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Primary Feeds for the Goonhilly Satellite-Communication Aerial*

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The 85-ft. diameter aerial at Goonhilly Downs, Cornwall uses a focal-plane paraboloidal reflector illuminated from a primary feed at the focus. Circularly polarized waves are transmitted and received. For optimum gain and uniformity of the aerial radiation patterns, circular symmetry of the primary feed radiation pattern is desirable. The primary feed has therefore been made circularly symmetric.

The following terms, which are particularly applicable to large-aperture low-noise parabolic-reflector type aerials, are used in the present account of the feed design: *Aerial Gain Factor* (G): the ratio of the actual gain obtained to that of a uniformly illuminated aperture of the same area; *Illumination Efficiency* (e): the ratio of the energy illuminating the reflector to the total energy radiated by the feed; *Radiation Spillover:* the energy radiated by the feed, not illuminating the reflector; *System Figure of Merit:* the ratio of aerial gain to the total receiving system noise-temperature in degrees Kelvin. Other terms and symbols are given in Appendix 1.

Primary feed radiation patterns usually have a field intensity which is maximum in the direction of the vertex and which tapers towards the periphery of the reflector. Spillover is normally permitted to obtain an optimum gain factor. However, for the reception of low-level signals, when the aerial is pointing towards a low-temperature sky, some consideration must be given to spillover which results in the reception of thermal radiation from the earth. The spillover permitted with a receiving aerial may then be less than that with a transmitting aerial for optimum working conditions. The optimum spillover for reception also varies with the aerial elevation, but 5° is an appropriate elevation for consideration since then the sky temperature has the fairly low figure[1] of about 20°K and the spillover noise temperature is very nearly maximum. At low angles of elevation, approximately one half

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of the spillover energy is at the average sky temperature (assumed to be 6°K) and the other half at the temperature of the earth.

The experiments with the Telstar and Relay satellites require transmitting frequencies at the ground stations of about 6390 and 1725 Mc/s respectively, and a common receive frequency of about 4170 Mc/s. The initial time available for development made it imperative to consider at the outset a separate primary feed design for each experiment. However, a composite feed unit capable of accommodating all three frequencies is now in use.

AERIAL GAIN FACTOR AND SYSTEM FIGURE OF MERIT

The gain factor of a parabolic aerial is given by[2]:

$$G = \cot^2 \frac{\psi}{2} \left| \int_0^{\psi} \left[G_f(\phi) \right]^{\frac{1}{2}} \tan\ (\phi/2) d\phi \right|^2. \qquad (1)$$

The classes of primary feed patterns considered analytically by Silver[2] are given by:

$$G_f\phi = G_0 \cos^n \phi \qquad (2)$$

between the limits $\phi = +\frac{\pi}{2}$ and $-\frac{\pi}{2}$, and where $n = 2, 4, \ldots$ etc.

When $n = 2$, the optimum aperture ψ is about 66° and the gain factor obtained is about 0.83. The primary feed illumination at the reflector periphery is then about −10 db relative to that at the vertex. In the case of the focal plane paraboloidal reflector, the angular aperture, ψ, is $\pi/2$ and the gain factor is

$$G\pi/2 = \left| \int_0^{\pi/2} \left[G_f(\phi) \right]^{\frac{1}{2}} \tan\ (\phi/2)\ d\phi \right|^2. \qquad (3)$$

For the feed pattern given by Equation 2, the gain factor is only 0.57. To obtain a higher value therefore it is necessary to broaden the feed pattern allowing some spillover. This can be considered analytically by assuming a primary feed pattern given by

$$G_f\ (\phi) = G_0 \cos^n m\phi \qquad (4)$$

between the limits $m\phi = +\ \pi/2$ and $-\ \pi/2$, and where m lies between 0.5 and 1.0.

When the gain factor obtained from Equation 3 is plotted against the parameter m, the curve in Fig. 1 is obtained for $n = 2$. This curve

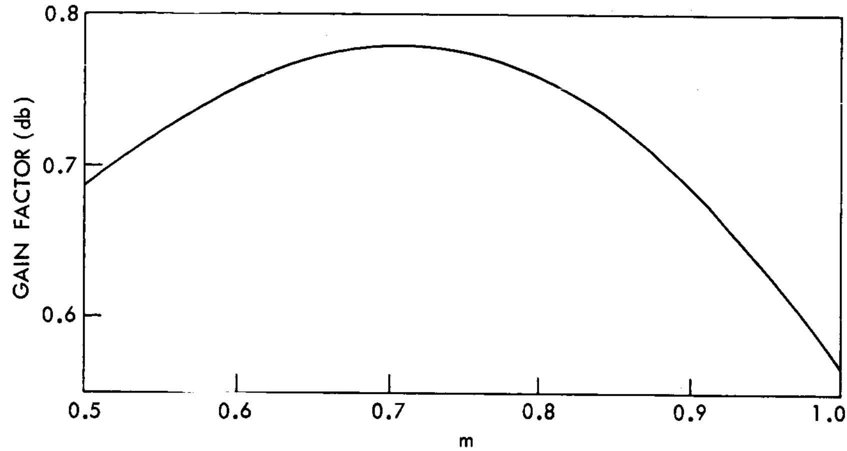

Fig. 1 — Variation of aerial gain factor with m.

indicates that an optimum gain factor of about 0.78 is obtained with $m = 0.7$.

When the effects of radiation-spillover are considered, the following approximate formula for the system noise temperature is obtained:

$$T_S = T_1 + eT_2 + \frac{(1-e)}{2} T_3 + \frac{(1-e)}{2} T_4,$$

where T_1 = noise temperature of the receiving equipment (apart from the aerial)

T_2 = sky temperature seen by the aerial main lobe (20°K is assumed at 5° elevation)

T_3 = average sky temperature, assumed to be 6°K

T_4 = effective ground noise-temperature

Curves are plotted in Fig. 2, giving values of figure of merit for an 85-ft. diameter focal-plane aerial with various values of ground noise-temperature and with a receiving apparatus noise-temperature of 50°K. A ground temperature of 280°K is the figure assumed where the reflexion coefficient of the earth is zero, i.e. the earth is regarded as a black body radiator. A temperature of 180°K is where the ground reflexion coefficient is about 0.6, as estimated at Goonhilly Downs, and the case of 6°K is where the use of an earth-screen is possible, giving an image of the sky in the lower hemisphere of radiation. The latter is an interesting case because the spillover temperature is lower than that of the main lobe. The condition for maximum figure of merit is then very nearly coincident with the requirements for maximum gain factor, and the effective aerial temperature is less than that of the main lobe. Optimum figures for the three ground temperatures and for apparatus temperatures of 50° and 30°K are summarized in Table 1.

TABLE I — OPTIMUM PERFORMANCE FIGURES OF THE FOCAL-PLANE PARABOLOID FOR VARIOUS GROUND NOISE TEMPERATURES

Ground Temperature (°K)	m	System Figure of Merit (db)	Aerial Gain Factor	System Noise Temp. (°K)
Equipment temperature = 50°K Sky temperature = 20°K				
280	0.8	41.2	0.758	73.1
180	0.77	41.3	0.77	72.8
6	0.69	41.6	0.777	68.6
Equipment temperature = 30°K Sky temperature = 20°K				
280	0.815	42.6	0.75	52.5
180	0.78	42.7	0.765	52.4
6	0 68	43.1	0.777	48.7

Primary feed radiation patterns for m values of 0.8 and 0.69 are shown in Fig. 3.

RADIATION FROM A SMALL APERTURE

The radiation patterns of a TE_{11} wave from an open-ended circular waveguide have been calculated by Chu[3], and the normalized patterns are given by:

The E-plane field, $$E_{(E\text{-plane})} = \frac{2\left(1 + \frac{\beta}{k} \cdot \cos\theta\right) J_1\,(ka \sin\theta)}{\left(1 + \frac{\beta}{k}\right) ka \sin\theta} \quad (5)$$

and the H-plane field,

$$E_{(H\text{-plane})} = \frac{\left[\frac{\beta}{k} + \cos\theta\right]\left[J_0\,(ka\sin\theta) - J_2\,(ka\sin\theta)\right]}{\left(1 + \frac{\beta}{k}\right)\left(1 - \frac{k^2\sin^2\theta}{k^2{}_m}\right)} \tag{6}$$

At 4170 Mc/s, the E and H radiation patterns from a 2 inch circular waveguide (Fig. 4) show that for use as a primary source of a low-temperature aerial the rearward radiation is excessive. It could be reduced by increasing the waveguide aperture, but then the breadth of forward radiation would not be obtained.

A circular flange placed about the waveguide aperture has a marked effect upon both the rearward radiation and the shape of the forward lobe. A feed with a 3½ inch diameter flange about a 2 inch aperture

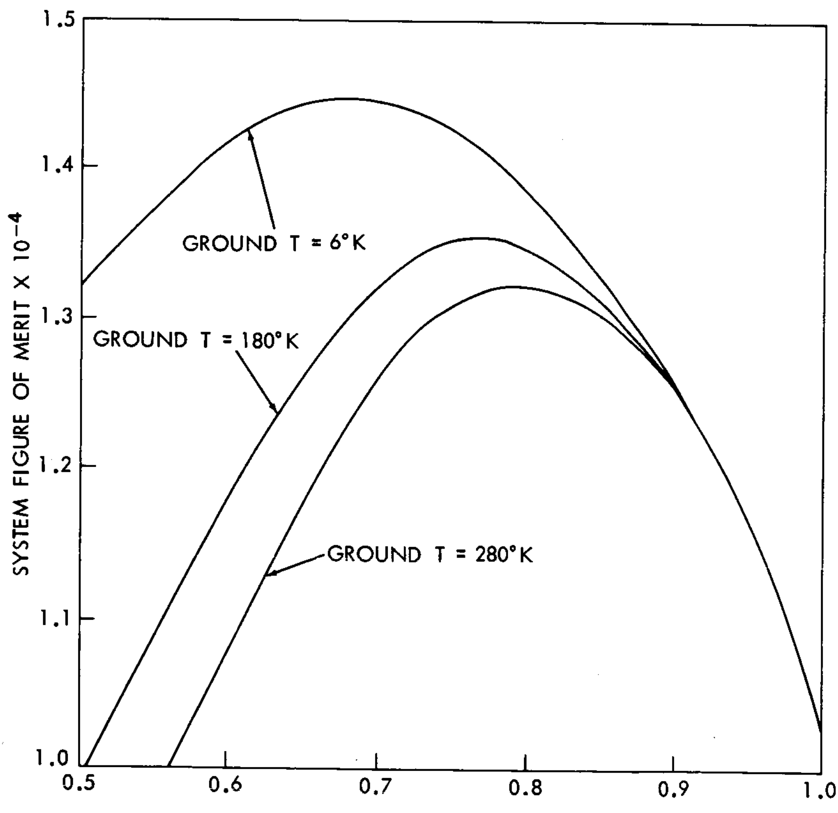

Fig. 2 — Dependence of system figure of merit on the radiation pattern of a primary-feed illuminating an 85-ft diameter reflector.

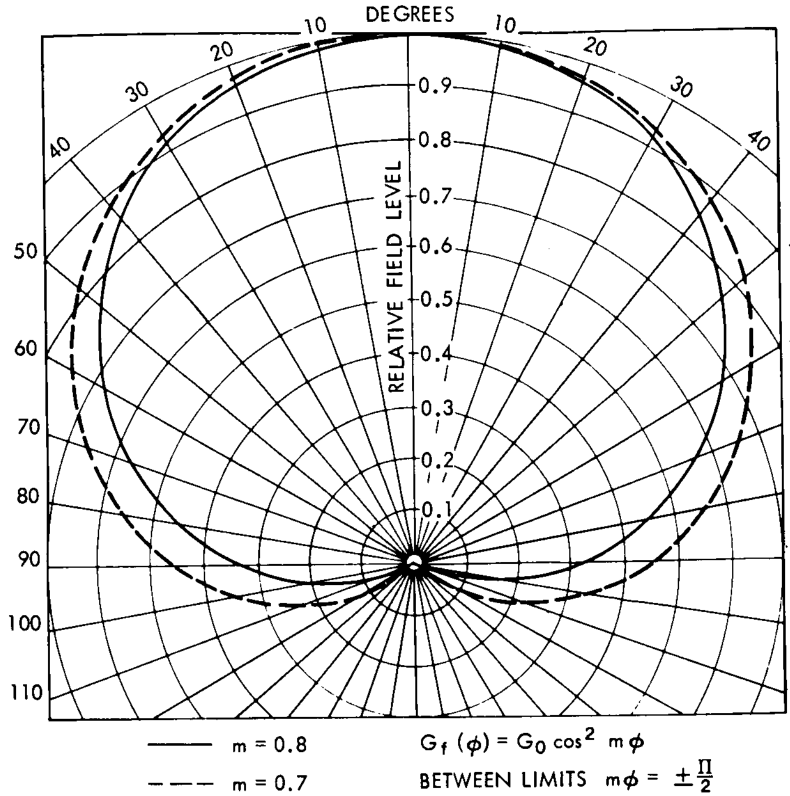

Fig. 3 — Primary feed radiation pattern.

has measured radiation characteristics showing reduced rearward radiation although increased directivity. The aerial gain factor and noise temperature obtained with this feed are estimated to be 0.53 and 5°K respectively. Improved radiation patterns were, however, obtained by placing the flange at critical distances behind the aperture, and further improvements were made by using two or more flanges. Experiments resulting in 3 inch and 4½ inch diameter flanges positioned ¼ and 1½ inches respectively behind the aperture yielded the radiation patterns shown in Fig. 5. Since the waveguide wall adversely affected the pattern, its thickness beyond the 3 inch flange was reduced to a knife-edge. The Telstar feed is based on the above, but the Relay and composite feeds with 5 inch diameter tubes have alternative flange assemblies.

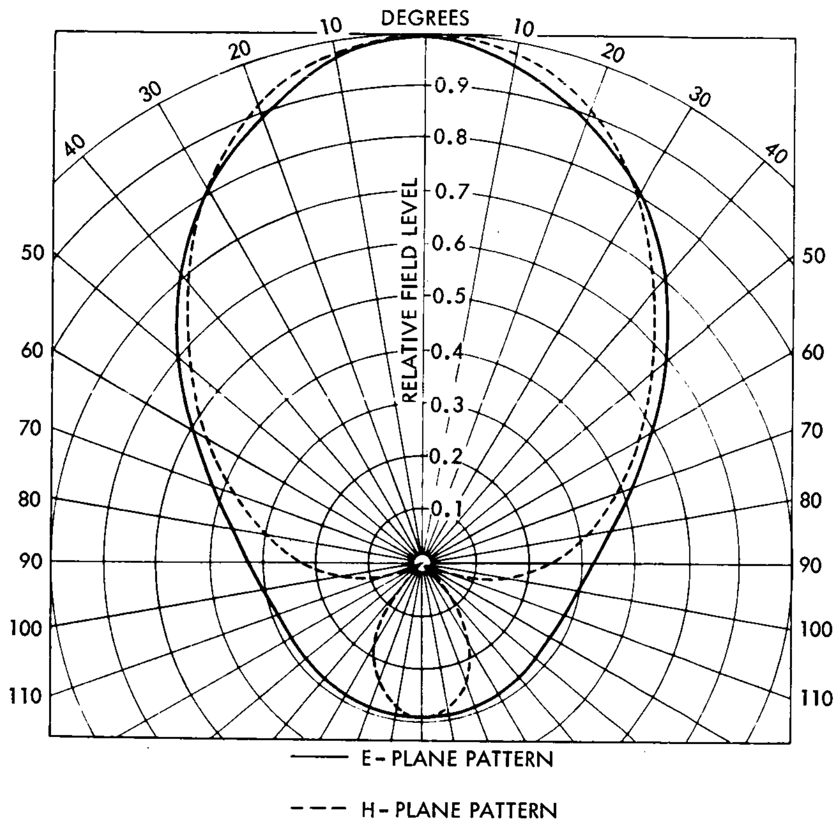

Fig. 4 — Radiation pattern (theoretical) of open ended 2″ diameter circular waveguide.

TELSTAR FEED

General

The Telstar feed is in the form of a diplexer, the transmit frequency being higher than the receive frequency. Greater emphasis has been given to obtaining optimum operation over the receiving band about 4170 Mc/s. But since the minimum usable aperture at this frequency has a diameter of about 2 inches a more directional feed pattern is obtained at the transmit frequency, resulting in slight aerial beam broadening and reduced gain factor. Since the flanges used for pattern shaping and noise reduction at 4170 Mc/s affect only slightly the 6390

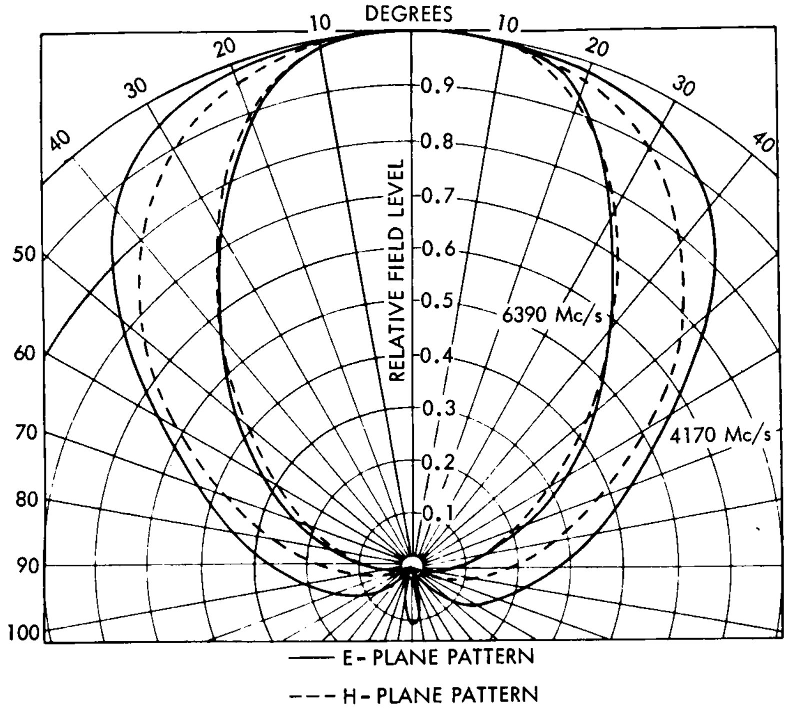

Fig. 5 — Radiation patterns of Telstar feed.

Mc/s pattern, the form of aperture used in the Telstar feed (Fig. 6) is that referred to below.

Matching

The impedance discontinuity at the feed aperture without compensation is greater at 4170 Mc/s giving a voltage standing wave ratio (VSWR) of about 0.74 compared with 0.96 at 6390 Mc/s. Matching is provided by interposing within the waveguide a section of guide of different impedance. The waveguide section is realized in practice by fitting a dielectric sleeve of the required dimensions within the 2 inch diameter guide. The sleeve has only a small effect on the matching at 6390 Mc/s as the length is about $0.5\lambda g$ at this frequency. The position of the sleeve and its thickness are such that improved matching is obtained at 4170 Mc/s.

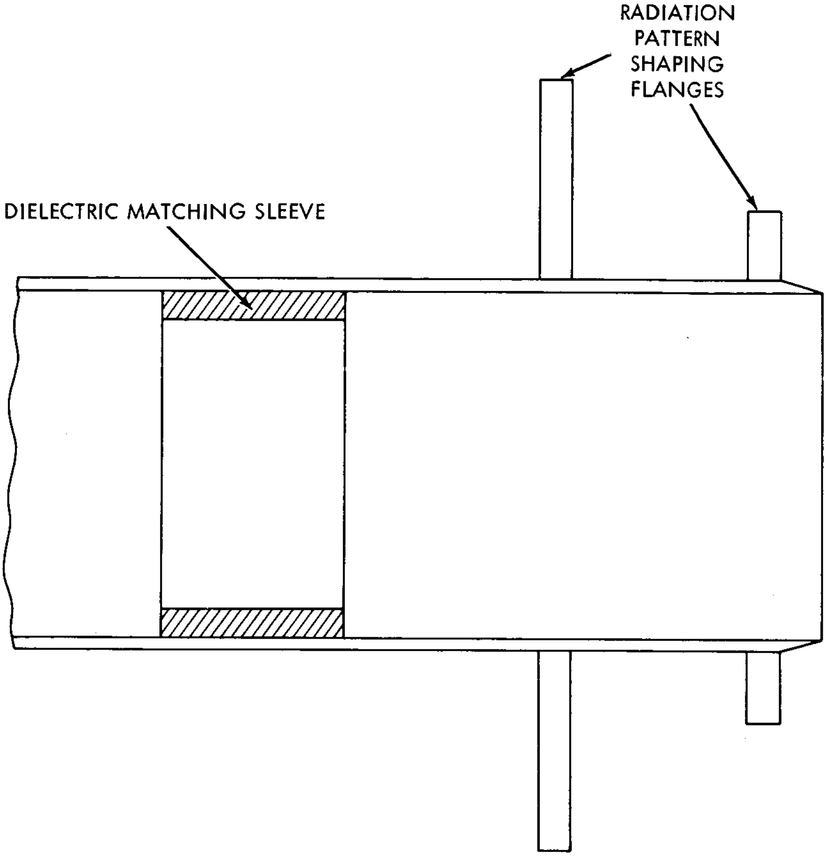

Fig. 6 — Telstar feed.

A VSWR of greater than 0.97 was thus obtained over the transmit and receive frequency bands.

Description

The Telstar feed (Fig. 6) has the circular brass flanges soldered on the outside of the waveguide, the aperture end of which has been chamfered. The dielectric matching cylinder is of *PTFE* and is set into a slight undercut in the waveguide. Adjustments to the position of the aperture on assembly are made by inserting circular waveguide spacers between the connecting flanges of the primary feed and the waveguide feeder.

Feed Performance

The radiation patterns of the Telstar feed (Fig. 5) show that at the receive frequency the average illumination taper is about −13db at ±90°. The aerial gain factor obtained from the feed pattern and the use of equation (3) is estimated to be 0.66. The illumination efficiency is about 0.966 and with a noise-temperature of 180°K due to the surrounding terrain, the effective increase in system temperature due to spillover is 2.5°K with the aerial at 5° elevation. The pattern at 6390 Mc/s is considerably more directional and yields a gain factor of 0.51 and an illumination taper of about −21db in the focal plane.

Aerial radiation patterns, calculated from the average primary feed patterns, have half-power beamwidths of 12.2 and 8.2 minutes at 4170 and 6390 Mc/s respectively.

RELAY FEED

General

In the case of the Relay feed, with the lower transmitting frequency of 1725 Mc/s, compared with the Telstar feed, a larger feed aperture was necessary. Since, however, maximum aerial efficiency and low noise temperature were again required at the receive frequency, it was imperative to consider the design of individual primary sources for transmission and reception. Of the types of feed investigated, a coaxial aperture was considered effective, the 1725 Mc/s signal being transmitted through a coaxial waveguide in the TE_{11} coaxial mode, and the 4170 Mc/s signal being received in the associated hollow inner conductor and supported in the TE_{11} circular-waveguide mode. Since the cut-off wavelength of the inner guide is less than the transmit wavelength, the highpower signal is rapidly attenuated along the receiving guide.

Description

The feed assembly (Fig. 7) has waveguide size WG_8 coupled to a power divider which divides the waveguide into two half-section guides. These diverge to allow the inclusion of a WG_{11} binomially-stepped corner in a waveguide combining section. The transducer following transforms the WG_{11} waveguide to 2 inch circular guide and the two half-section WG_8 waveguides to septate 5 in. diameter coaxial guide. The wedges through the transition provide mechanical rigidity as well as continuity of mode transformation. The septate coaxial guide is coupled to a coaxial section in which the transmitted signal

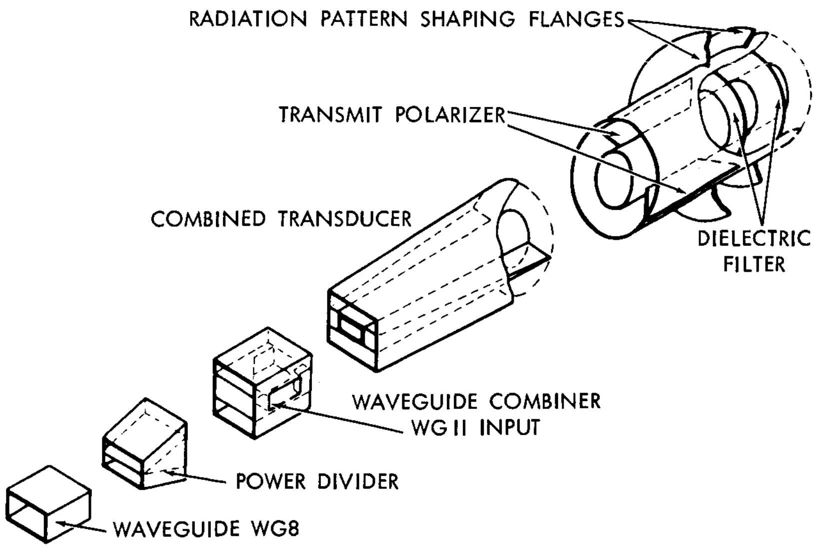

Fig. 7 — Relay feed.

is converted from linear to circular polarization through a matched pair of dielectric quarter-wave plates, of PTFE, having low-loss and a high melting point. The principle of operation of this polarizer, although in coaxial guide, is similar to that used in the Telstar feed, which has been described in a companion paper*. A dielectric filter near the coaxial aperture, whilst permitting low-loss transmission at 1725 Mc/s, provides substantial reflection at the receive frequency thus reducing radiation of noise from the "high-temperature" transmit aperture. The filter is positioned relative to the aperture to obtain a broad radiation pattern at the receive frequency consistent with low-level spillover. Circular flanges about the outer conductor provide pattern shaping at the transmit as well as the receive frequency.

The dielectric polarizer[4] and the matching in the inner waveguide are similar to those in the Telstar feed.

COMPOSITE FEED

Description

The composite feed (Figs. 8 and 9) comprises the component parts of the Relay and Telstar feeds. The Relay transducer is however sep-

* See pages 2127-2140.

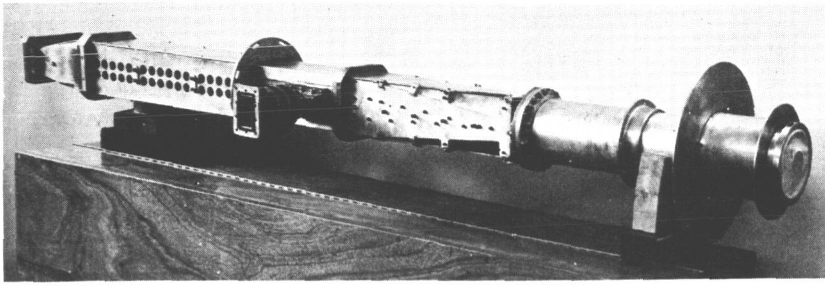

Fig. 8 — Telstar/Relay composite feed unit.

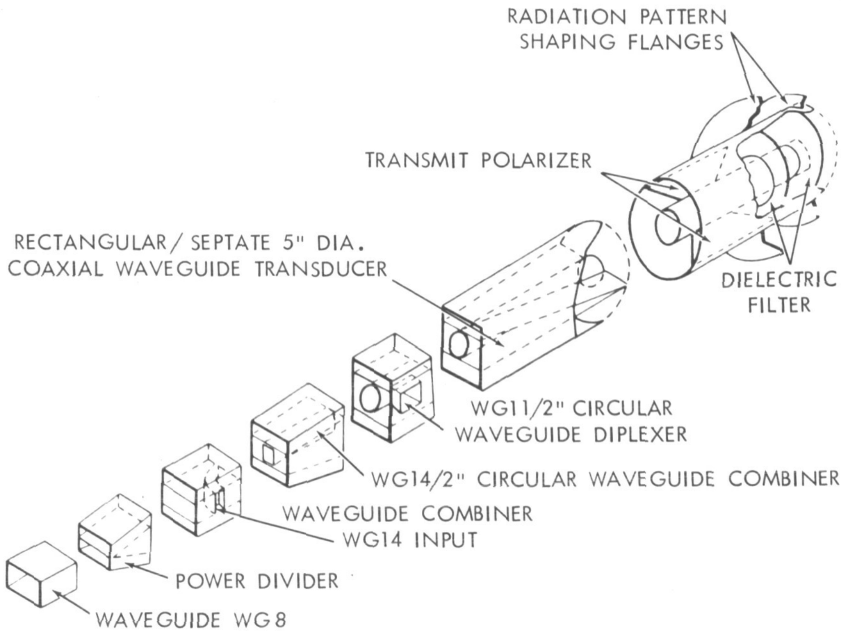

Fig. 9 — Composite Feed

arated to perform the waveguide transformations at different parts of the assembly.

The waveguide from the Relay transmitter is again coupled to a power divider to provide the two half-section guides allowing the inclusion of a WG_{14} bend. The components in the centre guide are then in the same sequence as in the Telstar feed and comprise a WG_{14} 2 inch circular waveguide transducer, WG_{11} 2 inch circular waveguide diplexer[4], dielectric polarizer[4] and the aperture matching section. In the transmitting outer guide the two half sections of WG_8 sandwich the inner guide as far as the second transducer, where the rectangular guides are transformed to septate coaxial guide. The coaxial section is then similar to that in the Relay feed.

In the Telstar experiments, the inner guide and its components are used, the 5 inch diameter aperture and flanges functioning only to shape the radiation pattern. In the Relay experiments, the WG_8 5 inch diameter coaxial guide carries the transmitting signal, and the internal circular guide receives the satellite signal, the diplexer transferring it to the main receive waveguide feeder.

Performance

The impedance matching into the composite feed gives a voltage standing wave ratio (VSWR) of 0.97 at 1725 Mc/s. The matching characteristic measured over a frequency range is that shown in Fig. 10.

The ellipticity ratio of the circularly polarized fields within the coaxial waveguide is about 0.98. The radiation pattern at the transmit frequency has a field intensity taper of −10db in the focal plane, and gives an aerial gain factor of about 0.67. The receive pattern is very similar to that of the Telstar feed and gives a gain factor of 0.66 and an illumination efficiency of 0.967.

MODEL AERIAL TESTS

During the period of feed development, some considerable experience was obtained with a 10 ft. diameter focal-plane reflector modelled on the Goonhilly aerial. The model primary feeds were scaled to operate

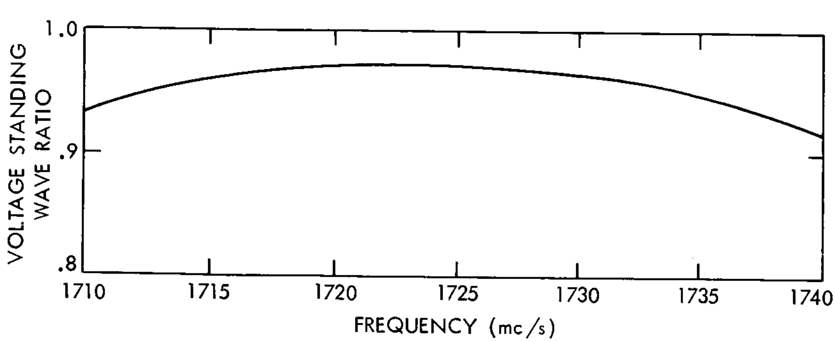

Fig. 10 — Composite feed, overall matching characteristic.

at about 11 Gc/s. A typical radiation pattern obtained with a model Telstar feed, vertically polarized (Fig. 11) shows that apart from the main lobe and immediate side lobes;

1. At bearings up to $\pm 20°$ relative to the electrical axis, the radiation is largely due to scatter from the tetrapod structure. This was shown by measurements with the tetrapod removed and the feed supported by thin nylon cords.
2. At bearings between $\pm 20°$ to $\pm 90°$ the radiation is predominately primary feed spillover.

The pattern with horizontal polarization showed a greater level of primary feed spillover consistent with the larger level measured in this plane in the primary feed radiation pattern (Fig. 6).

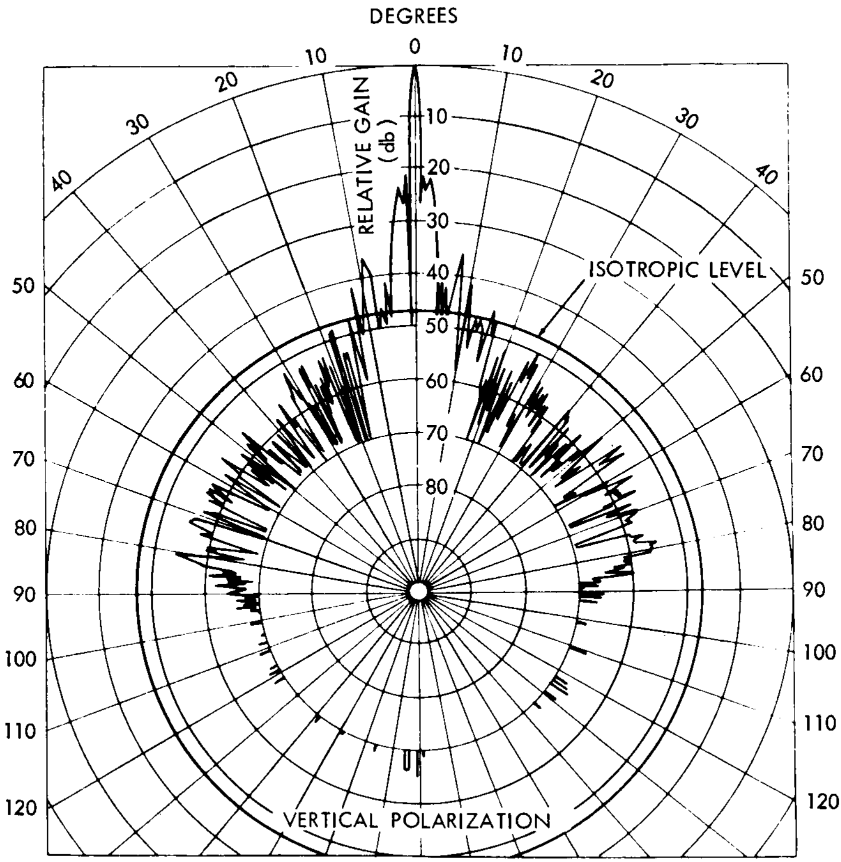

Fig. 11 — H-plane radiation pattern of model aerial with Telstar feed scaled to operate at 11.1 Gc/s.

CONCLUSIONS

Using idealized primary feed radiation patterns for guidance, it is evident that the permissible spillover is dependent upon the effective noise-temperature of the surrounding terrain, and to a lesser extent on the noise-temperature of the system receiving equipment. Where the equipment and ground temperatures are about 50 and 180°K respectively, a primary feed illumination taper of about −15db is required for an optimum figure of merit at low angles of aerial elevation. The effect of spillover is then to increase the system noise temperature by about 2.8 degrees, the gain factor being 0.77. However, if it were possible to reduce the effective ground temperature further, then the spillover could be increased to provide a greater aerial gain factor.

Experiments with circular flanges about a circular-waveguide aperture have resulted in primary feed patterns giving gain factors of about 0.65 and an effective noise temperature increase of about 2.5°K due to spillover (ground temperature = 180°K). The illumination taper at the reflector periphery is about 19db. If it were possible to broaden the feed pattern further to increase the gain factor, a closer approach to the ideal could be obtained.

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Appendix I

List of Symbols

G = Aerial gain factor
e = Illumination efficiency
ψ = Angular half-aperture of aerial, i.e. angle subtended by reflector periphery to the focus
ϕ = Angle subtended to focus
$G_f(\phi)$ = Gain function of primary feed radiation pattern
G_0 = Primary feed gain when $\phi = 0$
$G\pi/2$ = Aerial gain factor when $\psi = \pi/2$
β = phase constant $= \frac{2\pi}{\lambda}\sqrt{1 - \frac{\lambda^2}{\lambda_c^2}}$
k = $w\ (\mu\epsilon)^{\frac{1}{2}}$
k_m = $\sqrt{k^2 - \beta^2}$
μ = permeability of medium (henrys)
ϵ = dielectric constant of medium (farads)
λ = free space wavelength
λ_c = waveguide cut-off wavelength
λ_g = guide wavelength
w = $2\pi \times$ frequency
a = radius of waveguide
θ = angle subtended to centre of waveguide aperture
$J_n(\chi)$ = Bessel's function of nth order