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A4 3 Wireless Power Transfer Across the Earth-Moon Gap

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Abstract

Wireless power transfer using microwaves has been investigated for space-based solar power and planetary exploration. In this paper, using diffraction-limited beam spread and rectenna efficiency data from literature, we explore the feasibility of transmitting power from the Earth to the Moon. We demonstrate that conversion efficiencies remain the primary bottleneck in rectenna performance and apertures of orders of kilometers are required to provide a significant quantity of power to a lunar rectenna.

Introduction

The transmission of electrical power was initially proposed by Nikola Tesla [1] and was later developed through studies of microwave power beaming, particularly for space-based solar power (SBSP) [2].

Central to these systems is the rectenna, which is a receiver for microwave power transmission. Analogous to a solar cell, it converts incident electromagnetic radiation into direct current (DC) [3]. The antenna captures and converts microwave energy, inducing an alternating current, which is then impedance-matched through a low-pass filter being rectified by a diode into usable DC power.

Recent rectenna research spans low-power harvesting [4,5] and large-scale power beaming, providing key performance benchmarks. In this paper, we extend these concepts to an extreme case: transmission across the Earth-Moon gap, a distance of 384,400 km [6] as a case study in microwave propagation and rectification under diffraction-limited optics and energy conservation principles.

Theory

The angle of divergence of a circular aperture beam is limited by diffraction. According to the Rayleigh criterion for the first diffraction minimum, the divergence angle is given by

$$\theta = 1.22 \frac{\lambda}{D}, \quad (1)$$

where λ is the wavelength and D is the aperture diameter. At a propagation distance L , the beam spot radius on the Moon is given by [7]

$$r_{\text{beam}} = \theta L = \frac{1.22\lambda L}{D} \quad (2)$$

Equation (2) is used to determine the aperture D required to achieve a desired beam radius. In this analysis, the rectenna radius r_{rec} is distinct from r_{beam} : if $r_{\text{rec}} < r_{\text{beam}}$, only part of the transmitted beam is intercepted. The power density S on the rectenna is then approximated as [7]

$$S = \frac{P_x}{\pi r_{\text{rec}}^2} \quad (3)$$

where P_x is the total transmitted power.

The rectenna conversion efficiency (η), defined as the ratio of output to input power, is given by [3]

$$\eta(\%) = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100 \quad (4)$$

Thus, the collected DC power from a rectenna of area $A_{\text{rec}} = \pi r_{\text{rec}}^2$ is

$$P_{\text{rec}} = \eta S A_{\text{rec}} = \eta P_x \left(\frac{r_{\text{rec}}}{r_{\text{beam}}} \right)^2 \quad (5)$$

For this study, the rectenna diameter is assumed to be 10 km, consistent with large-scale SBSP designs [2]. Under this assumption, the rectenna’s effective collection area remain fixed, regardless of the degree to which the microwave beam spreads to the Moon. Atmospheric losses and beam steering effects are neglected. This assumes ideal vacuum propagation and perfect beam alignment between the transmitter and the lunar rectenna.

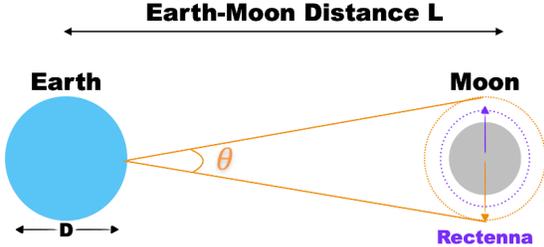


Figure 1: A schematic of the beam geometry, illustrating the Earth–Moon distance L , transmitter aperture D , beam divergence θ , and the sizes of the beam spot radius r_{beam} which is indicated in orange and the rectenna radius r_{rec} shown in purple.

Results

Considering two cases, both at a wavelength of $\lambda = 0.122$ m. Case A corresponds to a spot radius of 10 km and Case B at 100 km. The results are summarised in Table 1.

Quantity	Case A	Case B
Radius r_{rec} (km)	10	100
Transmitter D (km)	5.72	0.57
Power Density S (W m^{-2})	3.18	0.032
DC Power (MW)	150	1.5

Table 1: Delivered DC power at the lunar rectenna after applying the 60% efficiency conversion at two beam spots on the Moon.

We adopt a transmission frequency of 2.4 GHz (corresponding to $\lambda = 0.122$ m) and assume a transmitted power of 1 GW. The rectenna conversion efficiency is 60%, consistent with reported laboratory values [3, 5]. The Earth–Moon distance is 384,400 km [6].

Discussion

The two cases highlight diffraction’s central role. Narrower beams (Case A) yield high power density and higher usable output, while wider beams (Case B) distribute power over larger areas, cutting intensity by two orders of magnitude.

Relative to geostationary Earth orbit (GEO) studies, which require hundred-meter apertures, Earth–Moon propagation demands kilometer-scaled apertures to achieve comparable spot sizes. The resulting power densities remain consistent with the SBSP reports. Laboratory experiments report achieving efficiencies exceeding “60%” in strong fields [3], but these drop at low power densities [4, 5]. This emphasises the importance of beam focusing to ensure viable rectenna operation.

Conclusion

Our analysis shows that Earth–Moon wireless power transfer is physically possible but technologically demanding. Diffraction severely constrains efficiency at planetary scales, requiring multi-kilometer transmitting apertures to deliver measurable power to a rectifying rectenna. Although current research remains focused on GEO-based systems, this paper provides a quantitative framework for testing limits at planetary scales.

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