A MICROWAVE POWERED HIGH ALTITUDE PLATFORM

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ABSTRACT

Recently the world's first flight of a fuelless airplane powered by microwave energy transmitted from the ground took place. A high-power transmitter at 2.45 GHz was used to beam energy to the aircraft circling overhead. A custom printed-circuit array of dipole antennas with associated rectifying diodes coating the underside of the plane converted the microwave energy to direct current to power the electric motor. This is the prototype of a much larger beamed microwave power transmission system that will have an unmanned airplane circle at high altitudes continuously for many months, and thereby be used as a platform for radio communications and surveillance applications.

INTRODUCTION

A program is being carried out at Communications Canada to develop a long endurance high altitude platform known as SHARP (Stationary High Altitude Relay Platform) (1). The platform would be an unmanned lightweight airplane, circling at an altitude of about 21 km, and would be used to relay radio communications signals over an area on the ground up to 1000 km in diameter. Since its use will be to provide communications and broadcasting services, it is essential that the platform remain aloft at the mission altitude for weeks or months at a time. Having examined the weights and endurance capabilities of conventional fuels and power sources, it was concluded that transmission of power by microwaves to the aircraft was the only way to achieve this.

As illustrated in Figure 1, microwave power would be transmitted from a large array of antennas on the ground, about 85 metres in diameter, to the aircraft where the energy is focussed to a spot area with a half-power diameter of 30 metres. Approximately 500 kW of microwave power would be radiated to produce a power flux density of 500 W/m^2 at 21 km altitude. The underside of the airplane would be coated with a thin-film array of thousands of half-wave dipole rectifying antennas (rectennas), which convert the received microwave energy to dc. With 100 m^2 of rectenna surface on the airplane, 35 kW of dc power would be delivered, of which 25 kw would be used by SHARP's electric motor for propulsion and the remainder available for the payload electronics.

A unique airplane configuration suitable for high altitude microwave-powered flight has been developed (2) and a 1/8-scale test aircraft built. In addition, extensive research has been conducted to develop efficient high-power dual-polarized rectennas with low spurious emission levels. As a result of these two developments, low altitude microwave-powered flight tests were conducted to demonstrate the feasibility of the proposed system. Details of this work are reported here.

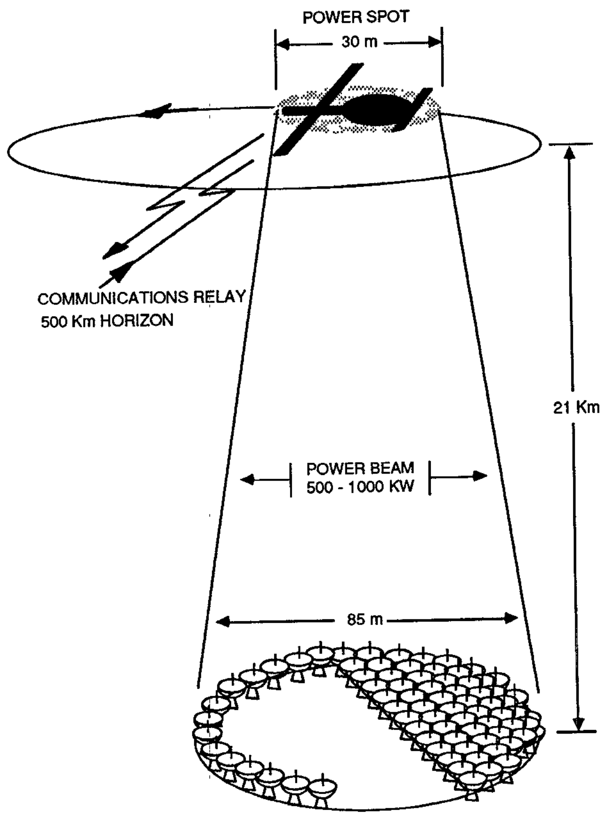

Figure 1. Configuration of SHARP system

THE LOW ALTITUDE MICROWAVE POWERED FLIGHT

On September 17, 1987 at 0720h, a prototype SHARP (Figure 2) flew on beamed microwave power continuously for 20 minutes. This was the world's first sustained flight of a microwave powered aircraft (3). Since that time, several flights of up to an hour's duration have been conducted.

The remotely-controlled airplane was launched from the hand of a runner and climbed to a target altitude of 150m on battery power. At this point the battery was switched off and the microwave turned on. The beam was continuously steered to track the aircraft, which was constrained to fly anywhere inside a 50 degree cone centered at the transmitter, so that the beam incidence would remain near broadside.

The Microwave Beam

The microwave beam used to power the 1/8-scale SHARP airplane, was formed by a 4.5 metre diameter parabolic antenna transmitting 10 kilowatts of energy at a frequency of 2450 MHz.

A high power orthogonal-mode coupler was developed to combine the microwave energy from two low-cost 5 kW continuous-wave magnetrons. This produced a dual-linear orthogonally-polarized signal, suitable for reception by the rectennas, regardless of airplane orientation. The water-cooled magnetrons, whose high power microwave outputs were connected to the orthomode coupler and feedhorn using rigid waveguide, were mounted on the antenna and moved with it as the antenna tracked the airplane. This design avoided the requirement for high power rotary joints.

The transmitted energy was concentrated in a circular spot with a half-power diameter of about 3.5 m at the airplane altitude of 150 m. The power flux density at this point was about 400 W/m^2. Since the total rectenna surface area on the airplane is one square meter, only 10% of the energy was intercepted, the remainder passing through. Future designs having highly focussed beams could concentrate the energy towards the disc alone, thereby achieving capture efficiencies approaching 90%.

The Power Reception and Conversion System

The dual polarization rectenna, shown in Figures 3 and 4, and used for the conversion of the microwave beam to useful (dc) power, has its origin in the rectenna developed by the Raytheon Corporation under NASA sponsorship (4). Its predecessor consisted of an array of linear dipoles, for reception of the microwave energy, to each of these dipoles being connected conversion circuitry for dc power output. This linear rectenna was in the form of a thin-film plastic sheet with printed circuit elements, weighing only one-tenth as much as earlier rectennas and having comparable high conversion efficiency (80%), and power handling capability (4W per element).

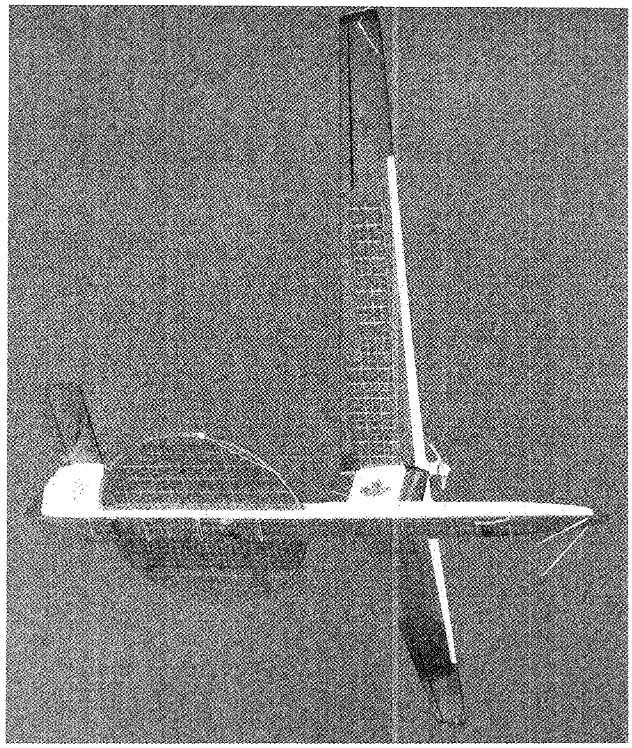

Figure 2. Microwave powered airplane (4.5 m wingspan)

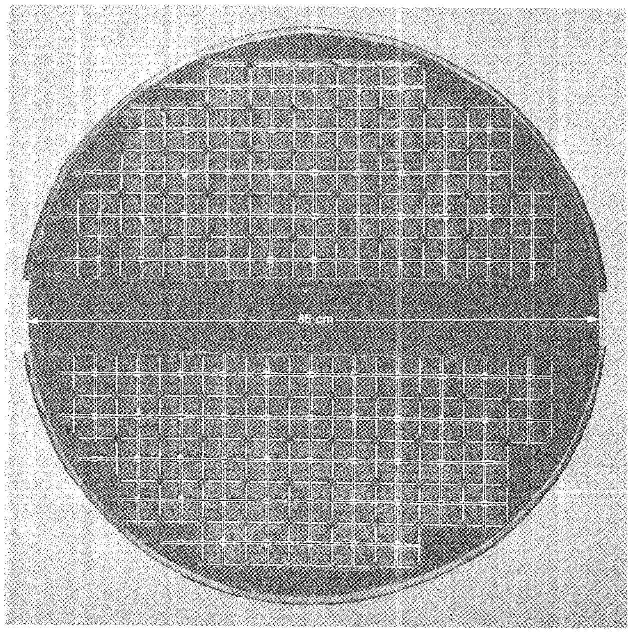

Figure 3. Airplane disc with dual-polarized rectennas

Investigations found, however, that a rectenna with this format had serious limitations in many power transmission scenarios. One of these disadvantages stemmed from the use of linear dipoles for the antenna array. For the powering of moving platforms, or in cases of depolarization due to Faraday rotation, rain etc., the transmission antennas, providing the power beam, would have polarization track to stay aligned with the dipoles on the platform, a costly and complicated process.

Another limitation, and of major concern, were the high levels of radiated EMI observed from VHF to beyond S-band. The Schottky diodes, used for microwave to dc conversion, exhibited intermediate frequency (I.F.) negative resistance when 'pumped' at 2.45 GHz by the powering beam, causing spurious oscillations. These high levels of EMI could interfere with payload and platform electronics, as well as distant electronic systems.

The dual polarization rectenna was developed to remove the limitations of previous arrays. It consists of two orthogonal linearly-polarized rectenna arrays (foreplanes), each collecting power of its corresponding polarization (Figure 4). The transmitted beam of two orthogonal polarizations, which may be unequal in amplitude and phase, includes the usual cases of linearly or circularly-polarized waves. These two orthogonal field components of the incident beam can be resolved into components aligned into each of two directions, x and y. On foreplane x is located an array of linearly-polarized dipole elements oriented parallel to the x direction. They are thus capable of selectively receiving the transmitted wave component oriented in the x direction.

The other orthogonal component of the transmitted wave, which cannot be received on the dipoles on foreplane x continues to propagate and is incident on foreplane y, parallel to foreplane x where the dipoles, oriented parallel to the y direction, selectively receive this other component of the transmitted wave. A reflector plane behind both arrays maximizes power absorbed by each rectenna foreplane.

By a specific choice of array format, dimensions and foreplane separations (US Patent pending), shielding by rectenna transmission lines and coupling effects between arrays may be minimized and the high efficiency of previous rectennas maintained without the need for polarization tracking. When the x and y foreplanes are separated by a distance m $\lambda/2$ (where m may take any integer value including 0) the effect of transmission lines may be compensated by adjusting the reflector spacing p to capacitively balance the effect of the inductive transmission lines at the rectenna foreplanes.

To confirm the usefulness of the dual polarization rectenna, tests were carried out using circularly polarized transmitted waves. It was found that reception efficiency degraded by less than 5% below that which could be obtained with a single rectenna array. This method of compensation is applicable to any specified angle of incidence. This angle is usually chosen as that most desirable for matching the antenna to its power conversion circuit over the operational range of beam incidence, and it (though not polarization orientation) can often be strictly controlled, in order to maintain the impedance stability necessary for total energy absorption.

In cases where the range of beam incidence cannot be carefully limited (for example banking of the aircraft relative to the microwave beam or movement of the reception system over long distances) the variation in rectenna reception efficiency due to varying angles of beam incidence may be reduced according to the compensation scheme described above, with suitable selection of foreplane separation and reflector spacing.

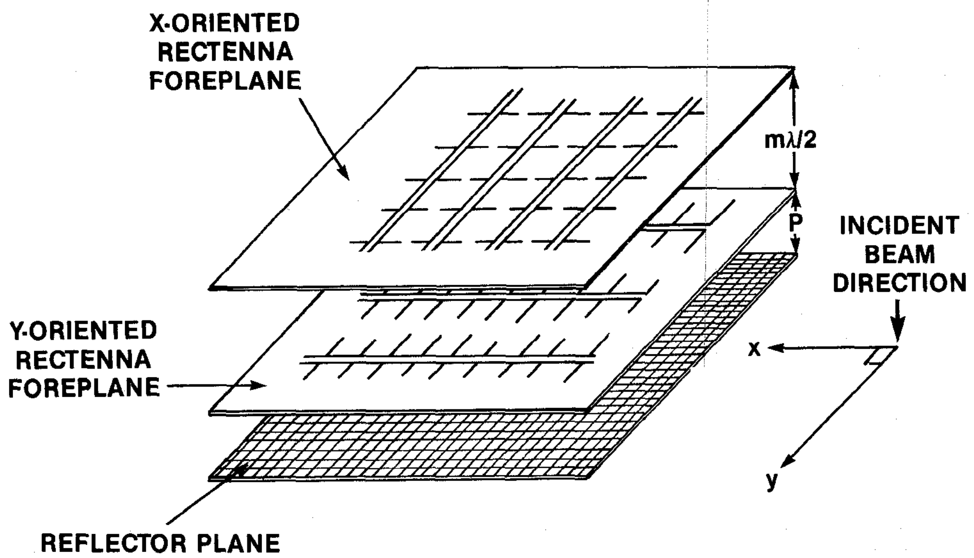

Figure 4. Dual polarization EM reception and conversion system

For example, for a dual polarization rectenna of foreplane separation 0.08λ and a reflector plane located 0.23λ behind foreplane y, the efficiency of power reception has been computed to vary by 16% from a maximum of 96% as the angle of beam incidence varies by ±50° from broadside. This may be compared to a change in efficiency from 100% to 67% for previous linear rectennas, over the same variation in angle of beam incidence.

The rectenna diodes used for this first flight were 4 HP2835 Silicon Schottky diodes per rectenna element in a series/parallel combination. The increased series resistance of these devices effectively 'damps out' the spurious oscillations previously observed, at the expense of a reduction in power handling capability (to 1W per element) and efficiency (to 70%). These diodes have the added advantage of being cheap and commercially available. Rectenna arrays are presently under development at the CRC capable of the high power and efficiency of their linear predecessors, with no spurious oscillations. Radiated EMI at the harmonics of the powering frequency remains a problem with all rectenna types yet built.

The Microwave Airplane

The design of a microwave powered airplane is driven by two key considerations. First, the power required to fly must be minimized, which can be realized by using a glider-like airframe with very long slender wings. Second the microwave power captured must be maximized, which can be achieved by employing large surfaces on the airplane to intersect the microwave beam.

The unique configuration of the SHARP aircraft, illustrated in Figure 2, is the result of balancing these opposing demands (2). The 1/8-scale airplane is characterized by a large flat non-lifting circular disc, about 1 m in diameter located along the fuselage aft of the wing. This disc serves only to carry rectennas (Figure 3), approximately twice as many as can be accommodated on the wings. The wings are mounted on an airfoil-shaped pylon, which serves to minimize aircraft banking during turns thereby ensuring that the rectennas on the underside of the plane do not angle away from the microwave beam.

The aircraft has a wingspan of 4.5 m, an overall length of 2.9 m and weighs only 4.1 kg. It is constructed primarily of balsa, with basswood, spruce and plywood used only where additional strength is needed, and the entire frame is covered with lightweight mylar film. A high energy-to-weight ratio electric dc motor drives a large-diameter (60 cm) high-efficiency propellor. Total power into the motor required to fly is 150 W.

The rectenna covers the undersides of the disc, the fuselage and the wings. To incorporate the required microwave reflector, critically spaced 1/4-wavelength behind the rectenna foreplane, thin-film aluminized-mylar sheeting is used on the upper surface of the disc, and is built into the wing and fuselage structures.

MICROWAVE TECHNOLOGIES FOR SHARP

The low altitude system was the first step in the development of the full scale 21 km altitude microwave powered platform. As shown in Figure 1, the microwave power transmission system is comprised of a phased array of mechanically steered antennas. A typical design at 2.45 GHz would have 250 5m-antennas each fed by a 5 kW magnetron or klystron. However, designs ranging from the use of a very large number of small antennas with1 kW modules to the use of only a few very large antennas with 50-150 kW power modules may be optimum, depending on relative cost and technical complexity. Alternatively, power transmission at 5.8 GHz, another useable band, would mean a significant reduction in antenna size. Ultimately, the technical and economic feasibility of this system depend greatly on developments in microwave technology. The prime areas are:

i) Microwave antennas: The near vertical tracking (± 10^{o}) and low steering rate (0.5 deg/sec) characteristics of this system allow the development of unique low cost steerable dishes or slotted waveguide arrays.

ii) High power phase-controllable CW microwave sources at 2.45 GHz and 5.8 GHz: Injection-locked magnetrons and high-power solid state modules may be alternatives to klystron amplifiers. Availability, cost, reliability and lifetime are important parameters.

iii) Rectenna technology: Circuit designs at 2.45 and 5.8 GHz with high conversion efficiencies (80%) and high power handling capability (1000 W/m^2) are preferred. These designs must exhibit low spurious and harmonic emission levels to prevent potential interference to sensitive communications systems.

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