REPRISE

by David R. Criswell

Microwaves from the Moon

In his letter (*The Industrial Physicist*, June/July 2002, p. 8), Jiri Polivka does not capture the entire loss budget of a wireless power-transmission (WPT) system, but he is nonetheless correct. There is substantial path loss in the moon-to-Earth transmission due to the inverse distance term in the propagation equations. However, Polivka fails to address the effective isotropic gain of the microwave aperture based on the moon in his calculations. It is precisely this effective gain that makes modern radar (and all microwave communication) possible. However, before attempting to work out a detailed loss budget, it is necessary to outline the basic operational parameters for such a microwave link.

Beginning with the assumption that the goal is to transmit the maximum power from an aperture on the moon to an aperture on Earth, it is necessary to determine the power footprint of the beam transmitted from the moon to Earth. The microwave aperture on the moon (assuming a uniform illumination to ensure minimum beam width) will have directivity proportional to the Bessel function of the first kind, order one, divided by the normalized angular coordinate. Most of the power in this beam will be contained in the main lobe, which will have an angular extent of approximately $2.44\lambda/D$ radians, where λ is the wavelength and D is the aperture diameter. Using this relation, it becomes a simple matter to perform some basic trades on transmitting- and receiving-aperture sizes and transmitting wavelength.

For example, the original article claimed that a lunar power base could efficiently deliver power to a rectenna [sic] as small as 400 m in diameter that outputs 25 MW of electrical power. To produce a main lobe 400 m in diameter on Earth, using 384,500 km as the mean Earth–moon distance, would require an angular beam width of about 10^{-6} rad. At 2.45 GHz (the operating frequency cited in the article), this beam width would require a transmitting-aperture diameter of approximately 287 km—clearly a difficult proposition. The beam could be larger, but the receiving aperture would couple proportionally less power because as the transmitting aperture is reduced and the beam width increases, system efficiency for such a small receiver aperture quickly becomes unacceptable.

A more illustrative example is to maintain transmitter and receiver apertures at similar sizes. In this case, the selected wavelength drives the aperture sizing. Using the Earth–moon distance cited, the apertures are sized at about 10,700 m in diameter at 2.45 GHz. At 10 GHz, the size is about 5,300 m, and at 30 GHz (where atmospheric loss at elevation angles of less than 60° is approximately 0.6 dB or 13%), the aperture size is about 3,000 m. These three aperture sizes are more on a scale of something that one could construct using currently available technology.

Significant engineering design and analysis will be needed to field a lunar-based WPT system. The original article glossed over many of the engineering complexities of such a system and gave the impression it could be realized quickly. In reality, the claim that a demonstration could begin delivering commercial power within 10 years of program start-up is wildly optimistic. The planning alone for such a project could easily exceed 10 years if the project was fully funded and staffed.

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Polivka correctly asserts that the recoverable part of the wireless transmission of energy from the moon would be attenuated by some 212 dB, because of propagation loss at a wavelength of 12 cm, which is the wavelength of 2.45-GHz transmission. Criswell, however, points out that this calculation must have been based on a single half-wavelength antenna, and that a large dish antenna or phased-array antenna collimates the microwaves into a beam. Astonishingly, he concludes that more than 95% of the power entering the beam at the moon will be delivered to the receiver on Earth under most atmospheric conditions. As a former radar-systems engineer, I wish to point out some difficulties imposed by this design requirement.

As Polivka notes, there is a power-efficiency problem because propagation loss is proportional to the squared inverse of distance and to wavelength. However, for large antennas, the beam width decreases with aperture size because of the multiple wavelengths, and the power loss decreases accordingly. The problem with Criswell's statements about beam collimation is that geometric representations of beam formers are only approximate, and diffraction effects are not taken into account. These diffraction effects are not incidental and also occur for optical lenses, and consequently they affect the antenna patterns to produce a nonuniform beam shape with side lobes rather than true collimation.

For an antenna with a *parabolic reflector*, the half-power beam width angle, θ, is given by

$$\theta = \frac{65\lambda}{a}$$

where λ is the wavelength and a is the antenna aperture. Therefore, an aperture 65 wavelengths wide produces a 1° beam width. For a *phased-array* antenna, which Criswell also mentions, the beam width is a little more than 50% greater than for the parabolic antenna. A 1° moon-based transmitting antenna is 7.8 m wide and would contain 10,000 half-wave elements with half-wave spacing.

The receiving antenna would be complex and huge. To collect 95% of the beam's power, the receiving antenna's aperture must be about 13,000 km wide, using 384,000 km for the Earth–moon distance.

The spot size of the beam illumination on Earth must be decreased significantly by using a much larger antenna on the moon, which would be the most practical solution. For a moon antenna that is 78 m wide, the beam width is only 0.1° and the spot size on Earth is reduced accordingly. A phased array of this size would have more than 1 million elements, which would make it costly to produce. The Earth antenna is now down to 1,300 km, having hundreds of millions of elements. The power in the side lobes is lost unless apodization is utilized to shape the beam profile and concentrate the power in the main lobe. Such large supergain antennas also have high reactive power, which generally results in significant power loss.

If the beam from the antenna on the moon is to illuminate a single antenna on Earth, then the huge Earth antenna must be phased such that its main lobe always points toward a point on the moon as it orbits Earth. Refractive effects, due to temperature and atmospheric conditions, can alter the angle at which the beam enters the receiving antenna and cause additional power losses.

Although Criswell only refers to the power entering the beam at the moon and neglects the power losses in creating the beam, to capture 95% of the power of this beam on Earth seems an incredible task. Nevertheless, it is a very interesting concept.

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[Author replies: Polivka and Vlasak assume that the Lunar Solar Power (LSP) System power beam of wavelength ~10 cm is projected to Earth by the microwave reflector of a single power plot (Figure 1, *The Industrial Physicist*, April/May 2002, p. 13). They then conclude that the peak intensity of the power beam decreases in proportion to the inverse square of the distance from the single microwave reflector. They thus infer that Fraunhofer, or far-field, diffraction of a small aperture governs the intensity pattern of this power beam. Their assumptions and contentions are incorrect.

A power beam transmitted to Earth does not originate on the moon from a single power plot and its reflector. A power beam originates from the power base. A single power base corresponds to one of the yellow circular areas behind Figure 1. Each power base consists of many power plots. All the power-plot reflectors overlap, when viewed from Earth, and form a filled circular aperture of ~ 30 to 100 km in diameter or about 300,000 to 1 million wavelengths across. This single synthesized aperture can project a convergent beam out to the distance $\sim D^2/w = (100\ \text{km})^2/10\ \text{cm} = 10^4\ \text{km}^2/10^{-4}\ \text{km} = 10^8\ \text{km}$, or 250 times the distance from the moon to Earth. An LSP beam can operate at Earth under Fresnel, or convergent geometric, optics. Major LSP functional elements have been demonstrated at the appropriate scale (Ref. 1).

Renaud argues that an angular beam width of approximately $1 \bullet 10^{-6}$ rad is clearly difficult. The Very Large Array of 28 radio telescopes west of Socorro, New Mexico, disproves this argument. It is 30 km across at maximum extension of the individual radio telescopes. VLA's phasing system has operated under automatic control for more than 15 years at, or shorter than, the 1-cm phasing accuracy necessary to achieve a beam width of $\sim 1 \bullet 10^{-6}$.

Vlasak found it an incredible task to capture 95% of the power beamed from the moon on Earth. The stated efficiency is achievable. Additional details on the Fresnel beaming to be used by the LSP System and its advantages over Fraunhofer beaming assumed in prior studies of solar-power satellites are provided in Ref. 2.

Vlasak also notes that "a moon antenna that is 78 m wide…would have more than 1 million elements and be costly to produce." He erroneously assumes that the LSP aperture must be completely filled by the surfaces of the expensive microwave transmitters. Transmitter area is proportional to the power to be delivered. The much larger synthetic reflector aperture is made locally of lunar materials. For a diameter of ~100 km, the aperture mass will be less than the mass of one solar-power satellite proposed to deliver 10 GW of electric power on Earth. The single lunar aperture could project in excess of 2,000 GW toward Earth in multiple beams. Complex electronics and physical optics are required to divide the total power of the base into many hundreds of beams.

Vlasak asserts that "the huge Earth antenna must somehow be phased such that its main lobe always points toward a point on the moon as it orbits Earth." Rectennas need not be phased. Rectennas demonstrated during the 1970s consisted of passive panels of half-wave antennas and diodes, connected in series and parallel, to obtain the desired voltage and current when exposed to the incident power beam. The panels converted ~85% of the incident microwave power into electricity. For maximum efficiency, the passive panels must face the moon or the relay satellite.

According to Renaud, planning for the project could exceed 10 years. The Apollo 11 landing on the moon occurred less than a decade after the program started. The mobile machinery necessary to install the power plots can have a unit mass on the order of the lunar excursion modules landed on the moon more than 30 years ago. Lunar rover development began after Apollo 11, and the first rover traversed the lunar surface 33 months later. Today, the basic human and technical infrastructures exist to establish a growing materials industry on the moon that is limited only by the cleverness of the industrial mind. After the return of lunar samples and years of study, we now understand the common lunar resources.

Development of the LSP System is described in my paper (Ref. 3) presented to the 18th World Energy Congress. The primary payoff for commercial companies will not come from "cost-plus" fees on government contracts. Companies will derive their profits from the sale of net new power and the new business opportunities resulting from accelerated growth of the global economy.

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2. Waldron, R. D; Criswell, D. R. Summary of Characteristics of Beamed Power Radiation Patterns and Side Lobe Residual Power Levels for Lunar Power System. *Acta Astronautica* **1993**, *29* (10/11), 765–769.

3. Criswell, D. R. Lunar Solar Power System: Industrial Research, Development, and Demonstration, Session 1.2.2: Hydroelectricity, Nuclear Energy, and New Renewables; 18th World Energy Congress 2001; http://www.worldenergy.org/wec-geis. Ω