincoln Laboratory," *MIT Lincoln Lab. J.* **2**, 5 (1989).
2. K.R. Roth, M.E. Austin, D.J. Frediani, G.H. Knittel, and A.V. Mrstik, "The Kiernan Reentry Measurements System on Kwajalein Atoll," *MIT Lincoln Lab. J.* **2**, 247 (1989).
3. J. Holland, "Multiple Feed Antenna Covers L, S, and C Band Segments," *Microwave J.* **24**, 82 (Oct. 1981).
4. M. Livingston, "Multifrequency Coaxial Cavity Apex Feeds," *Microwave J.* **22**, 51 (Oct. 1979).
5. R.W. Dawson, "An Experimental Dual Polarization Antenna Feed for Three Radio Relay Bands," *Bell System Tech. J.* **36**, 391 (1957).
6. M.S. Narasimhan and M.S. Sheshradi, "Propagation and Radiating Characteristics of Dielectric Loaded Corrugated Dual-Frequency Circular Waveguide Horn Feeds," *IEEE Trans. Antennas Propag.* **27**, 858 (Nov. 1979).
7. D.M. Knox and J.E. Doble, "The Modified Primary Feed and Tracking System for Goonhilly No. 1 Aerial," *Earth Station Technology,* IEE Conf. Publ. No. 72 (1970), p. 201.
8. J.P. Grabowski, "Tradex L/S Dual Frequency Monopulse Tracking Feed," Final Report, Contract AO F19628-70-C-0230, RCA/Government and Commercial System, Moorestown, NJ (June 1972).
9. J.C. Lee, "A Compact Q-/K-Band Dual Frequency Feed Horn," *IEEE Trans. Antennas Propag.* **32**, 1108 (1984).
10. T. Sato, "Dielectric-Loaded Horn Antenna," *Electron. Comm. Jpn* **54-B**, 57 (1971).
11. P.D. Potter, "A New Horn Antenna with Suppressed Sidelobes and Equal Beamwidths," *Microwave J.* **63**, 71 (June 1963).
12. A.J. Simmons and A.F. Kay, "The Scalar Feed—A High Performance Feed for Large Paraboloid Reflectors," *IEE Conf. Publ.* **21**, 213 (1966).
13. B.M. Thomas, "Design of Corrugated Conical Horns," *IEEE Trans. Antennas Propag.* **26**, 367 (1978).
14. F. Takeda and T. Hashimoto, "Broadbanding of Corrugated Conical Horns by Means of the Ring-Loaded Corrugated Waveguide Structure," *IEEE Trans. Antennas Propag.* **24**, 786 (1976).
15. J.C. Lee, "Compact Broadband Rectangular to Coaxial Waveguide Junction," U.S. Patent No. 4,558,290 (10 Dec. 1985).
16. W. Rotman and J.C. Lee, "Dielectric Lens Antenna for EHF Airborne Satellite Communication Terminals," *Technical Report 592,* MIT Lincoln Laboratory (16 Feb. 1982), DTIC #AD-A113250/5.
17. C.A. Lindberg, "A Satellite Antenna System in the 20 and 44 GHz Frequency Band," IEEE Milcom, Los Angeles, 21–24 Oct. 1984, p. 42.1.
18. Y.A. Yerukhimovich, "Analysis of Two-Mirror Antennas of a General Type," *Telecommun. Radio Eng.* **27**, 97 (Nov. 1972).
19. Y.A. Yerukhimovich and A.Y. Miroshnichenko, "Development of Double-Reflector Antennas with a Displaced Focal Axis," *Telecommun. Radio Eng.* **29**, 90 (Sept. 1975).
20. G.Z. Aizenberg, V.G. Yampolsky, and O.N. Tereshin, *SHF Antennas Part II,* in Russian (Svjaz Press, Moscow, 1977).
21. W.R. Rotman and J.C. Lee, "Compact Dual Frequency Reflector Antennas for EHF Mobile Satellite Communication Terminals," *IEEE Intl. Symp. on Antennas and Propagation, Boston, 1984,* p. 771.
22. F. Beltran, Raytheon Co., Wayland, MA, private communication (1988).
23. J.C. Lee, "A Compact Portable Antenna for ASCAMP," *MIT Lincoln Laboratory Report,* to be published.
24. J.C. Lee, "A Dual-Frequency Feed with Electronic Tracking Capability," *Technical Report 779,* MIT Lincoln Laboratory (22 May 1987), DTIC #AD-182213.

JOSEPH C. LEE
is a staff member in the Satellite Communications Technology Group. Since 1969 he has been with Lincoln Laboratory, where his focus of research is in antennas, feeds, microwave components, and intermodulation interference multipactor problems. Joseph received the following degrees in electrical engineering: a B.S. from the National Taiwan University, an M.S. from the University of Utah, and a Ph.D. from Stanford University. In his spare time, he enjoys reading and traveling.