A MICROWAVER POWERED, LONG DURATION, HIGH ALTITUDE PLATFORM

William C. Brown

Consultant, Microwave Power Transmission Systems
6 Perry Lane, Weston, MA

ABSTRACT

A complete microwave power transmission system for a long-endurance, high-altitude (60,000 ft.) airship is described. The system includes an electronically steerable, active phased-array consisting of thousands of identical radiating modules to beam the power, and a light weight, thin-film rectenna mounted on the underside of the airship to absorb and rectifying the incoming microwave power. Application to an airplane is also discussed.

INTRODUCTION AND SUMMARY

The use of free space microwave power transmission to supply power for the propulsion and payload of an air vehicle flying at high altitudes in the earth's atmosphere has long been an objective application of this technology. The first air vehicle to be considered was a helicopter which would be both powered and positioned by a fixed microwave beam formed by a large ellipsoidal reflector illuminated by a super power microwave tube (1). The current approach being actively pursued by NASA and the Canadian Communications Research Centre is an airship or airplane that circles aloft and which is automatically tracked by the ground array (2,3,4,5).

Figure 1 illustrates a microwave powered aircraft concept as applied to a streamlined airship that was studied in considerable depth by NASA (2, 3,4). Conventional electric power is converted into microwave power in the electronically steerable active phased array and beamed to the airship. At the airship a "rectenna" absorbs the microwave energy and simultaneously converts it back to dc power (6,7). The dc power is applied to brushless dc motors that power the propellors. Propulsive power is principally required to overcome the drag of prevailing winds.

The ground array is composed of several thousand identical radiating modules. For electronic steering purposes the output phase of each of these modules is controlled by digitized signals passed along the modules through a row and column matrix. The digitized data is derived from two interferometers that track the position of the airship in an approximate manner by means of a microwave beacon positioned in the center of the rectenna. Accurate centering of the beam on the rectenna to within a meter or less is achieved by sensing the centering of the beam on the rectenna at the aircraft and telemetering this information to close the beam steering loop. The steering is updated every ten milliseconds.

A frequency of 2.45 GHz was selected for the proposed system because: (1) it is in the center of the ISM band (Industrial, scientific, medical) which is available for experimental applications of microwaves, (2) reliable transmission of power through the atmosphere under all meteorlogical conditions, and (3) reliable and inexpensive components. The availability of such components is especially important because of the physical and electrical size of the transmitting station, being of the order of several thousand square meters and one or more megawatts of radiated microwave power. The very low cost but efficient microwave oven magnetron has been found to be an excellent source of amplified microwave power when used with a ferrite circulator to create a directional amplifier that is operated in a phase-locked mode to preserve the input phase at the output under high gain (30 dB) conditions. The directional amplifier is combined with a 64-slot slotted waveguide array to form a radiating module as shown in Figure 2. The schematic for the radiating module is shown in Figure 3. Several thousand of such modules are used in the system to provide the needed power and to allow electronic steering with an angular sweep of 6 degrees (8,9).

The airship proposed for this system was designed by ILC Dover, Frederick, Delaware (4). In concept it is a steamlined, dirigible-shaped vehicle that flies at an altitude of 12 to 14 miles. The airship provides its own lift but intermittently requires a large amount of power for propulsion purposes - as much as 100 kilowatts to counter the drag on the vehicle at high wind velocities. The power is supplied from a thin-film, etched-circuit rectenna, that would be mounted along the bottom of the airship. Such a rectenna, having a specified weight of one kilogram per kilowatt of DC power output, operating at efficiencies in excess of 80%, and capable of producing 800 watts of power per square meter has been developed and tested (6,7).

Although the expected power requirements of a microwave powered airplane to perform the same mission are considerably less-20 to 30 kilowatts-a smaller amount of the beam is intercepted so that the requirements imposed upon the ground array are similar. The microwave power transmission technology presented here is therefore similarly scaled for both airship and airplane applications.

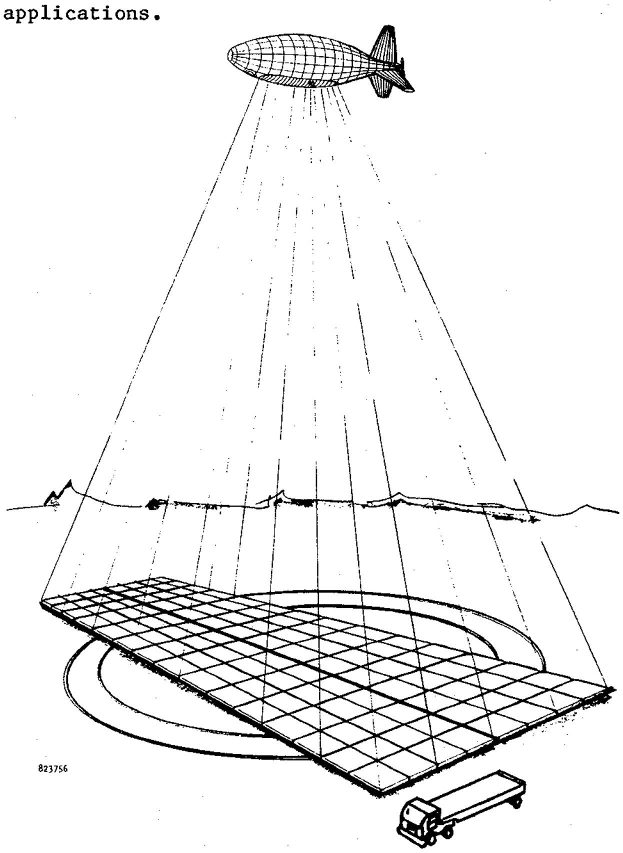

Fig. 1. Artist's Sketch of a Microwave Power Transmission System for a Microwave Powered Airship Flying at 70,000 Meters Altitude. Beam is Formed and Electronically Steered by a Phase Array Composed of Many Radiating Modules. Power at Airship is Absorbed and Converted in DC Power by a "Rectenna" for Payload and Propulsion Purposes.

The cost of the microwave power transmission system is a prime consideration in evaluating the economic potential of the overall aircraft system. While there can be no relaxation in the reliability and life requirements, the fact that the system is a "constant frequency" system with continuous output, has only a limited angular scan requirement, and can make use of many low cost, readily available components, reduces the cost to an acceptable level, lower by an order of magnitude than a radar or communications system of comparable power handling capability.

Although the ncessity of some format of the thin-film rectenna for the receiving end of the microwave beam is universally accepted, there are other conceptual approaches to the forming and steering of the microwave beam. The major factor in arriving at the electronically steerable active phased array approach described in this paper is the immediate availability and the low cost of the system in comparison with other approaches.

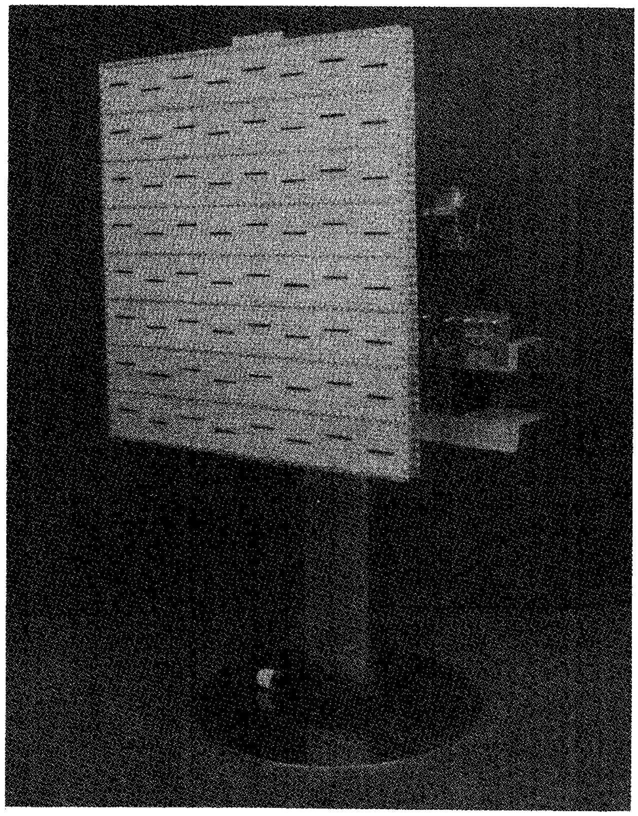

Fig. 2. 64 Slot Slotted Waveguide Array that Forms the Antenna Portion of the Radiating Module.

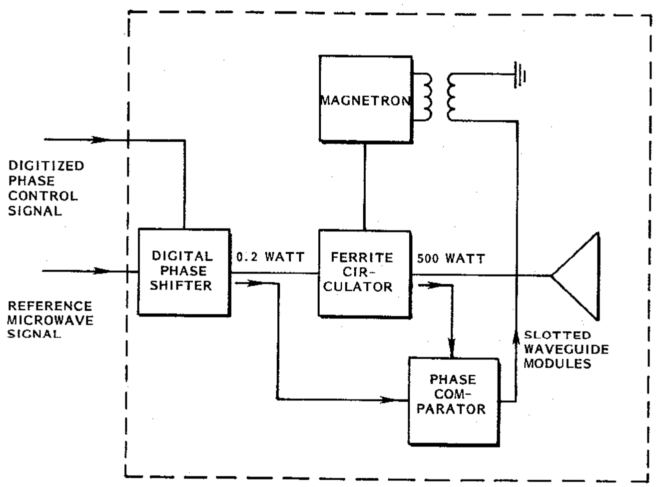

Fig. 3. General Schematic of the Radiating Module. Module Contains Phase Changing Electronics and a High Gain, Phase Locked, Magnetron Directional Amplifier as the Source of the Radiated Power.

DETERMINATION OF THE POWER AND DIMENSIONAL SCALE OF THE GROUND SYSTEM

An understanding of the factors that determine the power and dimensional scale of a typical microwave power transmission system for a high altitude aircraft may be obtained from the following expression which is derived from the standard antenna gain formula for uniform illuminated transmitting apertures.

$$P_d = \frac{A_t P_t n}{\lambda^2 h^2} \qquad (1)$$

Where: P_d is the density of the microwave power impinging on the rectenna, A_t is the area of the transmitting antenna, P_t is the total radiated microwave power, λ is the wavelength of the microwave radiation, h is the altitude, and n is an efficiency factor that decreases the intensity of the beam as it is steered off axis. The dc power output density, Pdc, from the rectenna is equal to $P_d\, n_r$, where n_r is the overall efficiency of the rectenna, typically 80 to 85%.

The use of these expressions for aircraft use has several restrictions. The need for reliable transmission through the atmosphere under all global atmospheric conditions necessitates that the wavelength be in the S-band region. The ISF (Industrial, scientific, medical) band at 2.4-2.5 GHz is in that region. The occasionally very high wind velocity at lower altitudes combined with the comparatively high density of the air necessitates that the altitude of the aircraft be over 55,000 feet to minimize drag. Tradeoff considerations between the power density demands of the aircraft and the cost of the microwave power transmission system give typical dc power densities at the aircraft, P_{dc}, of about 400 watts per square meter.

If we substitute the value of λ =0.1225 meters (2.45 GHz) h = 20,000 meters, P_d = 0.5 Kw/m^2, then the product $A_t P_t$ in expression (1) becomes 3 x 10^6/n, measured in Kw m^2 units.

The tradeoff between A_t and P_t is constrained by the allowable aperture area of the radiating module, the operating power level of the available microwave generator, and the need to associate one microwave generator with one radiating module.

Constraint Imposed by the Allowable Aperture Size of the Radiating Module by the Factor n - As the microwave beam is steered off the vertical axis; the density at its center falls off approximately as $\sin^2 x/x^2$ where $x = \pi a \sin\theta$, θ is the off axis angle, and a is the side dimension of the array. It is expected that the balloon and airplane can stay within a cone angle of 2.86° at an altitude of 20,000 meters.

At this off-axis angle the efficiency factor n is 92% for a 4 x 4 slot array with an "a" of 0.375 meters while for an 8 x 8 array shown in Figure 2 it is 0.73. From a cost point of view it is better to use the larger array because the number of microwave generators is reduced by a factor of 4.

Constraint Imposed by the Power Output of the Microwave Generators - There is a severe cost constraint in the $P_t A_t$ tradeoff imposed by the cost and availability of microwave generators. The only generator that is low in cost and readily available is the microwave oven magnetron that is limited to a power output of 250 to 1000 watts. Fortunately, it is highly efficient, operating typically at 65%, and possesses low noise and long life.

The magnetron may be combined with a ferrite circulator device to convert it into an amplifier with high gain but with an intolerably rapid phase shift across the device as a function of frequency as shown in Figure 4. However, the addition of a phase locked loop not only locks the output phase to the input but allows operation over a much broader frequency range as shown in Figure 4. In this kind of operation, the low noise and long life properties are retained.

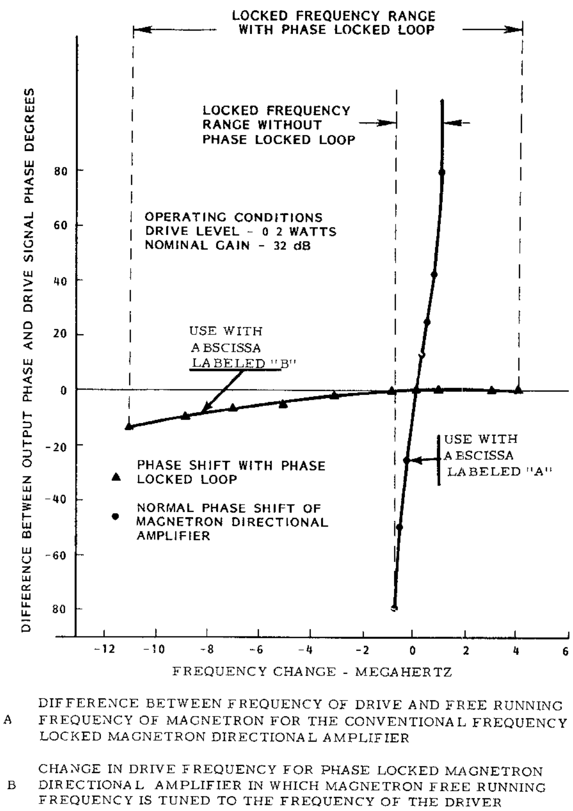

Fig. 4. Comparison of Conventional Frequency Locked and Phase-Locked Magnetron Directional Amplifiers.

The phase locking at high gain is achieved by tuning the free running frequency of the magnetron to that of the drive frequency by changing the anode current by means of a buck boost coil in the magnetic circuit. Changing the anode current also changes the power output of the device. The power output can therefore be varied by changing the drive .

Joint Constraint Imposed by the Microwave Generator Power Output and the Allowable Aperture Area of the Module; Determination of Total Antenna Area and Radiated Power - If a radiated power of 500 watts is selected for a 0.75 meter square slotted waveguide module, the radiated power assocated with each square meter of antenna area is approximately 0.9 kilowatts. Then the total power P_t radiated from the array is 0.9 A_t. By substitution, A_tP_t in expression (1) becomes 0.9 A_t^2. If the previously selected values for other parameters in expression (1) are used, solving the equation for A_t gives A = 1827 square meters. The resulting transmitting array, 42 meters on the side and consisting of 3,248 modules is one half the size of a football field. The corresponding radiated power is 1644 kilowatts. If the 0.25 Kw operating point for the magnetron is selected then A_t becomes 2,576 square meters and the radiated power becomes 1,176 kilowatts.

Although these power levels and antenna areas are large in comparison to those used for communication or radar systems at the same frequency, the relative simplicity of the system, the modular construction, and the availability of low cost components are expected to make it cost effective for a long duration, high altitude atmospheric platform for performing surveillance and communication functions. Currently, there is no cost effective way of performing a continuous, high altitude service over a fixed location on the earth.

THE RECEIVING PORTION OF THE SYSTEM

The receiving portion of the system is identified with the rectenna in its thin-film, etched-circuit format is shown in Figure 5. The rectenna converts any incident microwave power into dc power with an overall collection and rectification efficiency of greater than 80%. It is also non-directive in the sense that its efficiency remains nearly constant with a ± 20° variation in the arrival angle of the microwave beam. The rectifying element in the rectenna is a GaAs diode that has been proven highly reliable and long-lived in previous applications and tests. The performance of the rectenna has been discussed extensively in references 6 and 7.

CONCLUSIONS

The microwave power transmission technology for microwave powered aircraft has now matured sufficiently to make this application of near term interest.

ACKNOWLEDGMENT

The support of NASA and the Raytheon Company in developing the technology is acknowledged.

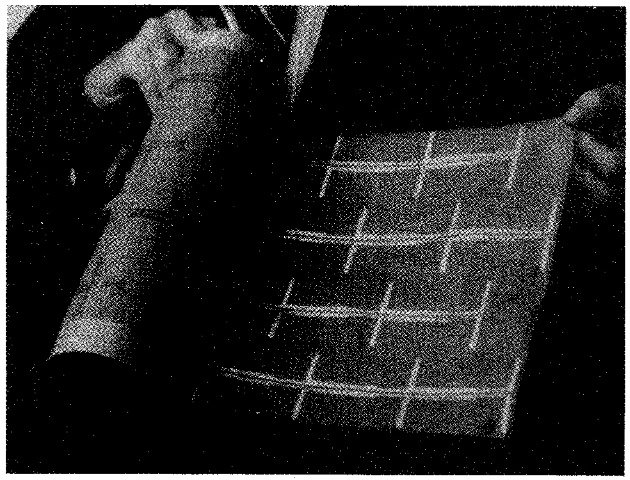

Fig. 5. The Thin-Film, Etched-Circuit Rectenna.

REFERENCES

(1) W.C. Brown, "Experiments Involving a Microwave Beam to Power and Position a Helicopter", IEEE Trans. of Aerospace and Electronic Systems, Vol. AES-5, No. 5, PP. 692-702, Sept. 1969.

(2) "Design Definition of a Microwave Power Reception and Conversion System for Use on a High Altitude Powered Platform", NASA Contractor Report CR-15866, Contract NAS6-3006, Wallops Flight Facility.

(3) "Design Study for a Ground Microwave Power Transmission System for Use with a High-Altitude Powered Platform", NASA Contractor Report 168344, June 1983, Raytheon Report PT-6052, Contract No. NAS6-3200.

(4) H.C. Needleman, R.W. Weis, Jr., W.C. Brown, "Recent Studies on a Lighter-Than-Air, High-Altitude Powered Platform, "AIAA Lighter Than Air Systems Technology Conference at Annapolis, Maryland, July, 1981.

(5) J.J. Schlesak, A. Alden, and T. Ohno, "SHARP (Stationary High Altitude Relay Platform) Rectenna and Low Altitude Tests" CRC, Dept. of Communications, Ottawa, Canada. Given at the IEEE Global Telecommunications Conference in New Orleans Dec. 4, 1985.

(6) W.C. Brown, J.F. Triner, "Experimental Thin-Film, Etched-Circuit Rectenna", 1982 IEEE MTT-S International Microwave Symposium Digest, IEEE Cat. No. 82CH1705-3.

(7) W.C. Brown, "Performance Characteristics of the Thin-Film, Etched Circuit Rectenna", 1984 IEEE MTT-S International Microwave Symposium Digest.

(8) W.C. Brown, Microwave Beamed Power Technology Improvement" Raytheon Final Report PT-5613, May 1980 on JPL Contract No. 955104, Part of NASA Contract NAS7-100.