Deep reflector prime focus feed for space communication

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Abstract
In this paper, design of a prime-focus feed for a deep reflector, Earth–Moon–Earth space communication system is described. The feed is based on a circular waveguide equipped with two chokes in order to minimise sidelobes and illuminate the deep dish with a high aperture efficiency of 70%. Based on sun noise measurements, it is estimated that the antenna system presents very low noise temperature values, below 30 K, making this feed favourable for space communication.

1 | INTRODUCTION

EME (Earth–Moon–Earth) communication [1] uses the Moon’s surface as a passive reflector to direct radio signals originating from Earth back to Earth. Operation on the lower frequency bands (144 and 434 MHz) has become technically manageable; however, due to experiencing about 289 dB signal attenuation along its round-trip path [2], as well as other technical difficulties, EME communication is especially arduous and daunting for 10 GHz (3 cm) and higher frequency bands. Recently, 10 GHz EME communication has increasingly become more accessible to a wider range of radio amateurs due to incredible advancements in power amplifier and LNA (low noise amplifier) semiconductor design, fabrication, and availability.

For economic reasons, discarded parabolic reflectors retrofitted with appropriate primary radiators are usually used in amateur EME systems.

This paper describes such an antenna system, addressing the design of a high-performance, low-noise prime-focus feed for a deep, 3 m diameter, parabolic reflector with focal length to diameter ratio $f/D = 0.3$ and documenting the associated 10 GHz band operating performance of the ensuing EME system. The rationale for choosing a dish reflector with the given parameters was simply its availability.

2 | FEED DESIGN

The selected parabolic dish reflector requires a feed having a wide radiation pattern to efficiently illuminate the $f/D = 0.3$ reflector with a total subtended angle of 159.22°.

In principle, there are two design options for reflector illumination. The first is to obtain maximum gain, $G$, while the second is to obtain the highest possible gain to antenna noise temperature ratio, $G/T_a$ [3]. Since for EME operation the same antenna is used for both transmission and reception, its feed design is a performance compromise between these two operating modes.

The proposed coaxial-cavity multimode feed horn design was inspired by Kishk and Moharram [4], [5] and consists of a 0.74λ diameter circular waveguide fitted with a principal resonant choke, 0.5λ wide by 0.43λ deep. See Figure 1.

Regrettably, this single-choke design choke exhibits relatively high back- and side-lobe levels which could contribute to elevated antenna noise temperature [3]. Therefore, to decrease the magnitude of these minor lobes, a 0.13λ wide by 0.25λ deep choke was added to the principal choke’s outer rim. This reduces the level of the undesirable lobes by about 5 dB as seen in Figure 2. Furthermore, it produces an appropriate radiation pattern with a dip in the centre that mitigates blockage loss.

For deep reflectors, like the one considered here, the chokes must be placed behind the waveguide aperture; in our case, they...
FIGURE 1 Top - model and main dimensions of the proposed feed (\(\lambda\) being free-space wavelength at 10,368 MHz), bottom - feed during the measurement at the anechoic chamber.

FIGURE 2 Simulated radiation pattern cuts for one choke (in green) and two chokes (in red). H- and E-plane at left and right, respectively. Cross-polar patterns (dashed lines) are for the \(\phi = 45^\circ\) plane.

are positioned 0.17\(\lambda\) back. This ensures the required widening of the feed’s radiation pattern to properly illuminate the deep dish.

Demand for this feed design encourages using a standard-size, WR75 rectangular waveguide at the feed port to simplify RX to TX switching with waveguide relays and ensure compatibility with other WR75-sized system components such as power amplifiers and LNAs. This, in turn, requires employment of a rectangular to circular waveguide transformer, which is also depicted in Figure 1. Additionally, to improve the overall impedance match, an iris is utilised.

The feed constructed in this manner represents a very good compromise between achieving maximum gain and having acceptable antenna noise properties [3]. CST Studio Suite 2021 [6] was used for all simulations.

FIGURE 3 Simulated and measured radiation pattern cut in the E plane. Note that the curves are normalised to their maximums and are slightly off-central axis.

FIGURE 4 Simulated and measured radiation pattern cut in the H plane. Note that the curves are normalised to their maximums and are slightly off-central axis.

3 | SIMULATED AND MEASURED RESULTS

The feed was tested using an NSI-MI farfield system [7] with an RFspin model DRH20 [8] reference antenna. Comparisons of simulated and measured cuts for E- and H-planes are plotted in Figures 3 and 4.

We also performed crosspolarisation measurements in both E- and H-planes. The crosspolarisation values were very low, confirming the simulated results. Maximum crosspolarisation levels peaked approximately \(-16\) dB at the \(\phi = 45^\circ\) and \(\phi = 135^\circ\) cuts as expected. However, EME communication in the 10 GHz band is one of the few applications where crosspolarisation can subtly increase the efficiency of the antenna system due to backscatter depolarisation [9].

Simulated and measured impedance matching in terms of reflection coefficient \(S_{11}\) is shown in Figure 5. A standard coaxial to WR75 transition was used for the measurement. We note that the EME band is narrow, 10,368–10,368.1 MHz. Since matching is very good below \(-25\) dB in the frequency range 10,300–10,700 MHz, the feed could also be used in other applications using the satellite downlink band 10,489.5–10,499 MHz.
4 | PERFORMANCE OF THE ANTENNA SYSTEM

The gain of the entire antenna system was calculated using two numerical methods (I and T solvers in CST) running on a computer fitted with two XEON Gold processors @ 3.6 GHz with 384 GB RAM.

The first, a hybrid method, considers the feed’s radiation pattern as a farfield point source to illuminate the reflector in the frequency domain integral solver. No aperture blockage by the feed or struts was taken into the account in the hybrid method.

The second approach is completely full-wave in the time-domain solver. Due to the rotational symmetry of the antenna, we were able to reduce the number of simulation meshcells by 75% (to a manageable level), by simulating only a single quadrant and ignoring struts aperture blockage. We used 12 cells/\( \lambda \) resulting in 1400 Mcells in total.

The struts aperture blockage cannot be taken into account in the single-quadrant simulation since the struts, shown in Figure 6, are asymmetrically distributed with respect to the quadrants.

Gains evaluated by hybrid and full-wave methods were comparable: 49.1 and 48.7 dBi, respectively, see Figure 7. This corresponds to a 70% aperture efficiency.

Note that ignoring the struts blockage was estimated to be only 0.08 dB using a simple geometrical shadow calculation.

Simulated \( S_{11} \) of the entire antenna system at the operating EME frequency band is −27 dB.

The sun noise measurement (see Figure 6) was performed on 2nd October 2020, when the solar flux density \([10] \) was \( S_0 = 282 \cdot 10^{-22} \text{ Wm}^{-2} \text{Hz}^{-1} \) at 10,368 MHz. The measured sun noise value was \( \gamma = 56.23 \) (17.5 dB) using a receiver having a noise figure of 0.9 dB (\( T_{RF} = 67 \text{ K} \)). The \( T_{RF} \) noise figure was measured with an Agilent HP89700 noise figure meter, an HP346B noise source (\( T_{ref} = 290 \text{ K} \)) and an advanced microwave component AMC206 coaxial to WR75 transition (The transition adapter could introduce some small deterioration of noise figure).

Also note that the antenna sky temperature dependence on the frequency and elevation angle is described in \([11], [12] \).

To evaluate the figure of merit, gain to system noise temperature ratio, \( G/T_s \), we used the following formula \([10] \)

\[
\frac{G}{T_s} = 10 \log \left( \frac{8\pi k(\gamma - 1)}{S_0 \lambda^2 C a} \right),
\]

where \( T_s \) is system noise temperature \( T_s = T_a + T_{RX} \) consisting of antenna noise temperature \( T_a \) and receiver noise temperature \( T_{RX} \). Furthermore, \( k \) is Boltzmann’s constant (1.38 \( \cdot 10^{-23} \text{ J/K} \)), \( \gamma \) is the measured difference between source noise power density and cold sky power density, \( S_0 \) is solar flux density, \( \lambda \) is wavelength, \( C \) is beam correction factor (assumed \( C = 1 \)) and \( a \) is atmospheric absorption correction factor (also assumed \( a = 1 \)).
Equation (1) evaluates to \( \frac{G}{T_s} = 29.1 \, \text{dB/K} \) and consequently, the estimated antenna noise temperature \( T_a \) is below 30 K, which is a very good value \([13]\).

In prime focus parabolic antenna configurations, the dominant antenna noise temperature contribution arises from reflector spillover when the feed acquires thermal noise from the ambient environment behind the reflector. To support our favourable value of \( T_a \), we performed a numerical spillover efficiency calculation \([11]\) which results in

\[
\eta_{\text{spillover}} = \frac{\int_{0}^{2\pi} \int_{0}^{\Psi_0} f^2(\theta, \phi) \sin \theta \, d\theta \, d\phi}{\int_{0}^{2\pi} \int_{0}^{\pi} f^2(\theta, \phi) \sin \theta \, d\theta \, d\phi} = 0.973. \tag{2}
\]

In the above equation, \( \Psi_0 \) is half the subtended angle \( \frac{159.22}{2} = 79.6^\circ \) and \( f^2 \) is the power pattern of the feed. The spillover efficiency calculation indicates that only 2.7\% of the feed's radiated power is not intercepted by the reflector.

\section{CONCLUSION}

The design objective of the proposed coaxial-cavity, multimode feed horn was to maximise the reflector antenna system's 10 GHz space communication performance for both transmission and reception operating modes. This objective was achieved by producing symmetrical radiation patterns and suppressing the feed's minor lobes. High efficiency, good noise properties, and favourable impedance matching were confirmed by simulation and measurement.

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