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HISTORY AND STATUS OF
BEAMED POWER TECHNOLOGY AND APPLICATIONS
AT 2.45 GIGAHERTZ

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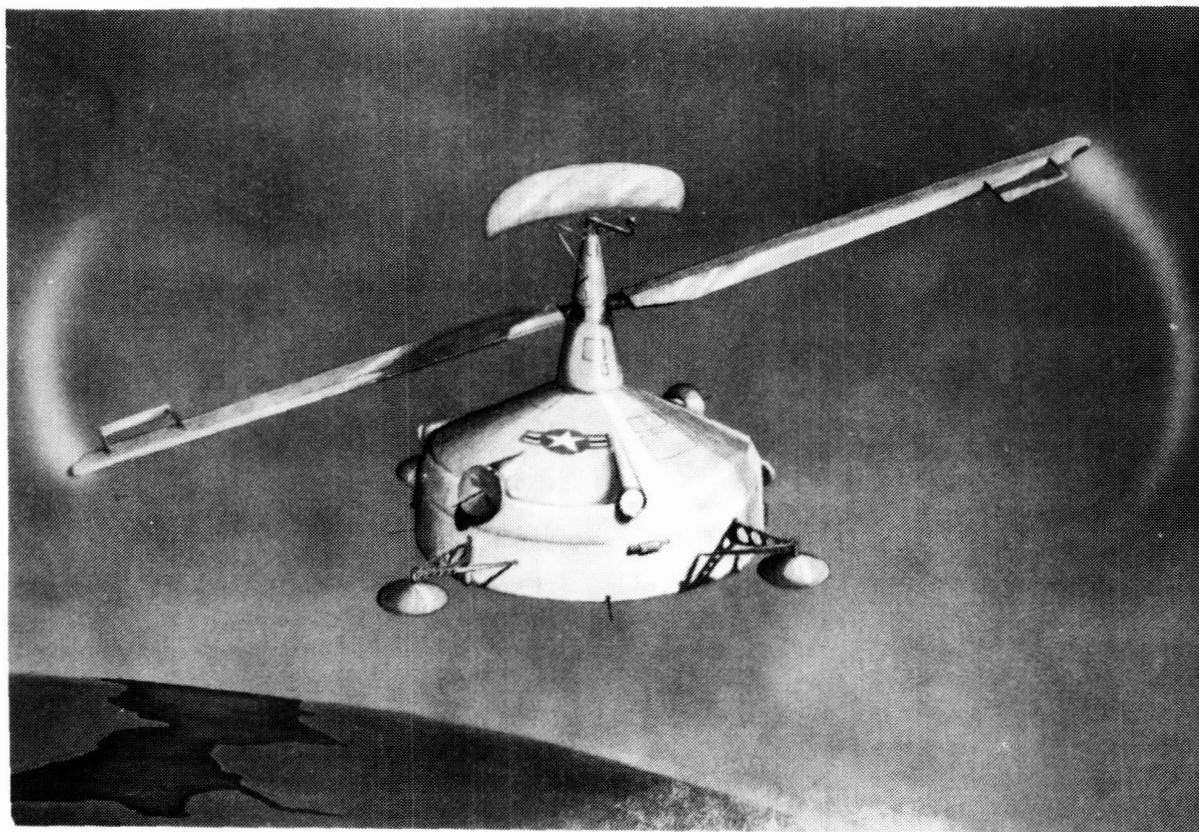
William C. Brown, Consultant
Raytheon Company
Microwave and Power Tube Division
190 Willow Street
Waltham, MA

THE FIRST PROPOSED APPLICATION OF BEAMED MICROWAVE POWER TRANSMISSION

A reciting of history begins at some point in time. In the case of beamed power transmission it could begin with Heinrich Hertz who first used parabolic reflectors or it could be with Tesla's unsuccessful endeavors.⁽¹⁾ But we will begin at the time when there were microwave power generators large enough to combine with large transmitting apertures to provide enough power at the receiving end for significant power applications.⁽²⁾

The first seriously proposed application made in 1959 was a microwave powered helicopter platform flying at 50,000 feet altitude that could communicate with another platform 700 miles away. The proposed platform was named RAMP, an acronym for Raytheon Airborne Microwave Platform*. Although its development was never actively pursued, the interest attending its proposal was responsible for the Air Force starting significant developments to improve the technology base.

One of the shortcomings of the proposed helicopter was that there was no technology at that time to convert microwave power directly and efficiently into electric power for motors. The RAMP concept depended upon using the microwave power to indirectly heat air which was then ejected from the rotor tips for propulsion purposes.



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*There is no readily available reference.

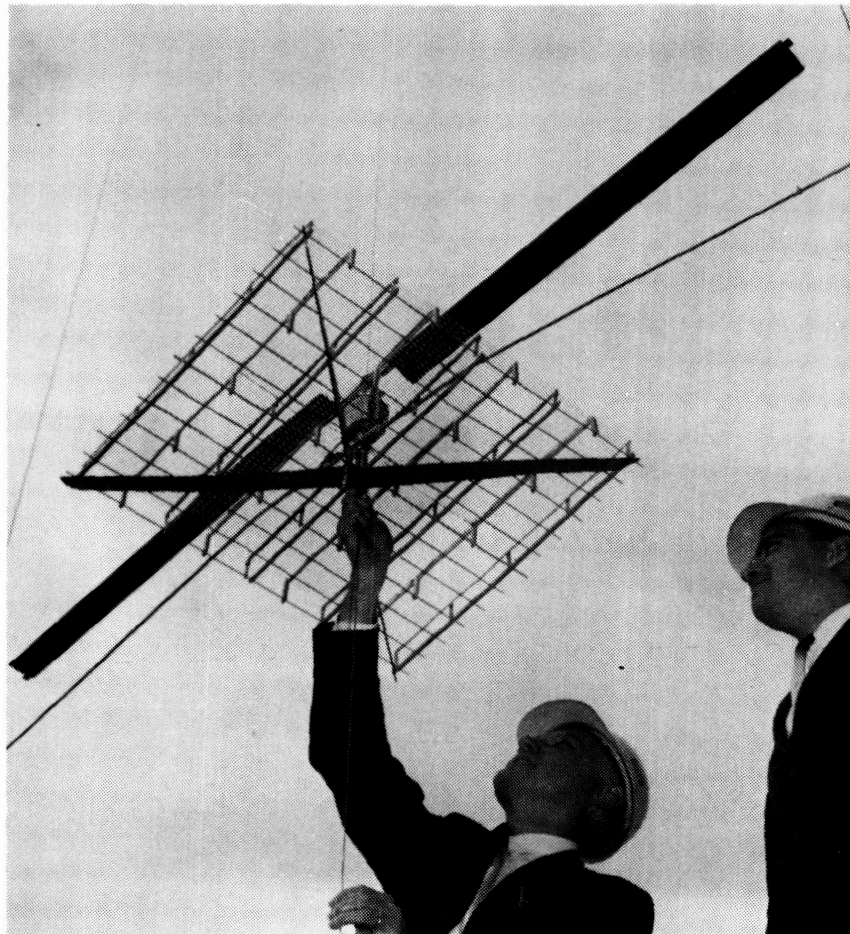
AN EXPERIMENTAL MICROWAVE POWERED HELICOPTER

The Air Force had sponsored a program at Purdue University under Professor Roscoe George to investigate solid state rectifiers to convert microwave power into DC power. (3) Out of this effort and a need for a nondirectional receiving antenna for aircraft use came the invention of the "rectenna" a term contracted from the words "rectifier" and "antenna". (4)

The rectenna looked like a phased array but because each receiving element was terminated in a diode rectifier circuit, it was "non-directive" and ideal for airborne vehicles that roll and pitch.

In 1964 such a rectenna was used with a small tethered helicopter to successfully demonstrate for ten continuous hours the flight of an aircraft powered only with a microwave beam. (5,6)

A non-tethered, beam riding helicopter, but not microwave powered, was successfully demonstrated in 1967. (6) With 400 kilowatts of continuous microwave power available (2), the technology was basically available for a high altitude helicopter platform. In the meantime, communication satellites were coming into use and it was not until the early 1980s that the need for such platforms was again acknowledged.



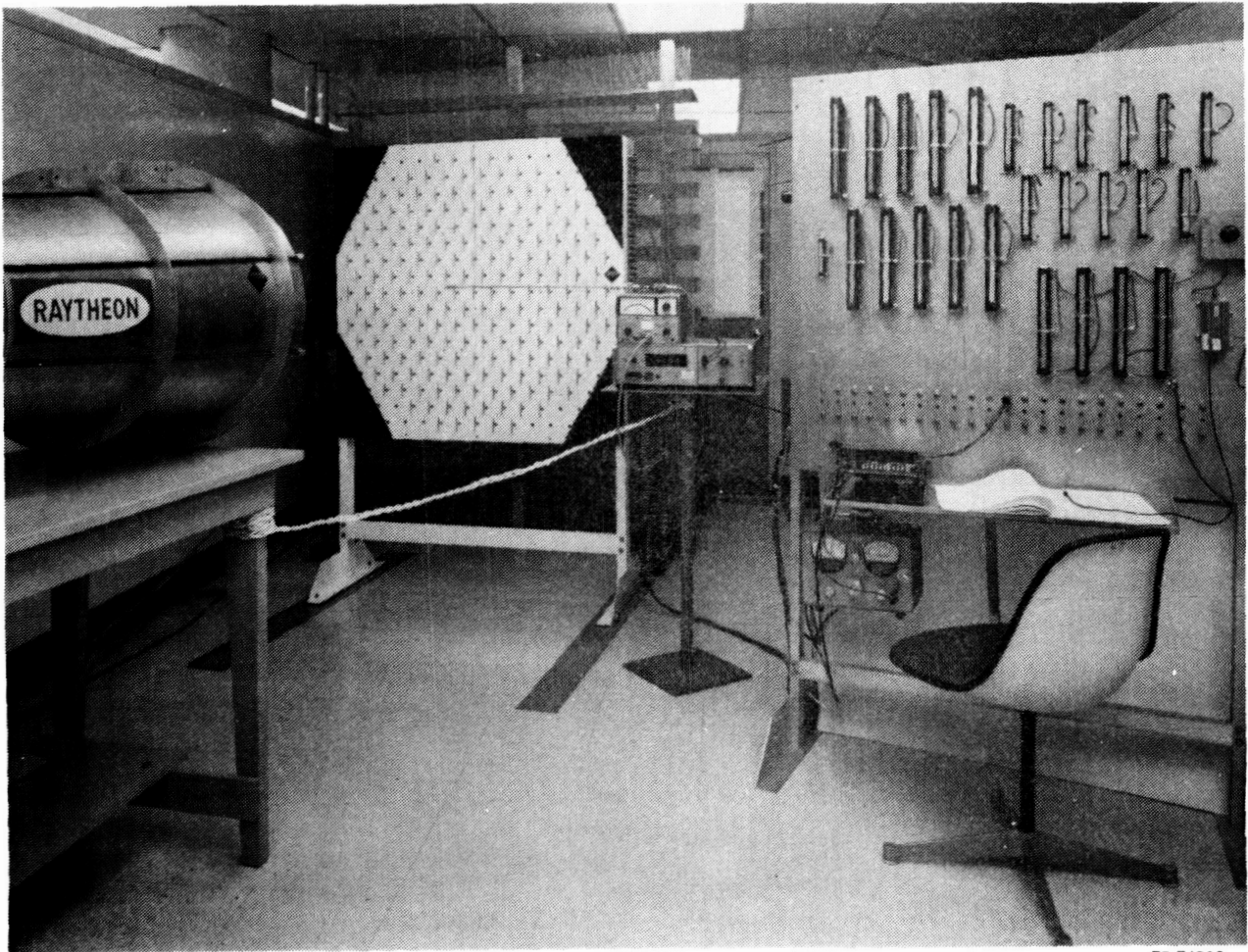
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INTO SPACE WITH MICROWAVE BEAMS

The next beamed power technology development support was motivated by the Space Station application. That activity, sponsored by MSFC in the 1969 to 1964 time period and carried out in the ISM (Industrial, Scientific, Medical) band of 2.4 to 2.5 GHz because of the cost effectiveness of using the technology already existing there, was responsible for great improvements in all parts of the technology, but particularly in rectenna technology. Ultimately, all of the advancements were put together in a demonstration of overall DC to DC efficiency of 48% in 1964. In 1965, the overall efficiency was raised to 54% and validated by the Quality Control Department of JPL at Raytheon. In this latter demonstration, the microwave generator efficiency was measured at 69%, the transmitted beam efficiency at 95%, and the rectenna overall capture and rectification efficiency at 82%. (7)

This demonstration at Raytheon and verification by JPL was essential to the acceptance of the technology by the scientific and engineering communities. For example, the antenna community is accustomed to capture efficiencies of uniformly illuminated apertures of not more than 80%. By adding the rectification function to each individual dipole antenna in the array, however, its capture efficiency increases to 100%. The array also becomes desirably non-directive and its overall capture and rectification efficiency is typically over 80% where most of the inefficiency is caused by diode and skin losses in the rectifier.



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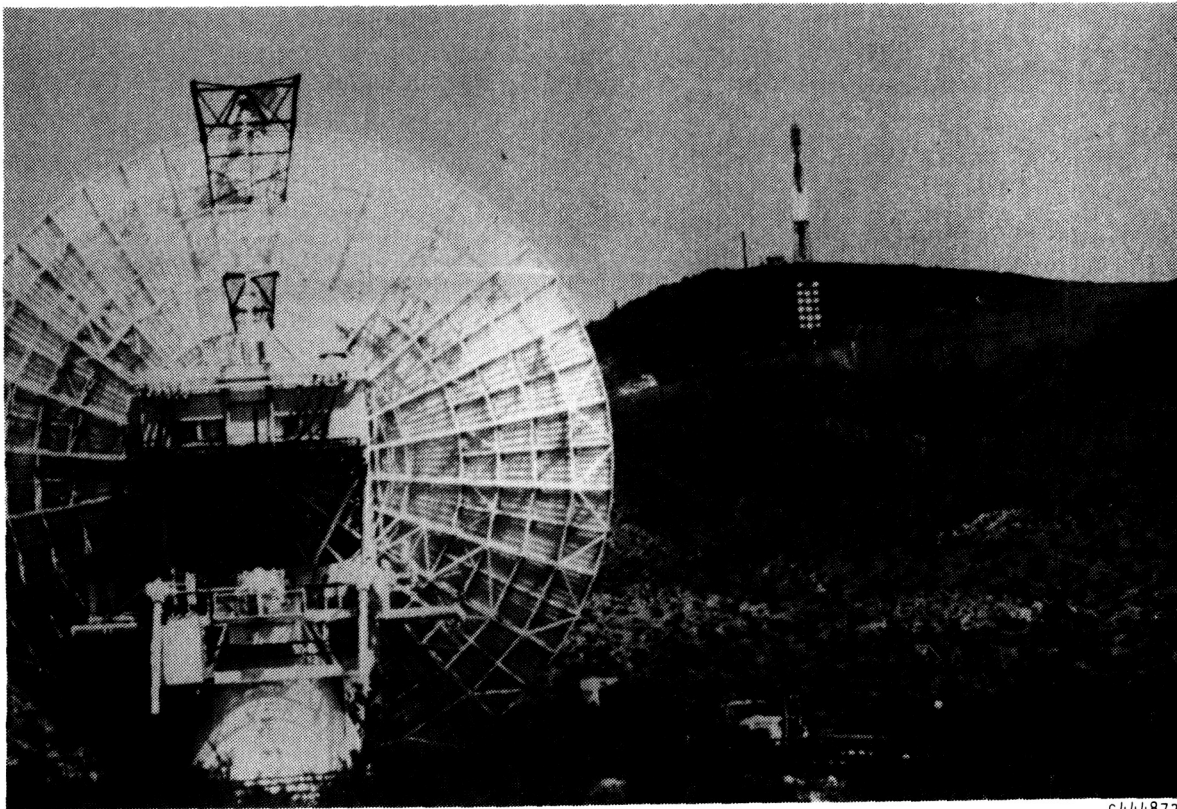
INTO SPACE WITH MICROWAVE BEAMS (Cont.)

Circa 1970, following a briefing by Dr. Peter Glaser and others to a Congressional Committee on the SPS, NASA's Office of Applications became interested in further development and demonstration of microwave technology with the SPS application in mind. It initiated responsibility to carry out its sponsorship through JPL and Lewis Research Center.

Four activities of importance came from this support. One was a study of the complete microwave subsystem including satellite and ground rectenna(8), one was a study and technology development dealing with rectenna for the SPS application(9), a third was a demonstration of beaming significant amounts of power over a significant distance(10,11), and a fourth was productive studies dealing with microwave power generation and antennas.(12)

Of all of these efforts, the 1985 JPL Goldstone demonstration of transmitting power over a distance of one mile and converting the incident microwave power at 84% efficiency to produce over 30 kilowatts of DC power was the most visible. A large 18 x 24 foot rectenna composed of 18 subarrays was designed and built by the Raytheon Company for the demonstration. The efficiency and success with which the demonstration was carried out attests to the soundness and reliability of the rectenna technology involved. The rectenna survived and was operable after a direct lightning strike on the tower in 1980, and which destroyed equipment on the ground.

The success of this demonstration was possibly essential to provide the credibility necessary to later undertake the joint DOE/NASA study of the Solar Power Satellite concept.



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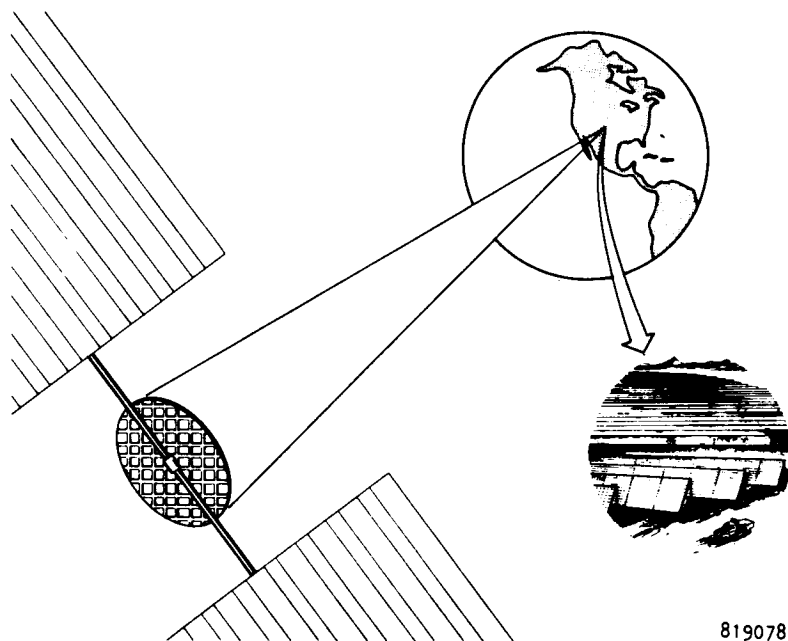
THE SOLAR POWER SATELLITE AND BEAMED POWER TRANSMISSION

The introduction of the concept of the Solar Power Satellite in 1968 by Dr. Peter Glaser of Arthur D. Little, Inc. had an enormous impact upon the direction of beamed power transmission.(13) The very large physical and electrical size of the beamed power system presented a tremendous challenge to engineers to solve the many problems involved.

The first organized activity to study the technical and economic feasibility of the Solar Power Satellite as a system was that of a four-company team comprised of Arthur D. Little, Inc., Raytheon Company, Grumman Aerospace Corp., and Textron, Inc. The results of this six month study carried out in 1971 were sufficiently favorable to encourage the management of the four companies to jointly send a letter to the Director of NASA recommending the support and study of this concept by NASA.

The first general recognition within NASA of the SPS as an important potential program grew out of NASA's comprehensive study entitled "Outlook for Space in the Year 2000". By this time, however, spurred on by the oil embargo of 1973, the government had created ERDA (Energy Research and Development Agency) and given it the charter for the development of all sources of energy to be used on the earth's surface in the United States. ERDA established a task group to study the SPS. This group recommended a detailed assessment of SPS covering technical feasibility, economic viability, environmental and societal acceptability, and the merits of SPS when compared with other future alternatives.

The recommendations evolved into a three-year study program termed the "DOE/NASA Satellite Power System Concept Development and Evaluation Program". The many detailed studies undertaken during this study, including important system studies by Rockwell International and Boeing Aerospace Company, were completed in the summer of 1980. A 670 page document summarizing the results of these studies was published.(14)



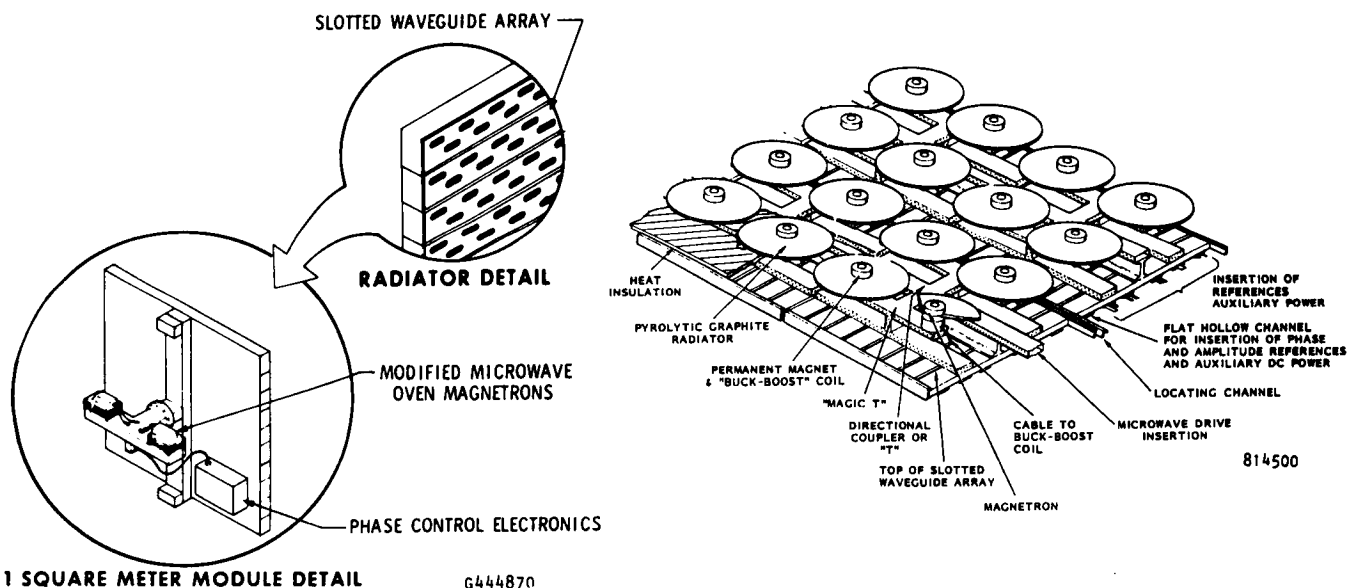
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BEAMED MICROWAVE POWER TRANSMISSION IN THE SPS

A portion of the funding for the three year SPS study, administered by NASA, was used for engineering studies. The particularly difficult problem of building a high power transmitter in space was addressed by several companies, including Boeing, Raytheon, North American Rockwell, and Grumman Aerospace. In the writer's opinion it was the contribution of R.M. Dickinson of JPL that pointed the design in the proper direction. The concept, as shown below, was an electronically steerable array composed of modules comprised of two magnetrons acting in conjunction with a passive combiner to excite a section of slotted waveguide array.

Dickinson's concept motivated an intensive evaluation of the magnetron directional amplifier as a generator for the SPS. (13) The evaluations used the common microwave oven magnetron for experimental data. It was determined that this tube generated very little extraneous noise, was highly efficient, and had an internal feedback mechanism to regulate its cathode temperature to achieve the longest possible life. (12) A subsequent study from MSFC designed a specific magnetron for the SPS application with projected 50 year life, 85% efficiency, and an external control loop to eliminate interfacing power conditioning with the photo voltaic array. (15)

The magnetron in combination with the slotted waveguide array became a radiation module that was combined with other modules to form a subarray of the large, one kilometer diameter, SPS transmitting array as shown below. The SPS magnetron application was recently updated with new technology. (16)



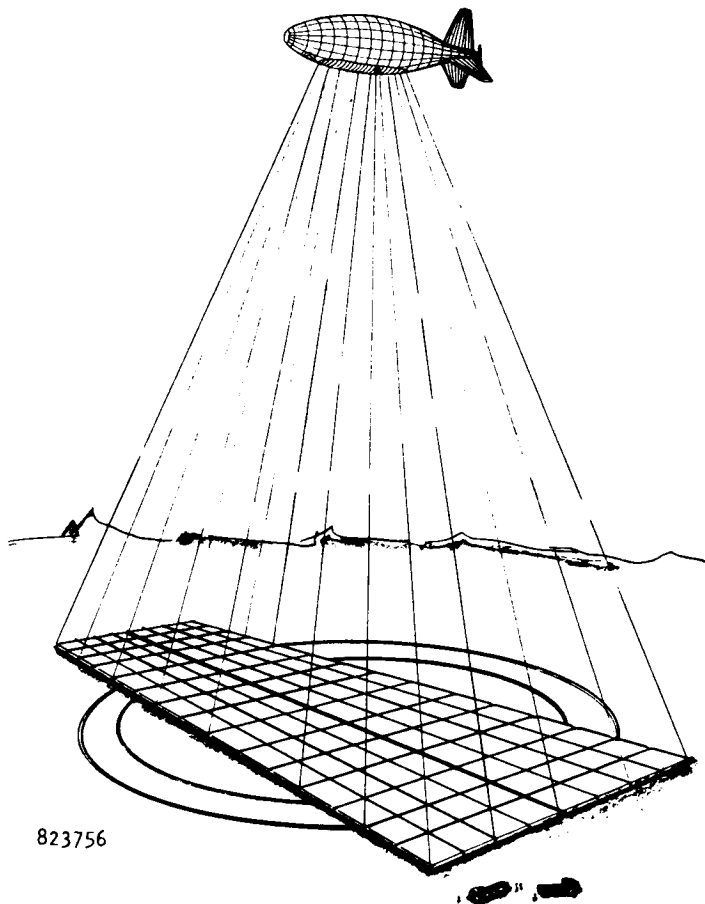
REINTRODUCTION OF MICROWAVE POWERED AIRCRAFT

Generic improvements in beamed microwave technology and the standing need for a long endurance high altitude platform led to a revival of interest within NASA in microwave powered platforms in 1978. Out of this interest came two microwave powered airship studies from Wallops Flight Facility. (17,18) These studies produced two outstanding technology advances.

The first of these was a new thin-film, printed circuit rectenna format which made its use in both air and space vehicles very attractive. (18) This format was later greatly improved upon and made ready for space use with the use of discretionary funding at LeRC. (19)

The second contribution was the conceptual design of an electronically steerable phased array composed of radiation modules similar to those for the SPS. (18) It was determined that a combination of an off-the-shelf microwave oven magnetron, a ferrite circulator, and a section of slotted waveguide array could become a building block for Earth-based transmitters for both space applications and for microwave powered aircraft.

It was subsequently found that the design could be greatly simplified by adding additional external circuitry to the microwave oven magnetron to greatly increase its gain while locking its output phase to the phase of the driver. (20)

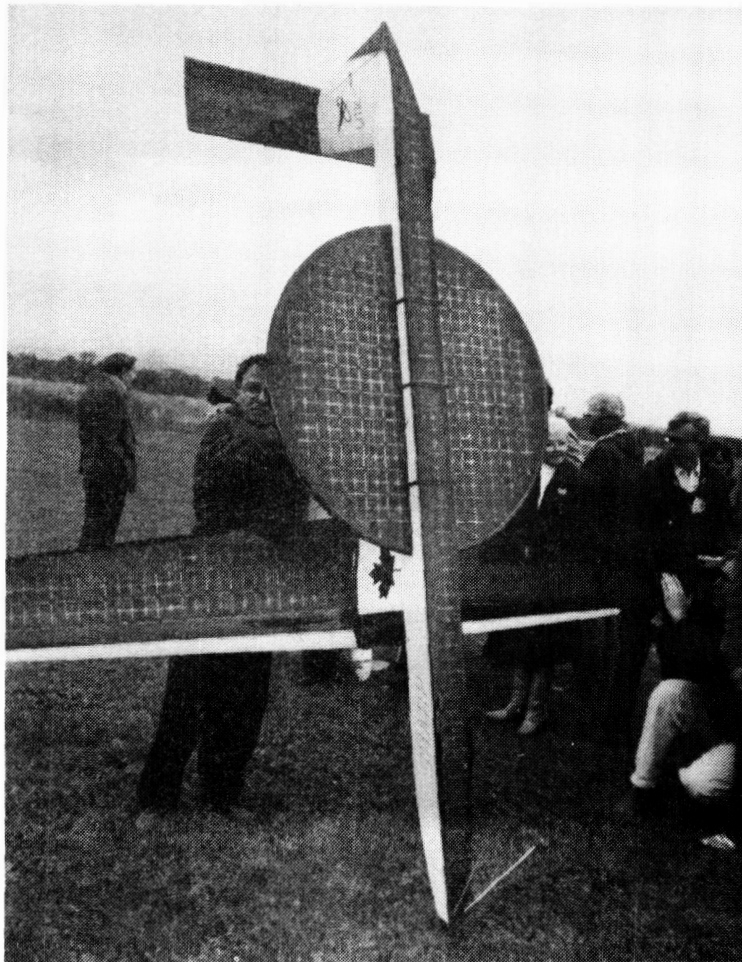


THE CANADIAN SHARP PROGRAM

The development of the new rectenna format remained unexploited experimentally in the USA, although it was studied in the context of a microwave powered airplane for atmospheric surveillance.(21) In 1981, however, the Canadian government embarked on the SHARP (Stationary High Altitude Relay Platform) program that in 1987 produced the first successful demonstration of the free flight of a microwave powered aircraft, in this case an airplane, shown below.(22) The Canadian team was successful in adding its own improvement to rectenna technology, a crossed polarized rectenna that would remain efficient regardless of the angular position of the airplane.

The SHARP program is projected to go through an intermediate stage of development before the final system which will support an airplane flying at 65,000 feet for months at a time, performing useful communication and surveillance functions.

The SHARP program today represents the cutting edge of active application of 2.45 GHz technology, and represents a logical step on the learning curve toward a space application. An electronically steered array for a microwave powered airplane flying at 65,000 feet could also be used experimentally to beam small amounts of power to a low Earth orbit satellite with a rectenna designed for low power density to explore the importance of refraction and attenuation in the Earth's atmosphere under a variety of weather conditions.



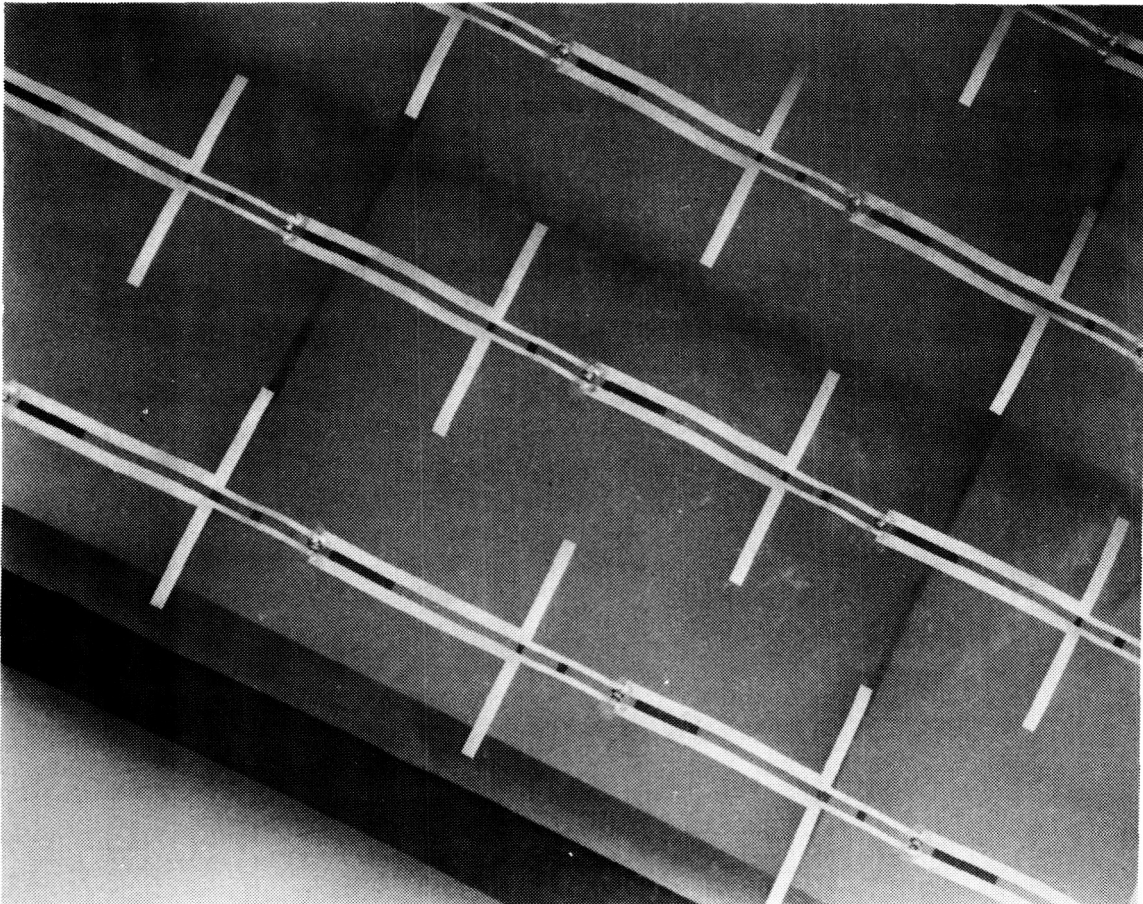
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THE RECTENNA FOR SPACE USE

The well developed rectenna at 2.45 GHz has many desirable qualities as a source of power in space where a microwave beam can be made available. These desirable qualities and other characteristics are

- | | |
|-----------------------------------|--|
| • State of Development | Substantially completed |
| • Specific Mass | Low, 1 kG/kW |
| • Efficiency | High, 85% overall |
| • Typical DC Power Density Output | 500 W/m ² |
| • Dissipation of Inefficiencies | Direct radiation to space |
| • Life | Very long, rectifiers can be shielded |
| • Incident Angle Tolerance | Efficiency nearly constant over 60° |
| • Critical Material Use | Negligible |
| • Reliability | Excellent |
| • Ease of Manufacture | Uses Existing Facilities |
| • Cost | Potentially low but dependent upon diode cost |
| • Transportability | Excellent |
| • Negative Factors | Current design radiates harmonics - new design would not |



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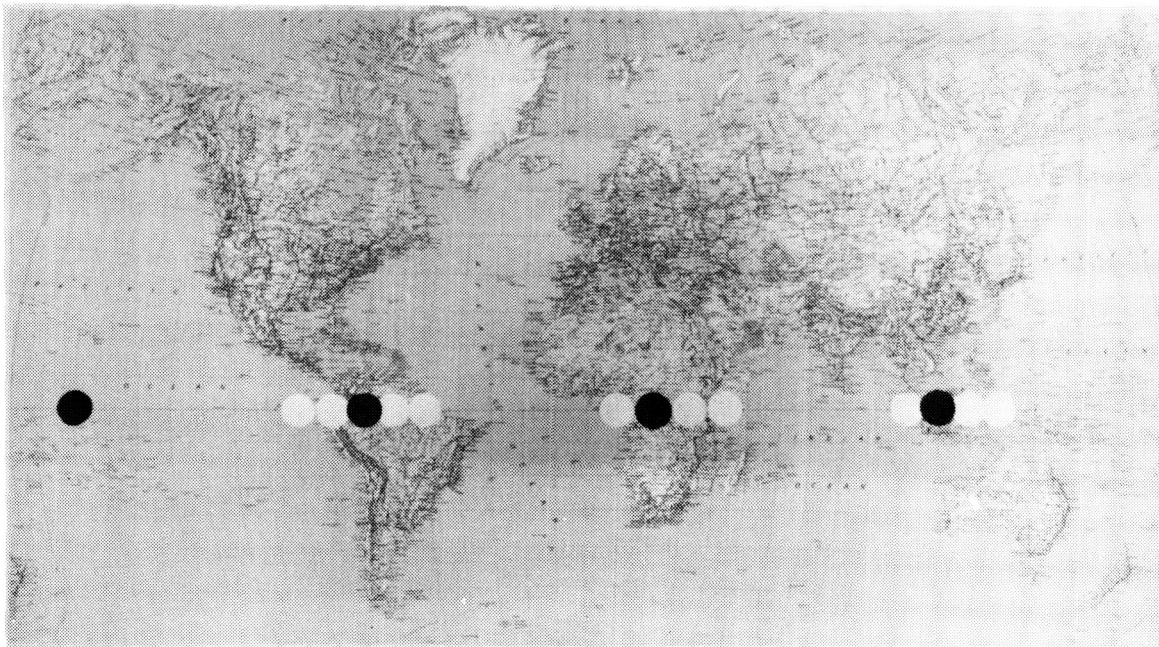
AN EQUATORIALLY BASED BEAMED POWER TRANSMISSION SYSTEM

Any beamed power transmission from Earth to low Earth orbit for peaceful purposes, whether by laser or microwave, should (must) be based in the equatorial plane to take advantage of a time of contact with the space vehicle that is at least 16 times that available from any other geographical location. The full exploitation of beamed power transmission system to space is an international project!

As shown below, a fully mature land-based system consists of four high power transmitters equally spaced around the Earth to interact with an all-electronic LEO-to-GEO transportation system, and 10 low power transmitters for use with orbiting industrial parks or other satellites in LEO. All transmitters use electronically steerable beams that sweep over a 90° total angle in the west to east direction.

A mature system is not necessary to achieve economic payback. Single transmitters are effective for both low Earth orbit use, and for the LEO to GEO transportation system. But as the system grows and matures, it allows higher duty cycle for both transmitters and satellites and the economics become very favorable.

The international geopolitical aspect of the use of the equatorial plane is particularly interesting from the commercialization of space viewpoint. The ownership of the ground based portion of the system could be modelled after Intelsat, and the various space vehicles could then purchase transmitted power from it, analogous to the domestic practice of buying power from the electric utilities. The financial investment in such a system would be relatively modest by business standards. The physical system is firmly based upon well developed technology at 2.45 GHz. Because of this, studies have shown that the first low power transmitter should be well under \$100,000,000.⁽²³⁾ Such a transmitter would provide 16,000 kilowatts of rectified DC power to a 200 meter diameter industrial park, with an efficiency of greater than 20% from 60~ Earth power to satellite DC power. Average power to one satellite with one Earth transmitter is 240 kilowatts, and three 400 kilowatts with all 14 ground based transmitters.



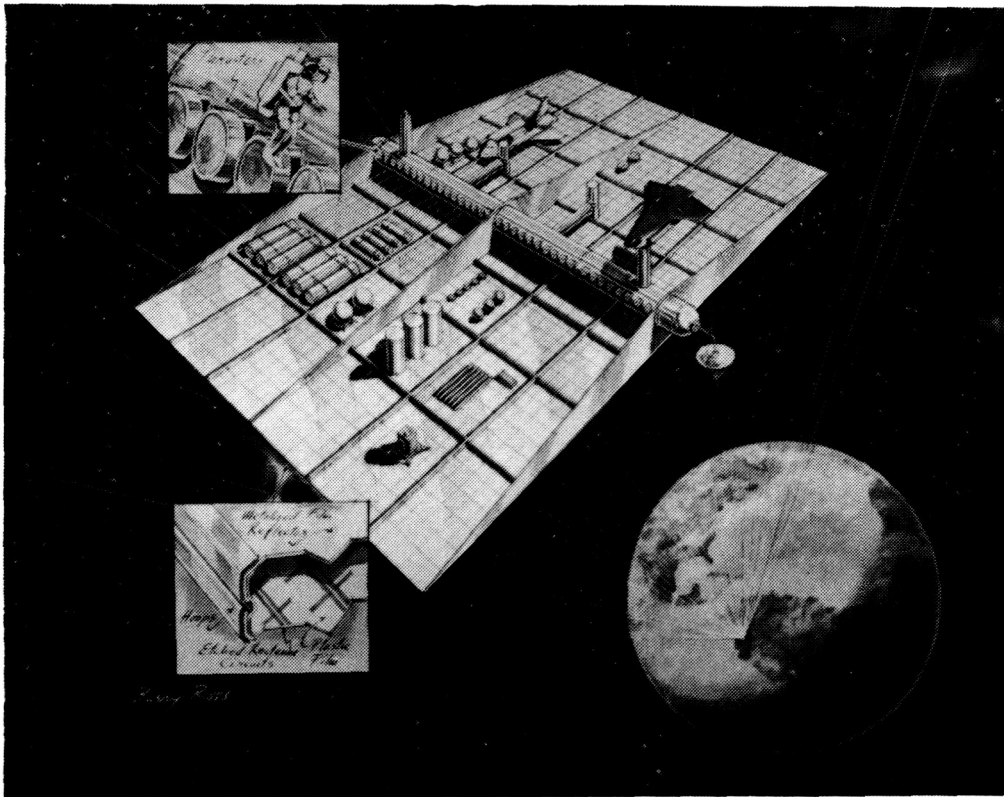
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AN ALL-ELECTRONIC LEO TO GEO TRANSPORTATION SYSTEM

It is well known that a much better transportation system from LEO to GEO than now exists with conventional chemical rocket propulsion will be necessary to develop space beyond LEO and to make large scale projects such as the SPS feasible. This is true even if a substantial portion of the material needed for SPS construction comes from the moon.

Electric propulsion with its much higher specific impulse could solve the LEO to GEO transportation problem if there were a suitable source of low mass electric power for the electric thrusters. Fortunately, there is. The thin film format for the rectenna developed by NASA can produce almost any needed amount of power at a mass penalty of only one kilogram for each kilowatt of DC power output. Further, the rectenna sections can be interconnected to make the power available at the high voltage required by such high specific impulse thrusters as the ion thruster and can eliminate much of the current power conditioning with other sources.

An all electronic propulsion system that combines the rectenna and microwave beam source with the thruster has been under study for some time. (24) It has gradually matured to the point where projections of its performance and cost can be made. (25) The vehicles for economic operation of the system are large by current standards but will be needed for such large scale operations as constructing solar power satellites. An artist's concept, guided by engineering input, is shown below. Such a vehicle could transport 50,000 kilograms representing a payload fraction of 51% to GEO and return to LEO in 35 days with four Earth based beams and in 140 days with one Earth beam. A fleet of such vehicles, going in convoy, could move very large amounts of material at low cost. In addition express trips to GEO with minimum payload could be made in a matter of 10 days with four beams.

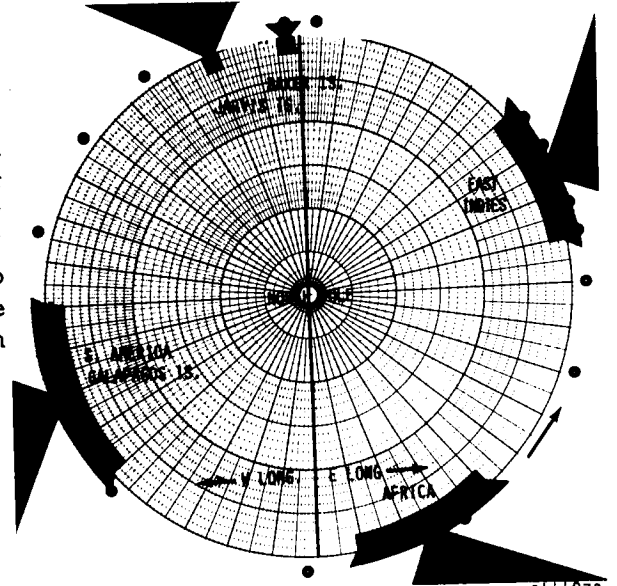


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AN ORBITING INDUSTRIAL PARK SYSTEM

The President's Commission on Space referred to Orbiting Industrial Parks in their published report. Such "industrial parks" will be very much dependent upon large amounts and low cost electric energy. However, they will quite likely be in low Earth orbit and not concerned with the geography beneath them. Hence, the industrial parks could be constructed in the equatorial plane and jointly use and buy electric energy from a land based complex of beamed power transmitters. (23) Such a complex viewed to scale from the North Pole, is shown below. The view includes four high power transmitters for LEO to GEO use.

A table showing the projected cost of electric energy from such a complex in terms of several scenarios of the stage of maturity of the system is given below. Cost of electric energy is seen to vary from a maximum of \$8.00/KWH for a single transmitter and park down to \$0.36/KWH for a fully mature system. The costs include amortization costs of both transmitters and rectennas over a ten year period. Learning experience in constructing the units is reflected in reduced cost of equipment built downstream. Initial costs do not include the cost of constructing the space park. The maximum duty cycle from land-based sites is 21%.



| SCENARIO | GROUND BASED TRANSMITTER | | | INDUS. PARK BASED RECTENNA | | | ANNUAL KW HR ENERGY DELIVERED 10 ⁶ KW HR | EQUIPMENT COST PER KW HR \$ | 60 CYCLE KW HR** CHARGE \$ | TOTAL KW HR CHARGE \$ |
|----------|--------------------------|------------------------------------|------------------------------------|----------------------------|------------------------------------|------------------------------------|--|--------------------------------|-------------------------------|--------------------------|
| | Q'TY | INITIAL COST 10 ⁶ \$ | YEARLY* COST 10 ⁶ \$ | Q'TY | INITIAL COST 10 ⁶ \$ | YEARLY* COST 10 ⁶ \$ | | | | |
| A | 1 | 80 | 8 | 1 | 80 | 8 | 2.1 | 7.61 | 0.20 | 7.83 |
| B | 14 | 560 | 56 | 67 | 2.680 | 268 | 1.970.0 | 0.16 | 0.20 | 0.36 |
| C | 14 | 560 | 56 | 1 | 80 | 8 | 29.4 | 2.17 | 0.20 | 2.37 |
| D | 1 | 80 | 8 | 14 | 560 | 56 | 29.4 | 2.17 | 0.20 | 2.37 |
| E | 4 | 240 | 24 | 4 | 240 | 24 | 33.6 | 1.42 | 0.20 | 1.62 |

* INITIAL COST IS CHARGED OFF EQUALLY OVER 10 YEAR PERIOD

** ASSUMES 25% OVERALL EFFICIENCY AND 60 CYCLE ENERGY COST OF 5¢/KW HR

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