Design of Earth-Moon-Earth (EME) Radar Antenna

Abstract:

This report investigates the requirements for an antenna to receive a radar signal that originates on the other side of the planet after it bounces off the moon. Due to the large propagation distance and signal attenuation the characteristics of our antenna must meet performance requirements. In this report I will use the radar range equation to achieve at least a 20 dB signal to noise ratio. Some key factors included would be path loss, antenna gain, and system noise which will be factors in our evaluation for our antenna design.

Introduction / Background:

Communication through Earth-Moon-Earth (EME), the concept of using the Moon as a reflector for transmitted radio signals, was explored during the Cold War. During this time the Central Intelligence Agency (CIA) developed techniques which used the Moon to intercept transmitted radar signals from distant locations that couldn't be observed directly from Earth. These experiments demonstrated that radar signals that were reflected from the Moon were extremely weak. They were much lower in magnitude than the original signals and therefore require large, high gain antennas to detect these signals [1].

The Radar Equation Introduction:

One of the biggest challenges of the EME bounce problem is the large propagation distance and the signals attenuation. The average distance from the Earth to the Moon is approximately 385,000 km [2]. Because the signal must travel from Earth to the Moon, and back to the Earth the total propagation distance is about 770,000 km. This results in a significant loss in magnitude for our signal, making it difficult to detect the signal.

In our EME system, the extreme propagation distance results in great signal attenuation. Before reaching our antenna, the signal spreads over a distance during transmission and again after reflecting off the Moon. The received power (P_r) decreases as it spreads out over the surface area of a sphere in all directions $\frac{1}{4\pi R^2}$ [3]. Because the signal spreads out on the way to the Moon and again on the way back, we can assume that the received power follows a relationship of $\frac{1}{R^4}$ [3] [2]. The estimated path loss of our signal is expected to be about 250-300 dB [2].

The radar equation for the received power, derived from [3], is given by:

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4}$$

In the equation P_t represents the transmitted power, G_t and G_r representing the gain of the transmitting antenna and the receiving antenna, R is the approximate distance between the Earth and the Moon, λ is the wavelength of the signal and σ is the radar cross section of the moon.

The equation explains how the power received at the receiving antenna decreases rapidly as the propagation distance grows. This shows the importance of the gain from our receiving and transmitting antennas, because to achieve a 20 dB signal to noise ratio (SNR) our gain must be high enough to overcome the power lost from signal attenuation.

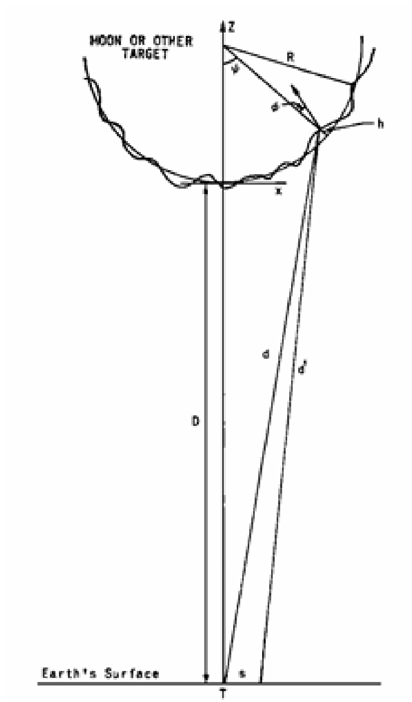

Figure 1: The figure from [4] above displays a signal and its reflection off the moon's surface. The moon in the figure is shown with a rough surface, so different parts of the signal will reflect at different angles.

System Assumptions:

Before making any calculations for the antenna requirements, reasonable system assumptions must be made. A carrier frequency of 1.3 GHz is assumed because of its common use in historical EME experiments. It is important to note that at frequencies above 1 GHz, the effect of space noise is reduced, making it easier to detect weak signals [2].

While early EME experiments used a 3 kW transmitted power, the maximum output power in the United States is about 1.5 kW. Therefore, a transmitted power of 1 kW is assumed as a reasonable value [2]. The Earth to Moon distance is taken as 385,000,000 meters for use in the calculations. For the moon reflection efficiency, a value of approximately 0.07 (7%) is used based on experimental results [2].

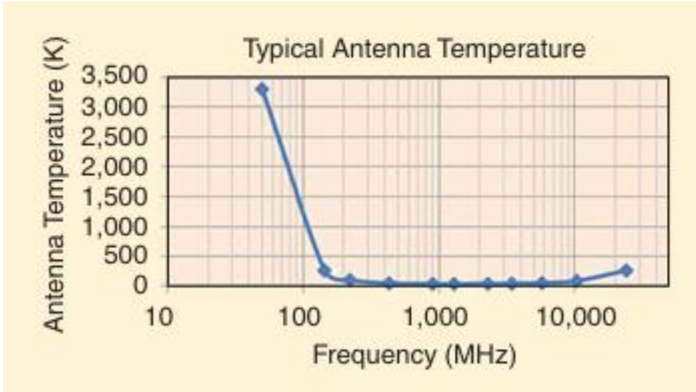

Figure 2: The plot above from [2] depicts how the Antenna Temperature changes as Frequency increases. Antenna Temperature is much higher as frequency increases. This means that lower frequencies systems will have more noise, supporting the chosen carrier frequency of 1.3 GHz

A system noise temperature of 290 K is assumed, which is a standard value for ambient noise temperature [5]. The noise bandwidth is assumed to be 1 kHz, which should assume to be approximately equal to the receiver bandwidth. We can assume this because reducing the system bandwidth helps reduce noise power given by the kTB equation for noise power [5].

$$P_n = kTB$$

System Calculations:

The first step we take in our calculations is to convert our power transmitted into dBm. Our assumed power transmitted of 1kW converts to 60dBm. Using this value, we continue and calculate our noise power using the kTB formula, using k, Boltzmann constant, T, our assumed noise temperature, and B, our assumed noise bandwidth.

$$P_n = kTB \;\rightarrow\; P_n = (1.38 \times 10^{-23} m^2 kg s^{-2} K^{-1})(290K)(1000Hz) \approx 4 \times 10^{-18} W$$

We continue by converting our calculation of noise power into dBm:

$$P_n(dBm) = 10log_{10}\left(\frac{P_n}{1mW}\right) \rightarrow P_n(dBm) = 10log_{10}\left(\frac{4 \times 10^{-18} W}{1mW}\right) \approx -144\, dBm$$

Because our signal to noise ratio must be at least 20 dB we can calculate the power received needed for our antenna:

$$P_{RX,required} = P_n(dBm) + 20dB = -144\, dBm + 20dB = -124\, dBm$$

From the radar equation we calculate the wavelength using the speed of light, c, and the assumed carrier frequency f. We also calculate the radar cross section of the moon, using the lunar diameter ($d = 3.476 \times 10^6$) [2] and reflection efficiency η:

$$\lambda = \frac{c}{f} = \frac{3.0 \times 10^8}{1.3 \times 10^9} \approx 0.231m \quad ; \quad \sigma = \eta\pi\left(\frac{d}{2}\right)^2 = (0.07)\pi\left(\frac{3.476 \times 10^6 m}{2}\right)^2 \approx 6.64 \times 10^{11} m^2$$

Now we solve the radar equation for both antenna gains G_t and G_r, we can assume that the gains are equal because it simplifies our system, allowing both gains to be expressed as G^2:

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 R^4} \rightarrow G_t G_r = \frac{P_r (4\pi)^3 R^4}{P_t \lambda^2 \sigma} = \frac{(-124\ dBm)(4\pi)^3 (3.85 \times 10^8 m)^4}{(60\ dBm)(0.231m)^2 (6.64 \times 10^{11} m^2)} \approx 4.9 \times 10^8$$

$$G_t G_r = G^2 = 4.9 \times 10^8 \rightarrow G = \sqrt{4.9 \times 10^8} = 2.21 \times 10^4$$

$$G(dBi) = 10log_{10}(2.21 \times 10^4) \approx 43.45\ dBi$$

Now that Gain is expressed in dBi, we can solve the diameter of the antenna dish needed for the EME signal. For this we also need to assume that the aperture efficiency η_a is 0.6. This is a reasonable value because the typical range of aperture efficiency is around 60%, and in some cases reach 80% so using 0.6 would be safe [7]:

$$G = \eta_a \left(\frac{\pi D}{\lambda}\right)^2 \text{ [6]}$$

$$D = \frac{\lambda}{\pi} \sqrt{\frac{G}{\eta_a}} = \frac{0.231m}{\pi} \sqrt{\frac{2.21 \times 10^4}{0.6}} \approx 14.1\ m$$

Contribution of each term in dB:

We now want to check if our radar equation matches that of the estimated path loss of the system. We can start by writing out the radar equation in terms of dB to get the total contributions of each term.

Radar equation in dB:

$$P_r(dBm) = P_t(dBm) + G_t(dBi) + G_r(dBi) + 20log_{10}(\lambda) + 10log_{10}(\sigma) - 30log_{10}(4\pi) - 40log_{10}(R)$$

$$P_r(dBm) = 60dBm + 43.45\ dBi + 43.45\ dBi + 20log_{10}(0.231m) + 10log_{10}(6.64 \times 10^{11} m^2) - 30log_{10}(4\pi) - 40log_{10}(3.85 \times 10^8\ m)$$

From here we can calculate our path loss from adding everything, but the gains and power transmitted from the antennas. We can also further calculate the power received by the receiving antenna in dBm.

$$P_{Loss}(dBm) = 20log_{10}(\lambda) + 10log_{10}(\sigma) - 30log_{10}(4\pi) - 40log_{10}(R)[2]$$

$$P_{Loss}(dBm) = -12.73\ dB + 118.22\ dB - 32.98\ dB - 343.41\ dB = -270.9\ dB$$

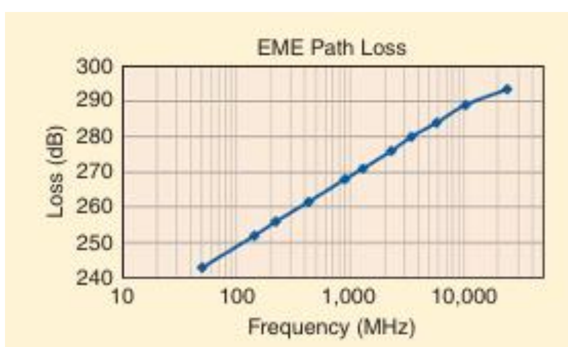

Figure 3: The plot above from [2] depicts the estimated path loss of our transmitted signal over different frequencies. From the plot we can see that the further in frequency the higher the path loss of our transmitted signal will be. This figure further confirms the estimated range of path loss being between 250-300.

The calculated path loss of the system is reasonable based on the estimated path loss of 250-300 shown in [2]. The calculated path loss falls within the range of expected values and further validates our calculations for antenna dish diameter.

And…

$$P_r(dBm) = 60\ dBm + 43.45\ dBi + 43.45\ dBi + P_{Loss}(dBm)$$

$$P_r(dBm) = 60\ dBm + 43.45\ dBi + 43.45\ dBi - 270.9\ dB = -124\ dBm$$

After calculating the power received, we can compare our power received to the noise power to confirm that our SNR of 20 dB is met:

$$SNR = P_r(dBm) - P_n(dBm) = -124\ dBm - (-144\ dBm) = 20\ dB$$

Evaluation and Final Conclusions:

Based on the calculations for the contributions of each term in the radar equation, the received power obtained is $\sim -124\ dBm$ further confirming our power required calculations. Comparing our received power calculation to calculated noise power gives a signal to noise ratio (SNR) of 20 dB meeting the minimum requirements of the antenna. However, because the SNR of the antenna exactly meets the requirements, the diameter of the antenna would likely need to be a little bigger than just necessary to factor in any additional losses that might affect our received signal.

It's also important to compare historical antennas used for EME, to determine if the diameter of the calculated antenna would be reasonable. For example, an antenna in Switzerland that was used for EME, it's dish diameter of such antenna was 15 meters [2]. 15 meters in diameter closely matches our calculations for a dish diameter that would meet the requirement of a SNR of 20 dB.

The antenna dish diameter of 14.1 meters exactly meets the requirements of a SNR of 20 dB. For a practical dish diameter size, it would be reasonable to recommend a dish diameter of closer to 20 meters in a practical setting, allowing the antenna to continue meeting the required SNR when accounting for any additional losses.

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