# Beamed Microwave Power Transmission and its Application to Space

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***Abstract*—The general principles and special components of beamed microwave power transmission systems are outlined and their application to the space program discussed. The beamed system is defined as starting with a dc source of power at the transmitting end, converting it to a microwave beam for transmission through space, and ending with the dc power output at the receiving end. Using this definition, an experimentally measured and certified dc to dc efficiency of 54% has been achieved. The major contribution of beamed power to the development of space is its unique ability to transfer energy across long distances and across large differences in gravitational potential, making possible such developments in space as the Solar Power Satellite system. In that system electric energy obtained from the sun by satellites in geostationary orbit is transmitted to Earth. The application that is discussed in detail is a low-Earth orbit to geostationary orbit (LEO to GEO) transportation system that depends upon vehicles propelled by electric thrusters whose power is supplied by a microwave beam originating at the Earth's surface. A scenario for such a system is chosen and the performance results presented. The advantages of the all electronic system over a chemically propelled system are enumerated. The principles of space propulsion, particularly as they relate to electric propulsion, are outlined. Key components at the terminals of the system are discussed including the "rectenna" which provides a source of continuous dc power in space with a revolutionary low ratio of mass to dc power output of 1 kg/kW. Environmental considerations are discussed.**

## I. Introduction

BEAMED microwave power transmission and its relation to space may be thought of as extending our two dimensional power transmission networks on the Earth to a three dimensional power transmission system in which power is beamed from the Earth into space or power collected in space is beamed back to the Earth. The power that is to be transmitted for the intended major applications in space are at the multimegawatt and even gigawatt power levels that are characteristic of electric utilities.

This new technology can fulfill two major needs for the further development of space. One of these needs is large amounts of electric power at reasonable cost for manufacturing operations in low-Earth orbit [1]. The other need, an extension of the first, is for large amounts of power for electric propulsion needed for a greatly improved space transportation system [2].

For example, with the combination of beamed power technology and electric thruster technology, it will be possible to replace conventional chemical rocket propulsion for missions beyond low-Earth orbit with enormous economic and safety benefits. Electric propulsion has long been recognized for its benefits if there were a suitable energy source for the large amounts of power required by the electric thrusters. Conventional prime power sources in space are massive relative to electric thrusters and must be accelerated along with the less massive parts of the vehicle. Further, they are expensive and costly to transport into space.

In contrast, beamed microwave power uses prime power sources on the Earth's surface. The receiving part of the beamed power system aboard the electrically propelled vehicle has a very low mass relative to other potential prime power sources in space. The all-electronic nature of this new transportation system has led to the proposed coining of a new word "TRANSPORTRONICS", derived from the words "TRANSPORT" and "electRONICS".

In the longer term, microwave beaming of power can serve as an efficient means of transporting to Earth electric power that is harvested from the sun in geostationary orbit. There the sun is in view over 99% of the time during the year. This completely electric and electronic source of base load electric power is referred to as the Solar Power Satellite or SPS system [3].

The microwave technology, supported by many NASA contracts over a long period of time, is in excellent shape to proceed with its application to space ([4]–[7], (reference [7] contains a long list of other references). However, there are two major factors standing in the way. One is a geopolitical factor in that the microwave system and space vehicles must be located in the equatorial plane. The second is the general lack of awareness that beamed microwave power transmission is the answer to a better architecture for the development of space. A major reason for that lack of awareness is that the applications are highly multidisciplinary in nature.

The purpose of this paper is to provide a tutorial overview of beamed microwave power and its use in space applications. The following discussions in sequential order will be: 1) the unique properties and basic principles

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of beamed microwave power transmission as applied to space, 2) the basic principles of space propulsion with particular emphasis upon electronic or electric propulsion, 3) the synergistic combination of electric propulsion and beamed power to create a new approach and possible new paradigm for space transportation, and 4) an outline of environmental considerations.

Although the general principles presented in this paper apply to all microwave and millimeter wave frequencies, the application examples focus upon the use of the 2.4 to 2.5 GHz ISM (Industrial, scientific, medical) band. The development and application activity at the higher frequencies are presented in another paper in this issue.

The MKS system of units will be used throughout this paper. In this system work or energy is expressed in Joules (watt-seconds), power is expressed in watts, and force is expressed in Newtons (one Newton = 0.2246 lb force). A glossary of terms and abbreviations is given at the end of the paper.

## II. Unique Properties and Basic Principles of Beamed Microwave Power Transmission

### A. Unique Properties

As a means of transferring energy from one point to another, beamed microwave power transmission has these features:

- No mass, either in the form of wires or ferrying vehicles, is required between the source of energy and the point of consumption.
- Energy can be transferred at the velocity of light.
- The direction of energy transfer can be rapidly changed
- No energy is lost in its transfer through the vacuum of space, and little is lost in the Earth's atmosphere at the longer microwave wavelengths.
- The mass of the power converters at the system terminals can be low because of operation at microwave frequencies.
- Energy transfer between points is independent of a difference in gravitational potential between those points.

These unique features are for the most part self evident. But the last one is particularly important for space applications. The only prime source of energy in space is solar. All other sources of energy, fuel cells, batteries, nuclear, and even the arrays that capture the sun's energy have to be transported to space across punishing gravitational barriers. Beamed microwave power avoids this penalty by placing the prime power source on the ground, leaving only a low mass microwave collection and rectifying portion of the system in space.

### B. Basic Principles of Beamed Microwave Power Transmission

Fig. 1 shows the basic parts of a beamed microwave power transmission system: 1) dc to microwave conversion, 2) a beam forming antenna, 3) free space transmission, and 4) Reception and reconversion to dc. For orientation purposes, typical and maximum efficiencies for the various portions of the system are shown. Although the maximum efficiencies shown for the individual components have been achieved, they have not been assembled into a complete system. On the other hand, a certified experimental dc to dc efficiency of 54% has been achieved in the laboratory [4]. If the experiment was to be repeated with a better matching of components, an overall dc to dc efficiency of as much as 76% could be expected.

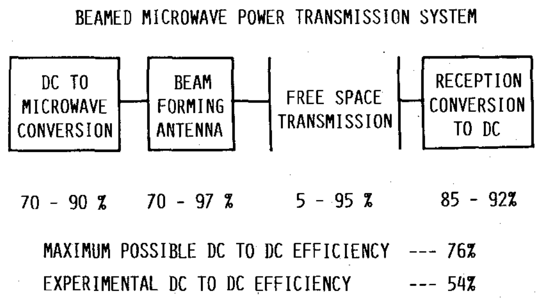


Fig. 1. Schematic diagram of the principal elements of a beamed microwave power transmission system, and the normal range of the element efficiencies. Top of range indicates maximum efficiency that has been obtained.

### C. Free Space Transmission

One of the remarkable things about transmission of microwave power in free-space is that it is indeed "free." Like the sea to ships, or the atmosphere to airplanes, there is no economic burden for its use. But to take advantage of the sea or the air, ships and airplanes have to be built. The analogy to ships and airplanes for transportation of energy through space by microwaves is transmitting and receiving apertures. The size and expense of these apertures has a direct relationship to the wavelength that is being used, the distance over which energy is being sent, and the desired efficiency of transmission.

Fortunately this relationship has already been derived for optimized systems by Goubau and others and has been rigorously checked experimentally [8], [9]. The relationship between the aperture to aperture efficiency and a parameter $\tau$ is shown in Fig. 2.

$$\tau = \sqrt{A_t A_r}/\lambda D \tag{1}$$

where

- $A_t$ is the transmitter aperture area
- $A_r$ is the receiver aperture area
- $\lambda$ is the wavelength of the microwave power being transmitted
- $D$ is the separation distance between the two apertures

It will be noted in Fig. 2 that the efficiency can approach 100% very closely, which means that there are very low sidelobes. This in turn means that there must be a tapered distribution over the surface of the antenna. These tapered distributions are part of the Goubau solution and are

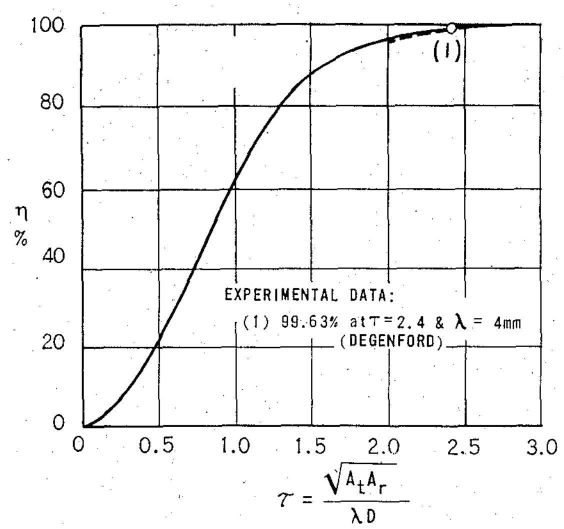


Fig. 2. Transmission efficiency as a function of the parameter tau for optimum power density distribution across the transmitting antenna aperture as shown in Fig. 3.

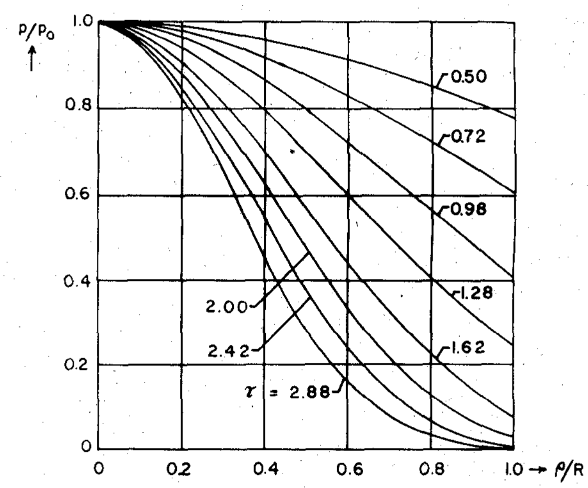


Fig. 3. Relative cross-sectional power density distribution across the transmitting and receiving antenna apertures for various values of tau as given in Fig. 2. R is the radius of the transmitting or collecting antenna and rho is the radial distance from the center. The field at the collector extends beyond its edges.

shown in Fig. 3. For very high efficiency the distributions on the apertures are essentially a Gaussian one.

From (1), a simple expression for the transmitter and receiver aperture areas can be derived with the assumption that the aperture sizes are equal. Under these conditions:

$$A_t = A_r = \tau\lambda D. \tag{2}$$

This is a revealing expression because it shows that the aperture area, rather than its diameter, varies with wavelength, and the advantages of going to higher frequency are diminished if the aperture areas are approximately equal as they tend to be for total overall economy. It is interesting to note that the value of aperture to aperture transfer efficiency associated with $\tau = 1$ is 60%.

However, there are applications where the reception area may be limited and where a particular intensity of the incident microwave illumination is desired. Under those circumstances we may make use of the following relationship:

$$p_d = A_t P_t / \lambda^2 D^2 \tag{3}$$

where

- $p_d$ is the power density at the center of the receiving location
- $P_t$ is the total radiated power from the transmitter
- $A_t$ is the total area of the transmitting antenna
- $\lambda$ is the wavelength
- $D$ is the separation between the apertures.

With this situation it is seen that to achieve a desired value of $p_d$ at the receiver site, while constrained by a transmitted power level $P_t$, the transmitting aperture area varies as the square of the wavelength of the radiation. For some applications, where the area available for a transmitter is limited, the short wavelengths are very attractive.

### D. Power Handling Capability of Devices in Space as a Function of Efficiency and Operating Temperature

It is observed that when microwaves are used to transmit power in the vacuum of space there is no resistive loss, and no limitation to power handling capabilities, as contrasted to wire transmission. However, the power handling capabilities of the transmitted and receiving apertures are limited by the dc-to-microwave and microwave-to-dc energy conversion efficiencies, and by the ability of the apertures to radiate directly to space any waste heat that results from the inefficiencies.

The radiation of waste heat in space is proportional to the radiating area and the fourth power of the temperature at which the heat is radiated. In the case of the transmitter aperture in space, the relationship between radiated microwave power per unit area to the generator efficiency and radiating temperature is:

$$p_r = \frac{n(5.67KT^4 \times 10^{-8})}{(1-n)}$$

where

- $p_r$ = the radiated microwave power density, W/m$^2$
- $K$ = the emissivity of the radiating surface
- $T$ = the temperature in degrees Kelvin
- $n$ = the operating efficiency of the power generator.

The same expression holds for the dc power density obtained from the receiving aperture with $p_r$ replaced with $p_{dc}$ where $p_{dc}$ is the dc power output density of the rectenna.

The factor $n/(1-n)$ is very important as shown in Fig. 4. Contours of radiated microwave power density, or alternatively, dc power density from the rectenna are shown as a function of the efficiency and the radiating temperature, assuming $K$ is unity. This plot shows that microwave tubes can handle much more power density by

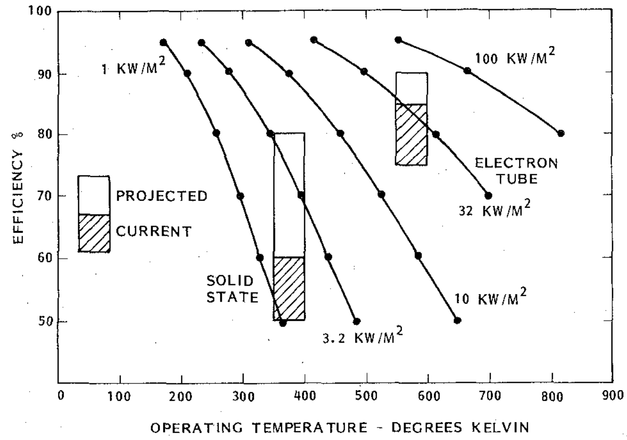


Fig. 4. Contours of microwave radiated power density, or alternatively, dc power density from the rectenna, as functions of conversion efficiencies and allowed operating temperature of the cooling surface that radiates heat directly to space. Unity is assumed for emissivity of radiator.

virtue of higher operating temperatures as well as higher efficiency than can solid state generators. However, that could change in the future.

The relationships shown in (4) are for direct radiation of heat into space at 0°K. It disregards the heat absorbed by exposure to the sun, assuming that such absorption can be minimized by selective coatings.

There are situations where it is desired to operate at high microwave power emission densities. The Solar Power Satellite is one of these. Here it is desired to operate in the center of the transmitting array in space at a radiated microwave power density of 25 kW/m$^2$, which is achieved as shown on Fig. 4 with a conversion efficiency of 79.5% and an operating temperature of 300°C or 573°K.

## E. *Choice of Frequency*

If there were complete freedom to select the best frequency for power transmission, the items that would have to be considered are: 1) The size of the aperture as given by expression (2), 2) the dependency of overall system efficiency, including the components at the two ends of the system, upon frequency, 3) the heat radiation problem in space associated with the inefficiency of components, 4) whether the transmission is all in space or in part through the Earth's atmosphere, and, *if* the atmosphere is involved, the degree of necessity to transmit reliability through the atmosphere under the poorest meteorological conditions, 5) the existing state of the art of available components, and 6) the impact of the use of the selected frequency upon other users of the electromagnetic spectrum.

With the exception of the aperture relationship which favors higher frequencies, and possibly the impact upon the users of the frequency spectrum, all of the above considerations favor lower frequencies.

For some applications such as the Solar Power Satellite which would supply base load electrical power, and the reliable propulsion of aircraft in the Earth's atmosphere, reliable transmission through the Earth's atmosphere is mandatory. Reliability is highly dependent upon the use of a lower frequency as shown in Fig. 5 [10].

However, the choice is highly constricted by the frequencies that may be available. It is quite likely that these frequencies will be limited to the ISM (Industrial, Scientific, Medical) bands which are 2.4 to 2.5 GHz, 5.8 to 5.9 GHz, and 24.125 GHz. For applications involving transmission through the Earth's atmosphere, the 2.4 to 2.5 GHz band is an excellent compromise. Further, the components and the technology are the most advanced at 2.45 GHz. The interference of this frequency with other uses of the spectrum will be addressed in the section on environmental issues. It is believed that there is a high degree of compatibility between beamed power transmission and other uses of the spectrum.

## F. *Microwave Power Generation*

In a beamed microwave power transmission system dc power must be converted to microwave power at the transmitting end of the system. Although many devices can perform this function, it was discovered during the comprehensive DOE/NASA study of the SPS that the microwave oven magnetron with the addition of external passive circuitry could perform as a phase-locked, high-gain (30 dB) amplifier for direct use in the radiating modules (Fig. 6) that compose an electronically steerable phased array [11], [12]. The low-cost ($15.00) and readily available microwave oven magnetron could be used directly in a ground based transmitter. For space use the same principle would be used but a special space magnetron would be developed.

The microwave oven magnetron provides a ready source of the large amounts of power needed for some space applications. To place this in perspective, it is noted that there are 40 million microwave ovens in the United States and that each one operates with about 600 W of microwave power. Their combined capacity is therefore 24 GW of microwave power. Because of the pulsed operation of these ubiquitous magnetrons they generate much spurious noise and are an entrenched source of interference that requires the entire ISM band of 2.4 to 2.5 GHz for its containment.

However, it was discovered during the extensive SPS study that this same tube when operated on a continuous dc power supply exhibited an extremely low spurious noise level if an internal feedback mechanism were allowed to operate by reducing or turning off the external source of filament power after turn-on. Extensive testing of a Raytheon production-built microwave oven magnetron of that time period using specially designed test equipment was carried out under two NASA contracts. The spectral (one-cycle bandwidth) noise level was 196 dB below the carrier at 15 MHz from the carrier [11]. To place this level of noise in perspective, a Solar Power Satellite operating with 10 GW of radiated power, would ra-

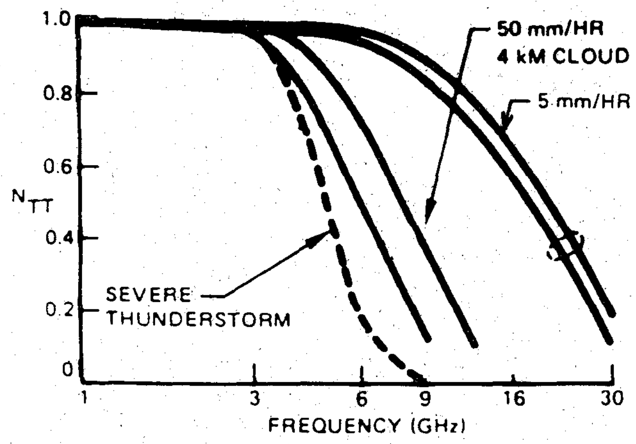


Fig. 5. Transmission efficiency through the atmosphere as related to frequency and condition of the atmosphere.

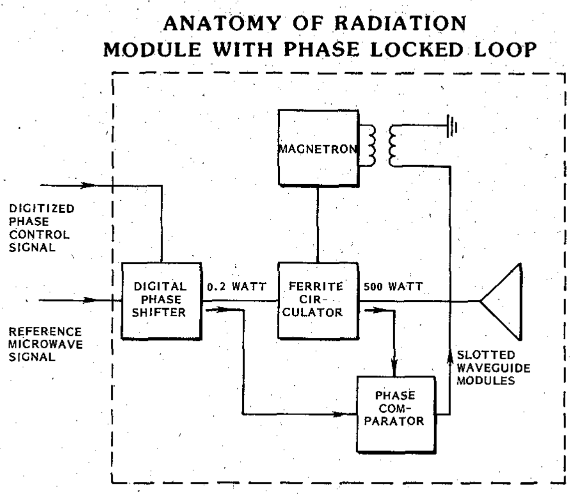


Fig. 6. Circuit for a phase-locked, high-gain (30 dB) magnetron directional amplifier. Diagram shows its application to a radiating module in an electronically steerable array antenna.

diate a total power of one microwatt in a 4000 Hz channel width removed from the carrier by 15 MHz.

Taking the directive gain of the radiating module and the 38 500 km distance from the Earth into consideration, the power density at the Earth would be 45 db. below the CCIR requirements.

The solar power satellite would use specially designed magnetrons similar to the oven magnetrons but at a power level of from 3 to 5 kW. They would self adjust their operating voltage to coincide with the most efficient interface with the solar photovoltaic arrays, and would passively radiate waste heat directly to space as suggested by the experimental magnetron shown in Fig. 7.

### *G. The Rectenna as the Receiving Portion of the System*

The rectenna is a unique device that was conceived and developed for beamed microwave power transmission [13]. It is spread out over the receiving aperture area and, as its name suggests, combines the functions of an antenna and a rectifier. In its simple form the rectenna consists of a collection of rectenna elements, each with a half-

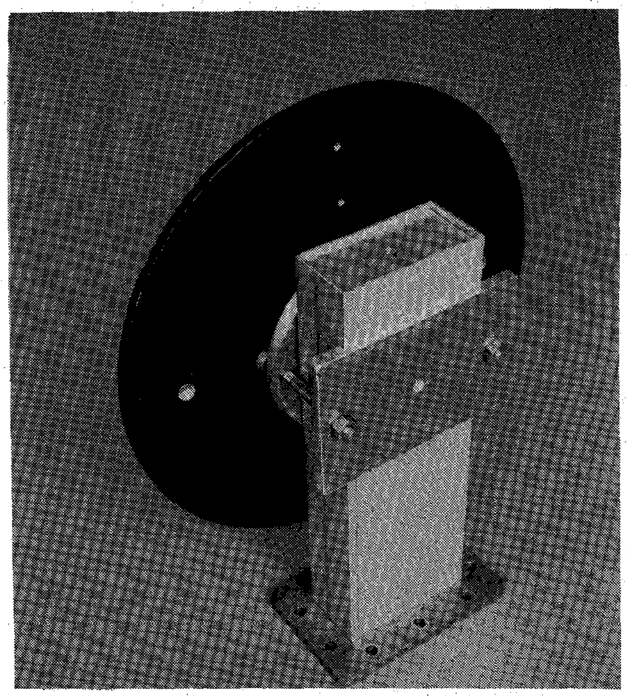

Fig. 7. QKH 2244 radiation cooled magnetron fitted with waveguide output transition coupling into 1.5 inch × 3.0 inch waveguide.

wave dipole that feeds a low pass filter circuit terminated in a rectifying diode, as shown in Fig. 8. The outputs of the diodes in a local region feed into a common dc bus. These busses can then be joined in series or parallel to match a common load such as a resistor, electric motor, or any other kind of load.

The rectenna has many desirable characteristics. They include: 1) in its "pure" form, a relatively nondirective aperture analogous to that of a single dipole, regardless of the size of the aperture; in this form the aperture collection efficiency is independent of the illumination density distribution across the aperture, 2) an overall efficiency from incident microwave power to dc power output that has been measured at over 85%, 3) a low specific mass of from 1 to 2 kg for each kilowatt of dc power output, 4) in newer formats, a power handling capability in space of as much as 5 kW/m$^2$ with passive radiation cooling, 5) a low Q with consequent relative insensitivity to both changes in frequency and tolerances on construction, 6) relative insensitivity of the overall efficiency to changes in the level of power input or load impedance, 7) extreme reliability because of high level of redundancy of elements, with internal fusing of diodes if they should fail, 8) high tolerance of diodes to space environment because they are Schottky barrier diodes in a package with shielding capability, and (9) small requirement for a critical GaAs material, less than 1/100 000 of that required for a solar photovoltaic array of the same area.

The rectenna has many variations in its format. The electrical circuit shown in Fig. 8 was put into a "thin film" format for air and space applications [14]. That format was tested on an airplane wing as shown in Fig. 9.

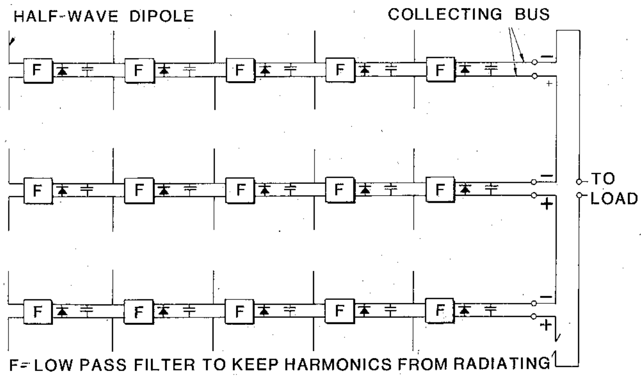


Fig. 8. Schematic diagram showing the functions performed on the foreplane of the two plane rectenna format. These functions are power collecting, harmonic filtering, and rectification into dc power.

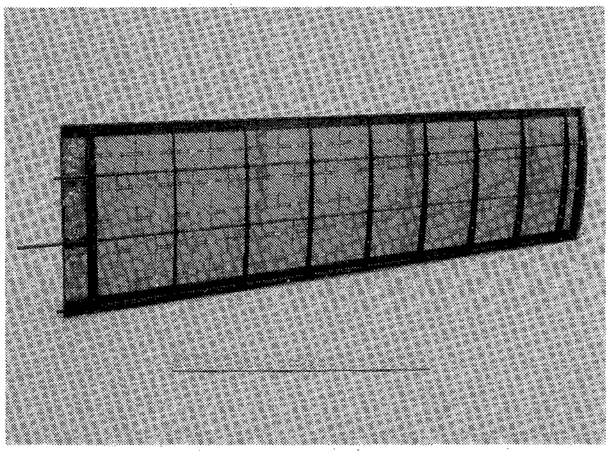

Fig. 9. Application of the thin-film, etched-circuit rectenna to a model airplane wing.

In a modified form it was successfully used by a Canadian research team in a microwave powered airplane [15].

The term "rectenna" is now used generically for the receiving aperture of any beamed power transmission system that combines the function of capture and rectification, even though in some formats there has been a departure from the "one on one" relationship between dipoles and diodes in the original "pure" form of the device. This departure results in directional sensitivity of the rectenna which may be tolerated for some applications.

### H. Transmitting Antenna Structure

The transmitting antennas for space applications associated with the technology at 2.45 GHz are active, electronically steerable phased arrays. The arrays are composed of radiation modules that consist of a high-gain, phase-locked amplifier (see Fig. 6) that supplies microwave power to a slotted waveguide array. The square array, shown in Fig. 10, is used to beam power to a high altitude airplane or from a solar power satellite. For applications using the equatorial plane, in which the beam sweeps over a large angle in the West to East direction, an array may be a long section of slotted waveguide as shown in Fig. 11.

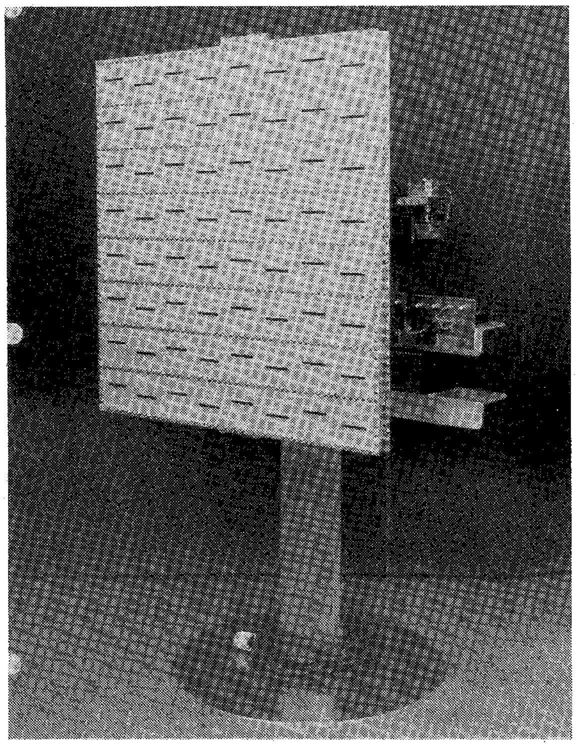

Fig. 10. Radiation module composed of a slotted waveguide antenna and a phase-locked, magnetron directional amplifier. Radiated power output of about 600 W.

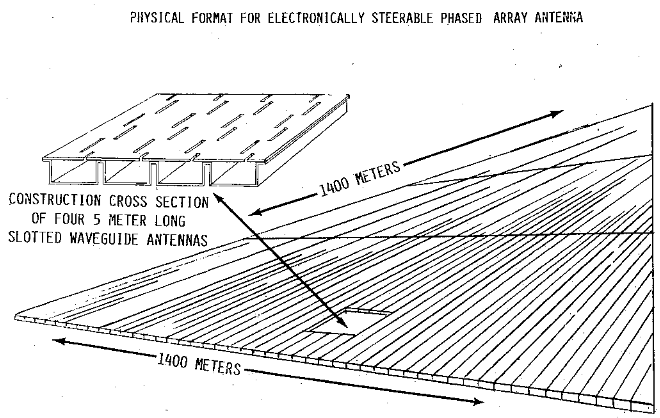


Fig. 11. Layout of ground based transmitter showing construction format for slotted waveguide antennas.

A unique folding fabrication procedure has been developed for forming slotted waveguide arrays from thin sheet aluminum as shown in Figs. 10 and 11. The procedure can be highly automated, so large expanses of antenna can be fabricated at costs that are largely determined by the modest cost of the thin aluminum sheet.

### I. Beam Guidance

Beam guidance is an area where the principles seem to be sound but where the experimental verification is lacking. The beam guidance requirements for Earth to space transmission are different from those for space to Earth, largely because the influence of the Earth's atmosphere is different for the two directions of transmission and because ground structures remain dimensionally stable with time whereas space structures may change their shape. However, there is a commonality in the use of a beacon centered in the rectenna. There is also a commonality in that the radiation modules are perceived to be assembled into a row and column matrix [16].

For the Earth to space application, the beacon in the orbiting space vehicle sends a signal toward the transmitter on the Earth. At the center of the transmitting antenna there is a sensitive interferometer which establishes the direction of the beacon. This directional information is sent to a microprocessor which then sends out two signals, one to the rows and the other to the columns in which the individual radiation modules are located. Each radiating module is a section of slotted waveguide about 5 m long. Using these signals as a reference each radiation module multiplies the signals by a term corresponding to its position in the row and column matrix to establish its phase relative to the center of the array. There is also a phase reference sent to each module. As part of a boresighting procedure, the phase reference at each module is adjusted to some integral multiple of 360 degrees relative to the source of the reference. Even though the total difference in shift between the radiation modules may be very great, only a low power level phase shifter of only 360 degrees is needed in each module.

Even though the tracking afforded by this principle may be very good, it is an open loop system and the microwave beam will not be precisely centered on the rectenna in space. It is easy to close the loop, however, by placing sensors on the periphery of the rectenna which can generate an error signal if not evenly illuminated. The error signal is then telemetered to the microprocessor at the transmitter site which then modifies the signal sent out to the radiation modules to change their phase relationships to recenter the beam on the rectenna.

The beam from the Solar Power Satellite is steered in analogous fashion but its mechanical axis is aligned with the rectenna on the ground so that any electronic steering is confined to a very small angle. However, more sophisticated pointing schemes must be used because of the warping and expansion of the antenna. The proposed approach is to use a retrodirective array.

### *J. Demonstration Milestones*

Many technical milestones in beamed microwave power transmission have been achieved. Illustrations of four important milestones are presented. They are: Fig. 12, the first demonstration of a microwave powered air vehicle [6]; Fig. 13, demonstration of a beam riding helicopter where many of the principles of using a microwave beam as a position and attitude reference for vehicle control are of generic importance in the space applications [6]; Fig. 14, the achievement of a certified overall dc to dc efficiency of 54% in the laboratory [4]; and Fig. 15, the transmission of power over a distance of one mile with over 30 kW of dc power collected at the rectenna with 84% overall rectenna efficiency [5]. Reference [7] describes all of these demonstrations.

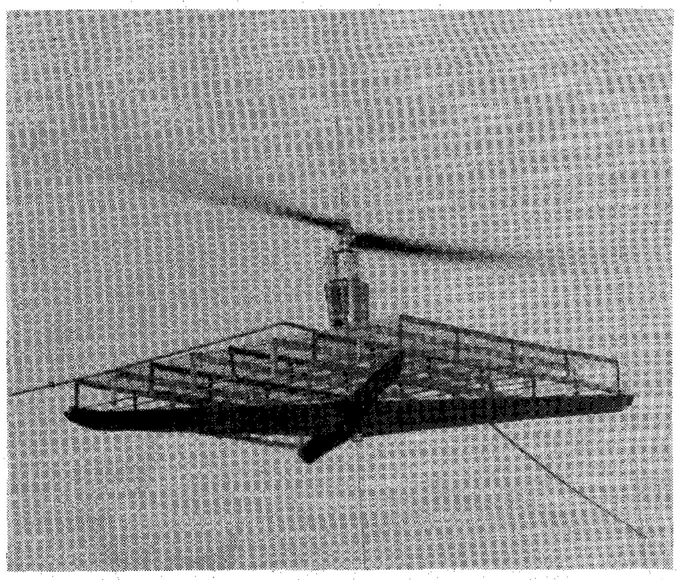

Fig. 12. First flight of a microwave powered aircraft occured in 1964 at the Raytheon Co. 200 W of power was supplied to the electric motor from the rectenna that collected and rectified power from a microwave beam.

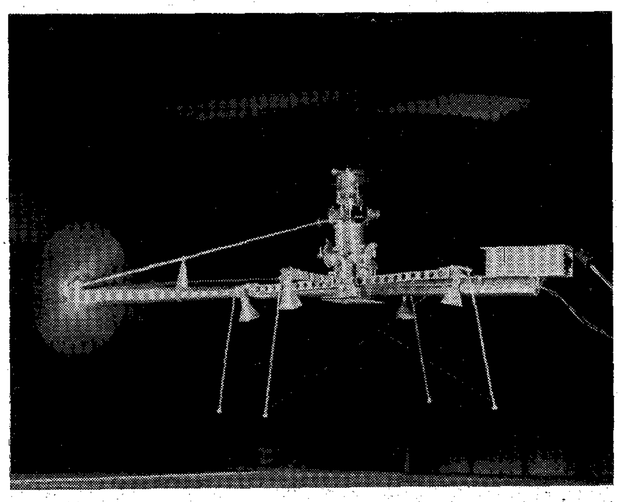

Fig. 13. This beam riding helicopter self guided itself over the beam by using the microwave beam as a position reference for roll, pitch, yaw, and $x$ and $y$ translation.

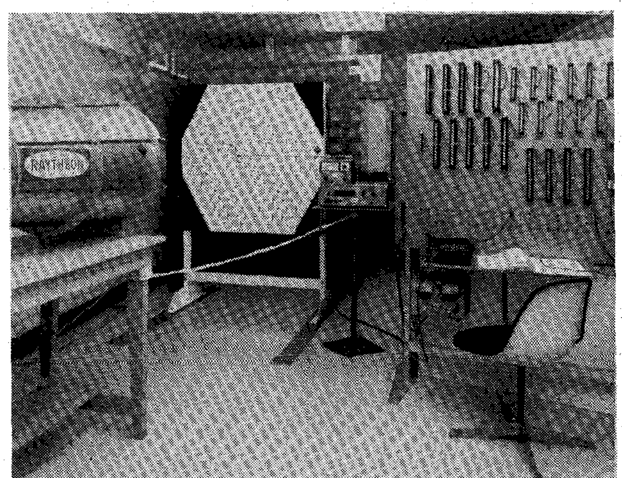

Fig. 14. Certified demonstration of 54% overall dc to dc efficiency in the laboratory. Rectenna dc power level was 600 W. Frequency was 2.45 GHz.

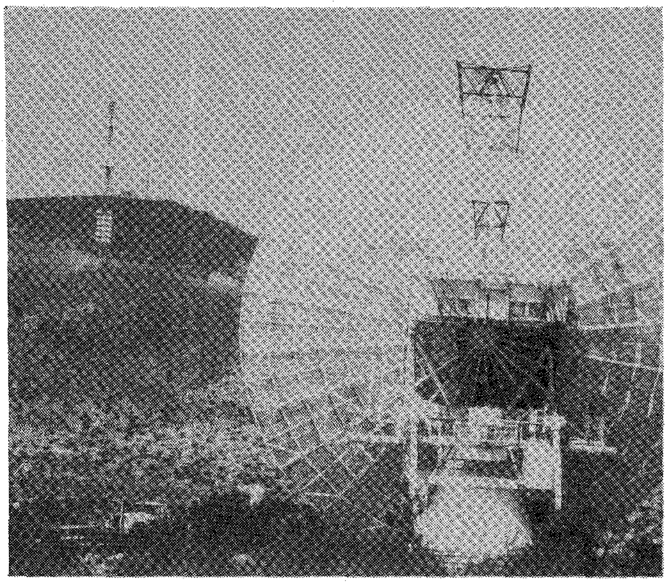

Fig. 15. Demonstration of beamed power over one mile distance at the JPL Goldstone facility in the Mojave Desert. Of the microwave power intercepted by the rectenna array, 84% was converted into a dc power level of over 30 kW. Frequency was 2388 MHz. Power was used in matrix of illuminating lamps in front of rectenna.

## II. The Principles of Electric Propulsion and the Importance of a Low Mass Power Supply for It

There is a mystique about space propulsion that can be demystified by two very simple expressions—one for the thrust that is obtained by accelerating propellant to a high velocity, the other one for the power required to sustain that thrust. These are:

$$N = dm/dt\ v \tag{5}$$

$$P_p = 1/2\ dm/dt\ v^2 \tag{6}$$

where

$N$ = thrust in Newtons (1 N = 0.2248 lb force)
$m$ = propellant mass, kg
$dm/dt$ = time rate of propellant flow, kg/s
$v$ = velocity of the propellant, m/s
$P_p$ = propulsion power, watts

Expression (5) will be recognized as a variation of the familiar $f = ma = m\ dv/dt$, where the mass flow is the time variant and not the velocity. Likewise, expression (6) will be recognized as the time derivative of the mass flow in the expression $1/2\ mv^2$ for work or energy.

A third very useful expression is to divide expression (6) by expression (5) to give the ratio of power to thrust, which is

$$P_p/N = v/2. \tag{7}$$

Equation (5) indicates that propellant consumption for a given level of thrust can be reduced if the terminal velocity of the propellant is increased. As will be shown, this is highly desirable, but with chemical propellants there is an upper limit to the velocity that can be achieved. The highest practical velocity is achieved with a mixture of oxygen and hydrogen, which is approximately 4000 m/s.

With electric propulsion very much higher velocities can be achieved by ionizing gases such as argon and xenon and accelerating them through an electric potential as shown schematically in Fig. 16. There has been a very satisfactory application of this principle to the ion thruster [18], [19]. A 30 cm diameter ion thruster is shown in Fig. 17. It converts 10 kW of dc input power into 7 kW of ion beam power. Using xenon as a propellant and a propellant velocity of 40 000 m/s, the resulting thrust is 0.37 N. It has a mass of about 10 kg and so has a specific mass, or mass to power ratio, of 1 kg/kW [19]. Although the ion thruster is a sophisticated device from the electrical engineering point of view, it has been designed as an assembly of sheet metal parts and lends itself to low-cost mass production where several hundred of them may be required for one vehicle. In addition to the 30 cm thruster a 50 cm thruster is under development with even lower specific mass and higher efficiency expected [20].

Referring to Fig. 16, the velocity given to an ion by the voltage $V$ is given by the simple expression:

$$v = \frac{(5.97 \times 10^5)\sqrt{V}}{\sqrt{m_i/m_e}} \tag{7}$$

where:

$v$ = velocity of accelerated ion, m/s
$V$ = the applied potential, volts
$m_i/m_e$ = ratio of the mass of the propellant ion to the mass of electron.

Substitution of the mass of the ions for argon and xenon into the above equation, together with an assumed applied potential of 1500 V, give velocities of 77 000 and 42 000, respectively or factors of 19.2 and 10.5 greater than for chemical propulsion. Therefore the time rate of propellant consumption for the same propulsive force is reduced by the same factors of 19.2 and 10.5, respectively.

What does this mean in terms of the amount of propellant that can be saved for missions of interest, and how important is it? A mission of great interest, and also one of concern because we cannot presently accomplish it, is to bring payloads back from geostationary orbit as well as taking them there. To accomplish this we must apply a propulsive force to the vehicle to change its velocity by an amount known as the $\Delta V$, which will take the vehicle to geostationary orbit, and the same $\Delta V$ to return it to low-Earth orbit. The one way $\Delta V$ involved is 4600 m/s, or a total round trip $\Delta V$ of 9200 m/s.

There is a well known relationship between the velocity to which the propellant is accelerated, the change in velocity that the vehicle must undergo to complete the trip, and the ratio of the initial mass (propellant mass plus terminal mass) to the terminal mass. This expression is:

$$M_i/M_t = \exp\ (\Delta V/v) \tag{9}$$

Where

$M_t$ = terminal mass (after trip is completed)
$M_i$ = initial mass (terminal mass plus propellant mass)

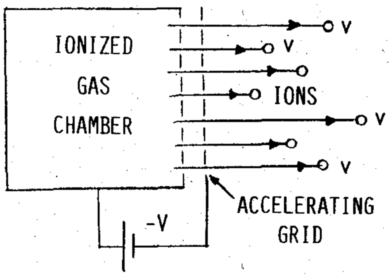


Fig. 16. Principle of the ion thruster. Positively charged gas ions are accelerated through grids with voltage V to produce ion mass particles with a velcoity v.

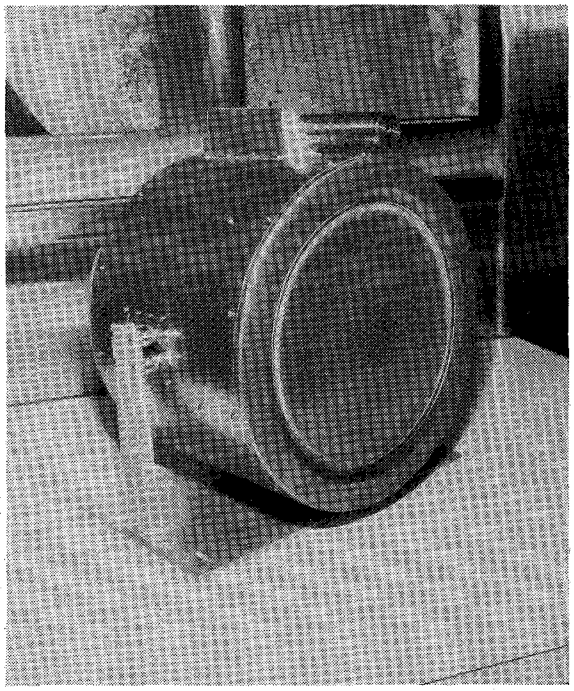

Fig. 17. Photograph of a 30 cm ion thruster. Thruster consumes 10 kW of power and has a mass of about 10 kg. Thrust produced at a propellant velocity of 40 000 m/s is 0.37 N.

$\Delta V$ = change in velocity required for the trip, m/s
$v$ = velocity of the propellant, m/s

If we insert a propellant velocity of 4000 m/s, typical of chemical rockets, and the $\Delta V$ of 9200 into this equation, we find the ratio of the initial mass to the final mass is 10. But if we use a value of $v$ of 40 000 m/s which is typical of an ion thruster propellant we obtain a ratio of only 1.26. The difference in the amount of propellant used is a factor of 35. Assume that the terminal mass consists of the dry vehicle and the payload, each being 5000 kg for a total of 10 000 kg. With chemical propellant the amount of propellant required would be 90 000 kg. The cost of transporting the propellant from the Earth to LEO at the current cost of $5000 per kilogram would be $450 million. By contrast the transportation cost of the electric thruster propellant would be $13 million, thus providing a net saving in propellant transportation costs from Earth to LEO of $437 million.

With such large savings in transportation costs, why are we not using electric propulsion? The answer is that within the conventional inventory of technology there is not a suitable source of the very large amounts of prime electric power that is needed for electric propulsion. Unlike the chemical rocket which provides its own power source through the exothermic reaction of mixing two chemicals and burning them, the use of electric thrusters requires a prime power source whose mass increases as the square of the propellant velocity as shown in expression (6) while the thrust grows only linearly with propellant velocity.

The lack of a suitable power source for electric propulsion has long been recognized. Ernst Stuhlinger, when he wrote his pioneering book on ion propulsion in 1964 stated, "Even a cursory look at the ion propulsion system reveals that the most critical component from the engineering standpoint is the source of electric power. The necessity of a concentrated effort to develop efficient and reliable nuclear-electric space power sources in the kilowatt and in the megawatt range cannot be overemphasized" [17]. What has actually happened in the intervening period is that the ion thruster has been developed to a very high level of performance but still lacks the nuclear power source which has just recently been placed under development in the 100 kw level. When this power supply is developed it may well be the source of power for a vehicle going into deep space, but its specific mass of 30 kg/kW, is too high to be practical in an orbital transfer vehicle. The power level is also far too low.

The other sources of prime power in space are solar photovoltaic and solar thermal. Only solar photovoltaic has been developed and used in space. However, it has proven to be very expensive and its practical specific mass when power conditioning, mechanical pointing toward the sun, and shielding for going through the Van Allen belt are included, is comparable to that of nuclear. Furthermore, it is eclipsed by the Earth from the sun for long periods of time making energy storage a problem for some applications. Therefore, although electric propulsion has much to offer for space transportation it has not been applied because there was no suitable power source.

## III. Solving the Space Transportation and Power Dilemmas with Beamed Microwave Power Transmission

Beamed microwave power represents a technological breakthrough because the mass of the rectenna on board the space vehicle is about equal to the mass of the electric thrusters, as contrasted to twenty to thirty times as much for nuclear or photovoltaic. The makeup of the complete vehicle, less the payload and the required propellant is shown for the two cases in Fig. 18. As a result of the very low specific mass of the rectenna and its power supply, the empty vehicle can have unprecedented accelerations for an electric propelled vehicle. When carrying a payload, the reduction in the mass of the power supply can be replaced with useful payload.

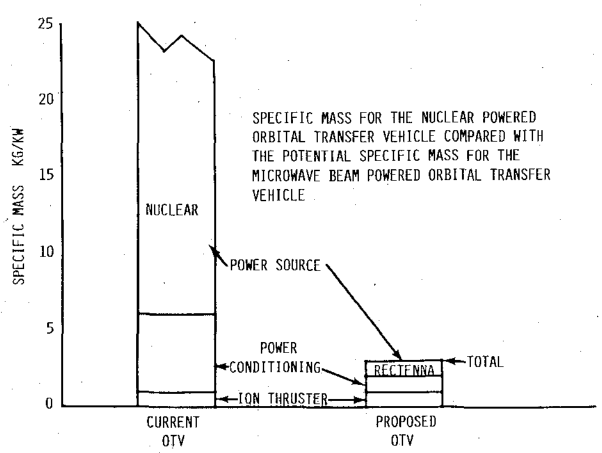


Fig. 18. Comparison of the specific mass of the rectenna with that of a nuclear power source now under development.

A block diagram schematic and a layout of the proposed microwave beam powered transportation system that would transport material between low-Earth orbit and geostationary orbit are presented in Fig. 19. The point of observation is from a point in space above the North Pole [2].

The complete system has four high-powered transmitters equally spaced around the Earth. The microwave beam associated with each transmitter is electronically steered in the West to East direction through a total angle of 90 degrees to automatically track and supply power to the interorbital vehicles. In low-Earth orbit the time of contact between the beam and the vehicle is short but increases rapidly with increasing orbital altitude, as shown in Fig. 19. A relationship has been found that gives the total elapsed time for the orbital transfer vehicle to reach any orbital altitude, taking into consideration the increasing dwell time between the beam and the vehicle as it ascends as well as the decreasing gravitational force acting upon it [21]. The rate of ascension tends to be exponential in nature as exhibited in Fig. 20.

Fig. 20 shows the results of a scenario for a system that can transport a 51% payload of 65 000 kg payload from low-earth orbit to geostationary orbit and then return to low-Earth orbit without payload [21]. The propellant fraction using xenon is 16%. Flight profiles are shown for a single beam system and for a four beam system. For the four beam system, flights to GEO ranging between twenty to thirty days are possible, depending upon the level of beamed power density above an altitude of 10 000 km which in turn depends upon the level of radiated power from Earth. Such short flight times for 50% payload ratios suggest that an express mission with small payload fraction could make the trip to GEO in ten days or less. That small payload fraction could be personnel.

Table I shows the electric and propulsion parameters of the design scenario from which the performance shown in Fig. 20 was derived. Fig. 21 shows an artist's concept of such a vehicle, which could become a true spaceship for the inner solar system if it were hybridized to include power from photovoltaic arrays on its top surface for flight beyond GEO.

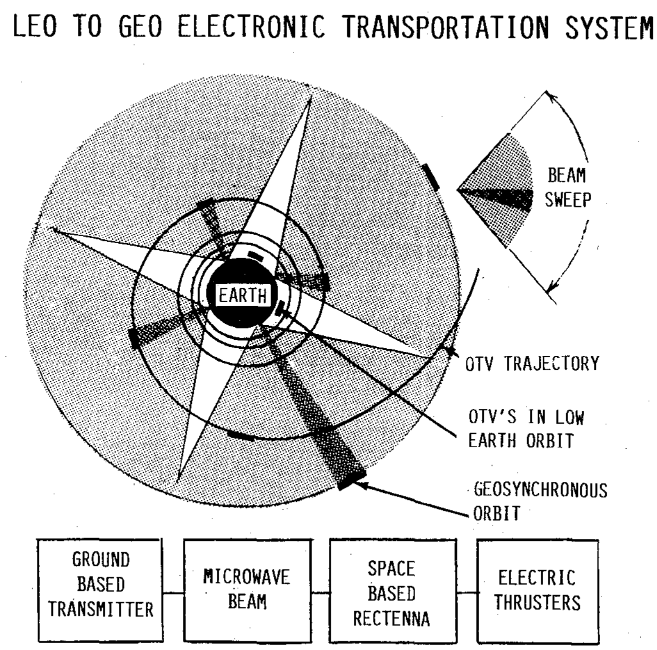


Fig. 19. LEO to GEO transportation system. Orbital transfer vehicles (OTV's) execute a circular spiral as they travel from LEO to GEO. The microwave beam tracks them through an angular sweep of 90 degrees.

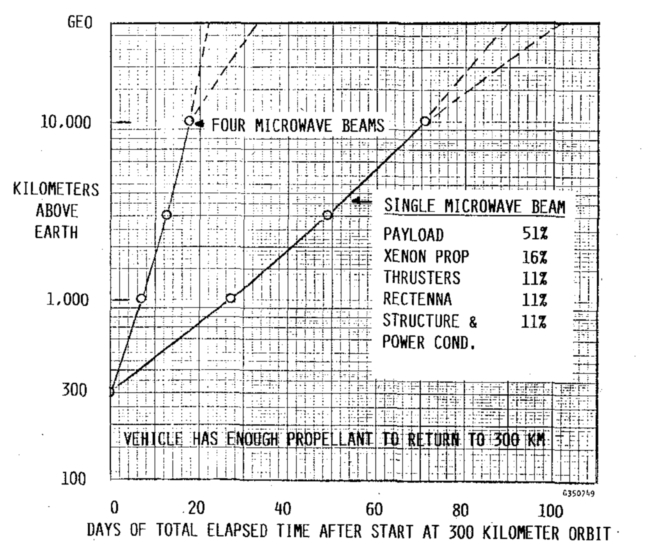


Fig. 20. Orbital altitude of OTV as a function of total elapsed time for a single and four beam system. After delivering a 51% payload of 65 000 kilograms OTV returns to Earth in about 1/3 of the "up" time.

Fig. 22 shows the layout on land surfaces of four high powered transmitters that are associated with the LEO to GEO transportation system, and 14 other lower powered transmitters that are primarily associated with supplying power to orbiting industrial parks [21], [1]. Although the primary purpose of the 14 lower power transmitters are for industrial parks, these industrial parks could represent the first application of beamed microwave power from the Earth, and therewith establish a major point on the learning curve for the construction of higher powered systems

TABLE I
INTERORBITAL VEHICLE-ASSUMPTIONS AND SPECIFICATIONS

| | |
|---|---|
| 1. Makeup of the mass of the empty vehicle | |
| Rectenna | 14 000 kg |
| Ion engines | 14 000 kg |
| Structure, power conditioning and propellant tanks | 14 000 kg |
| Total mass | 42 000 kg |
| 2. Propulsion specifications | |
| Rectenna dc power output | 20 000 kW |
| Rectenna dc power density | 400 W/m$^2$ |
| Rectenna area | 50 000 m$^2$ |
| Ion thruster | |
| Propellant | Xenon |
| Specific Impulse | 4200 s |
| Physical size | 50 cm diameter |
| Beam power | 30 kW each |
| No. of thrusters | 500 |
| Mass of each thruster | 28 kg |
| Total propulsive force | 750 N |
| Vehicle acceleration (empty) | 0.0178 m/s$^2$ |

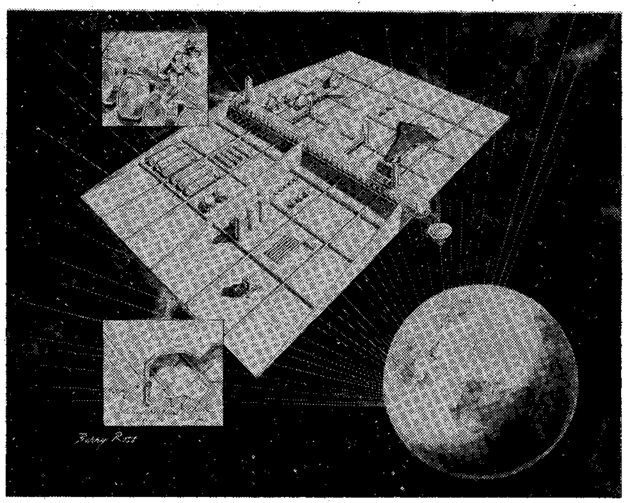

Fig. 21. It is being acknowledged that very large electrically propelled spaceships of the size illustrated above will be needed for inner solar system transport. The power sources for spaceships could be hybridized-microwave powered to geostationary orbit and then photovoltaic powered beyond GEO.

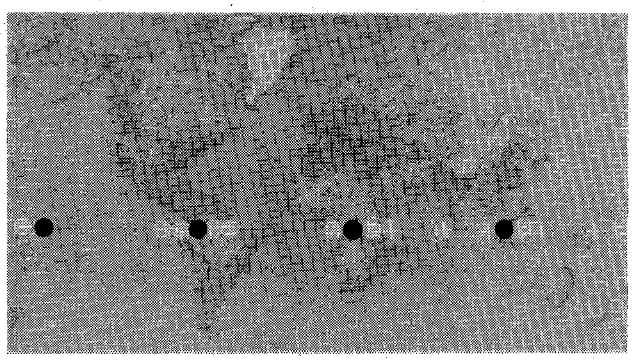

Fig. 22. A mature equatorial plane power transmission system may have 24 or more ground stations on the equator. The black disks represent large aperture transmitters to beam power to electric propelled vehicles bound for geostationary orbit. The white disks are smaller transmitters that could assist LEO to GEO vehicles but are primarily used to supply power to orbiting industrial satellites.

that would be used for the interorbital transportation system [23]. The orbital parks will need a large amount of electric power, and this can be beamed to them from the Earth at relatively low cost compared to the use of either solar or nuclear sources in space [1].

## IV. ENVIRONMENTAL CONSIDERATIONS

All environmental considerations, including biological and RF interference, were examined at length in the DOE/NASA sponsored study of the Solar Power Satellite in the 1977 to 1980 time period [22]. These studies found no "show stoppers" of any nature, including environmental considerations, to preclude a program of research and development to protect the SPS system option as a future energy source.

From a biological point of view, the photon energy level at 2.45 GHz is extremely low, only 1/30 000 of the peak of the infrared radiation given off by the human body. In addition, extensive testing under the DOE/NASA study found no effects at the specific frequency of 2.45 GHz in controlled experiments on animals and insects. Typical radiation densities from ground arrays for space transportation, and for orbiting industrial satellites and other satellites in lower-Earth orbits, are about 500 W/m$^2$ (50 mW/cm$^2$), about one third the intensity of sunlight. The fact that microwave beams would be encountered only in the equatorial plane and that the transmitters could be placed in sparsely settled areas simplifies the management of such beams for aircraft and civilian safety.

Interference with other users of the electromagnetic spectrum will need additional exploration. However, as indicated in the section on microwave generators, it has been found that the noise level of the magnetron directional amplifier (magnetron in combination with directional device), is extremely low at a distance from the carrier of 10 to 15 MHz which is well within the ISM band of 2.4 to 2.5 GHz [11], [12]. Harmonic radiation from both the transmitter and the rectenna can be held to very low levels through the use of harmonic filters. No doubt a considerable amount of experimental work will be necessary to optimize the reduction of noise and harmonic radiation from the system, and to consider what steps, if any, would be necessary to eliminate the impact of a continuous pure tone signal at 2.45 GHz upon the input of communications or other electronic equipment.

## V. SUMMARY

The elements of a beamed microwave power transmission system were presented; the components at the transmitting and receiving end of the system were examined; illustrations of important demonstration milestones were shown; the principles of electric propulsion were outlined and the importance of beamed microwave power transmission as a source of its prime power requirements was examined; a scenario of a LEO to GEO transportation system based upon the combination of electric propulsion and beamed power transmission was presented and its performance projected; environmental considerations were examined.

## Nomenclature

| | |
|---|---|
| GEO | Geostationary orbit. |
| LEO | Low-Earth orbit. |
| OTV | Orbital transfer vehicle. |
| SPS | Solar Power Satellite. |
| $A_t$ | Transmitter aperture area, $m^2$. |
| $A_r$ | Receiving aperture area, $m^2$. |
| $D$ | Separation between apertures, m. |
| $dm/dt$ | Time rate of propellant flow kg/s. |
| $K$ | Emissivity (black body = 1). |
| K | Kelvin temperature scale. |
| kg | Kilogram. |
| m | Meters. |
| $m$ | Mass, kilograms. |
| $M_t$ | Terminal mass after space trip, kg. |
| $M_i$ | Initial mass before space trip, kg. |
| $M_i - M_t$ | Propellant mass used during trip, kg. |
| $n$ | Operating efficiency of device. |
| N | Thrust in Newtons. |
| s | Seconds. |
| $T$ | Radiating surface temperature, Kelvin. |
| $p_d$ | Power density at rectenna center, $W/m^2$. |
| $p_r$ | Radiated microwave power density, $W/m^2$. |
| $p_{dc}$ | Rectenna dc power output density, $W/m^2$. |
| $P_p$ | Power required for propulsion, W. |
| $P_t$ | Total transmitter radiated power, W. |
| $V$ | Velocity of space vehicle, m/s. |
| $\Delta V$ | Change in velocity during trip, m/s. |
| $v$ | Maximum propellant velocity, m/s. |
| V | Potential applied to grid, volts. |
| W | Watt. |
| $\lambda$ | Wavelength of the radiation, meters. |

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