

Communications Research Centre

*Summary report on SHARP
(Stationary High Altitude Relay Platform)
Part A – Technical feasibility of microwave-powered
airplanes*

by
G.W. Jull

CRC REPORT NO. 1393

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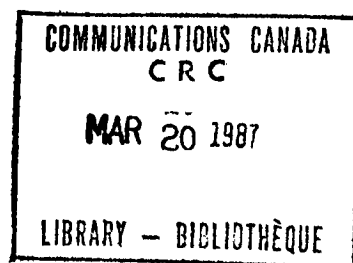
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Ottawa, September 1985

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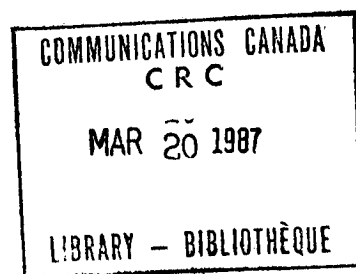
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A B S T R A C T

The SHARP (Stationary High Altitude Relay Platform) system concept envisages use of high altitude microwave-powered airplanes as platforms to relay telecommunications signals. The concept takes advantage of microwave power transmission developments associated with the Solar Power Satellite and High Altitude Powered Platform concepts and adapts these to Canadian needs. Microwave power would be transmitted from a large ground antenna system to an unmanned airplane circling at about 21 km. This power would be converted to dc power using rectennas on lower surfaces of the airplane. The dc power would drive lightweight electric motors.

Over the period 1981 to 1984, the Radar and Communications Technology Branch of DOC carried out a series of background research activities on technologies associated with SHARP. Between February 1984 and April 1985, the Space Technology and Applications Branch carried out a preliminary assessment of the feasibility of the concept under the leadership of Dr. E.J. Hayes. (Pre Phase A Feasibility Study). This report summarizes principal results and conclusions of the research and assessment studies as related to microwave powering of high altitude unmanned airplanes. Other studies defined telecommunications missions and assessed their commercial viability.

Various types of airplanes and power transmission systems were analyzed. It was found that the cost of a powering system would be considerably reduced if it were to be operated at an ISM frequency of 5.8 GHz rather than at 2.45 GHz. A currently available 2.45 GHz rectenna, capable of power conversion at a power flux density of 500W/m^2 , was tested to determine microwave to dc conversion efficiency and levels of out-of-band spurious emissions.

To gain experience with microwave powering of airplanes, a 1.3m wing span model airplane has been designed and fitted with a novel type of dual polarization rectenna. It is planned to fly this airplane on microwave power. A 6kW transmitter and a 4.5m tracking antenna will be used to provide the power flux density required to fly the airplane to altitudes of up to 70m.

It is concluded that there are no insuperable technical problems to achieving feasibility of the airplane and power transmission system. However, an acceptable rectenna has not yet been identified. Further, there are uncertainties in performance of lightweight airplanes in the operational environment.

1. INTRODUCTION

In the early 1980s, it was foreseen that airplanes and lighter-than-air vehicles (airships) could be used as radio relay platforms to complement terrestrial and satellite networks in Canada. Their operating altitudes make them potentially valuable for point-to-point or multipoint distribution of signals within relatively wide areas. However, with a few notable exceptions, (e.g. in underdeveloped countries), neither conventionally-powered airplanes (with limited endurance and operating altitude) nor tethered airships¹ have yet played a significant role as telecommunications relay platforms.

The **SHARP** (Stationary High Altitude Relay Platform) system concept envisages use of high-flying unmanned airplanes as platforms for relaying telecommunications signals. It seeks to exploit advantages and overcome limitations of operating altitude and endurance of conventional airplanes. The airplanes would circle slowly for many months at an operating altitude of 21km and relay signals within a diameter of coverage of 600 km, (which is about the width of a Canadian prairie province). A system of **SHARP** airplanes could potentially be used to extend various telecommunications services such as mobile radio or TV broadcasting to rural locations at the regional level.

Very high altitude airplanes have also been considered as platforms for surveillance missions or for *in-situ* monitoring of atmospheric trace constituents such as SO₂, NO₂ and CO₂. For example, the recently announced US NASA/DOE CO-OPS project² proposes to use a high altitude airplane platform to monitor concentrations of CO₂ over various sites around the earth.

A novel feature of both SHARP and CO-OPS systems is the proposed use of microwaves as a source of propulsive power for the airplanes. In these systems, microwave power would be transmitted from a large ground antenna system to a circling airplane, as illustrated in Figure 1. The power beam would be accurately focussed onto the airplane. A power reception facility, mounted on lower sides of airplane wings and other surfaces, would receive and convert microwaves to dc power. This facility has come to be known as a rectenna (for "**rectifying antenna**"). The dc power would be used to drive electric motors on the airplane for propulsion, to power the payload and control systems and to charge standby energy storage units.

The concept of power transmission using radio waves has a long history indeed, going back almost one hundred years to Heinrich Hertz and the very beginnings of radio in 1888. But it was only in the past decade that major technical barriers were reduced to a level such that power transmission by radio could be seriously considered as a practical proposition. In the mid-1970s, W.C. Brown and his colleagues at Raytheon, working with NASA scientists, demonstrated efficient transfer of 30 kW of dc power over a distance of one mile, using a microwave power

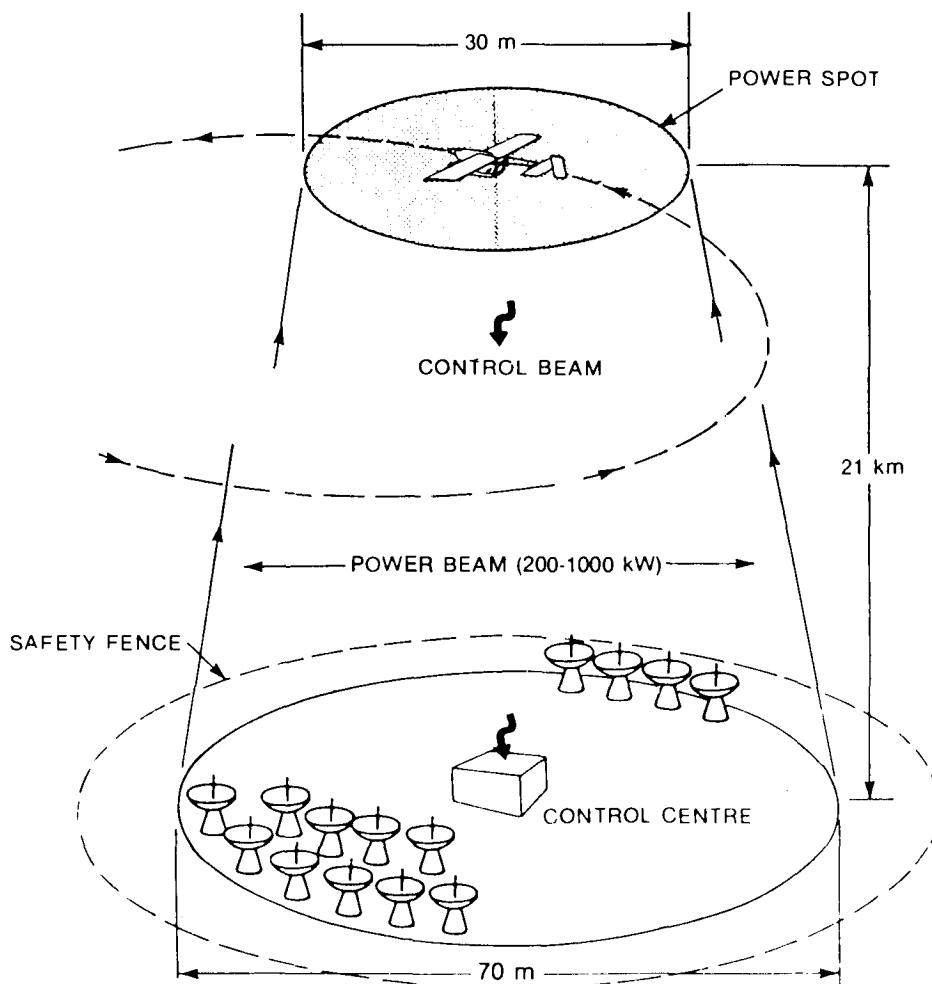


Fig.1 - Configuration Drawing of Stationary High Altitude Platform

transmission system³. Later, studies concerned with assessing the feasibility of the Solar Power Satellite (SPS)⁴ and the High Altitude Powered Platform (HAPP)⁵ found that magnetron power sources and various types of rectennas, operating at 2.45 GHz, could meet some of the requirements of microwave power transmission⁶. In the same timeframe, P. MacCready and his colleagues at Aerovironment and Astroflight, demonstrated that a manned lightweight airplane, Solar Challenger, powered by only 4 kW of electric power collected on solar cells, was capable of flight across the English Channel⁷ (Figure 2).

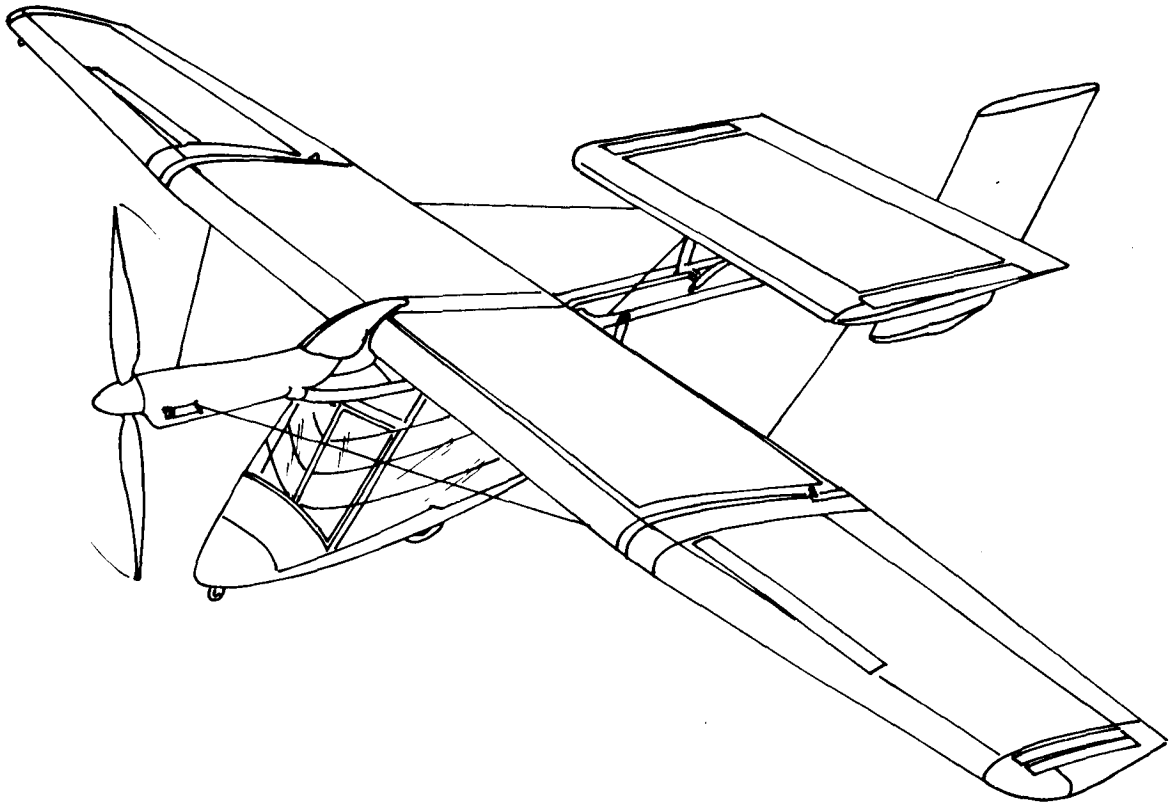


Fig.2- Solar Challenger

Successful flight of lightweight solar-powered airplanes coupled with development of lightweight brushless motors, has opened up new opportunities for electric-powered flight of unmanned airplanes. In principle, flight is now possible to altitudes previously inaccessible to conventional types of airplanes, provided only that a source of electric power can be made available, without incurring an excessive weight penalty. Today, a most promising choice is microwave power, transmitted from the ground to the airplane.

SHARP and **CO-OPS** propose to combine microwave powering and solar airplane technologies to produce airplanes with a flight endurance of many months, using microwaves as a weightless fuel. However, key questions remain unanswered. Among the most significant are: First, "Can lightweight airplanes be launched, flown on microwave power at altitudes well above jet stream winds and commercial air traffic and then safely retrieved after many months of operation?". Secondly, "Can **SHARP** airplanes carry out telecommunications missions in a cost-effective manner to

complement existing or projected terrestrial or satellite systems?". Thirdly, "What are foreseen impacts of microwave powering on the use of the radio spectrum and can legitimate environmental concerns be satisfactorily answered?".

This paper presents a summary report of preliminary studies now in progress at **DOC** to answer the first of these questions. The results reported here were obtained during the course of a recent study to assess the technical feasibility of the **SHARP** concept for Canadian application. The paper also summarizes results of some of the research studies designed to extend the state of the art in key technologies. Finally, the paper describes plans for flight trials of a scaled model airplane, designed to test the concept of microwave powering at low altitude.

2. BASELINE CHARACTERISTICS

Table 1 presents the baseline characteristics on which the feasibility assessment was based. The operational altitudes of 20 to 22 km place the **SHARP** airplane well above the altitude of commercial air traffic. It is also an altitude regime which exhibits a broad minimum in wind speeds. Average winter speeds have been found to be less than 25m/sec. at Canadian latitudes. On rare occasions, upsurges of the jetstream (normally at 10 km), result in wind speeds of 50m/sec. This has led to specifying the airplane design (max.) speed to be 60m/sec., with normal flight speed to range between 35 and 50m/sec.

Table 1- Interim Baseline Characteristics

AIRPLANE

Range of Operating Altitudes	20-22km
Radius of Containment	2km
Airplane Speeds (21km) max .	60 m/s
min .	35 m/s
Bank Angles, max .	$\leq 20^\circ$
Microwave Power Flux Density at A/C	500 w/m ²
Essential Services After Power Failure	Beacon
	Controls
	Min. Telecoms
Flight Endurance	6 mo.
Potential Antenna Stabilization	$\pm 1^\circ$
(Phase III Onwards)	

Standby power would be provided only to meet essential powering needs, excluding propulsion. These needs include powering of the airplane position location beacon, control sub-system and essential telecommunications.

The flight endurance is required to be greater than six months. Very extended flight endurance is a particularly important characteristic of the system. Achieving this objective would permit scheduling of airplane replacement to coincide with periods of favourable low and high altitude weather. In turn, this would increase platform availability and decrease platform depreciation rates.

It will be immediately obvious that the description of **SHARP** as a "**stationary**" platform is a misnomer when applied to use of airplanes as platforms. Unlike airships or helicopters (which were assessed at an early phase in the project), airplanes must move through the air to maintain lift. But it is equally obvious that, in order to increase the cost-effectiveness of microwave power transfer (and telecommunications relay), all airplane movements should be restrained as far as it is practical to go. In particular, excursions of the airplane from the zenith over the microwave power transmission system and variations of altitude of the airplane during its flight pattern, should be minimized.

The foregoing considerations have led to defining a station-keeping cylinder in space above the ground station with a diameter of 4 km and a depth of 2 km. The flight pattern will be contained within this station-keeping volume. The 4 km diameter corresponds to an operational angular beam steering range of $\pm 6^\circ$ at 21 km.

The maximum angular beam steering range is set at $\pm 10^\circ$ in order to permit acquisition of the airplane by the beam during "**launch**" phases of flight. One proposed, but untested method of launch, is to piggy-back the **SHARP** airplane to an altitude of 10 to 15 km, using a manned tug airplane. After separation from the tug, the **SHARP** airplane would continue its ascent to 21 km on microwave power.¹⁰

Morris⁸ carried out preliminary analysis of flight patterns for microwave-powered airplanes. His work has recently been extended by Gagnon to include flight strategies developed for the **SHARP** airplane⁹.

Figure 3 illustrates one pattern found by Gagnon to be optimum when the wind speed is less than about one half of the airplane ground speed. The airplane flies straight upwind and is provided with sufficient power to allow it to climb. Before reaching the edge of its station-keeping volume, it banks and turns downwind along a curved path (a portion of a cycloid) and descends as it completes a figure "D" pattern. Then it turns back upwind and repeats the pattern by flying straight and climbing. We note several features of this pattern. First,

when an airplane banks, it requires additional propulsive power to maintain altitude. Working against this, the directivity gain of the rectenna decreases during banking, because the angle of incidence of the microwave beam departs from the normal to the plane of the rectenna. Thus the power transfer efficiency drops. As a consequence, the dc power delivered to the motors will also drop unless the power flux density in the beam is increased to compensate for lower efficiency. The operational complexity of varying the power flux density whenever the airplane banks is avoided if, as illustrated, the airplane kinetic energy can be traded off against its potential energy to simplify operations.

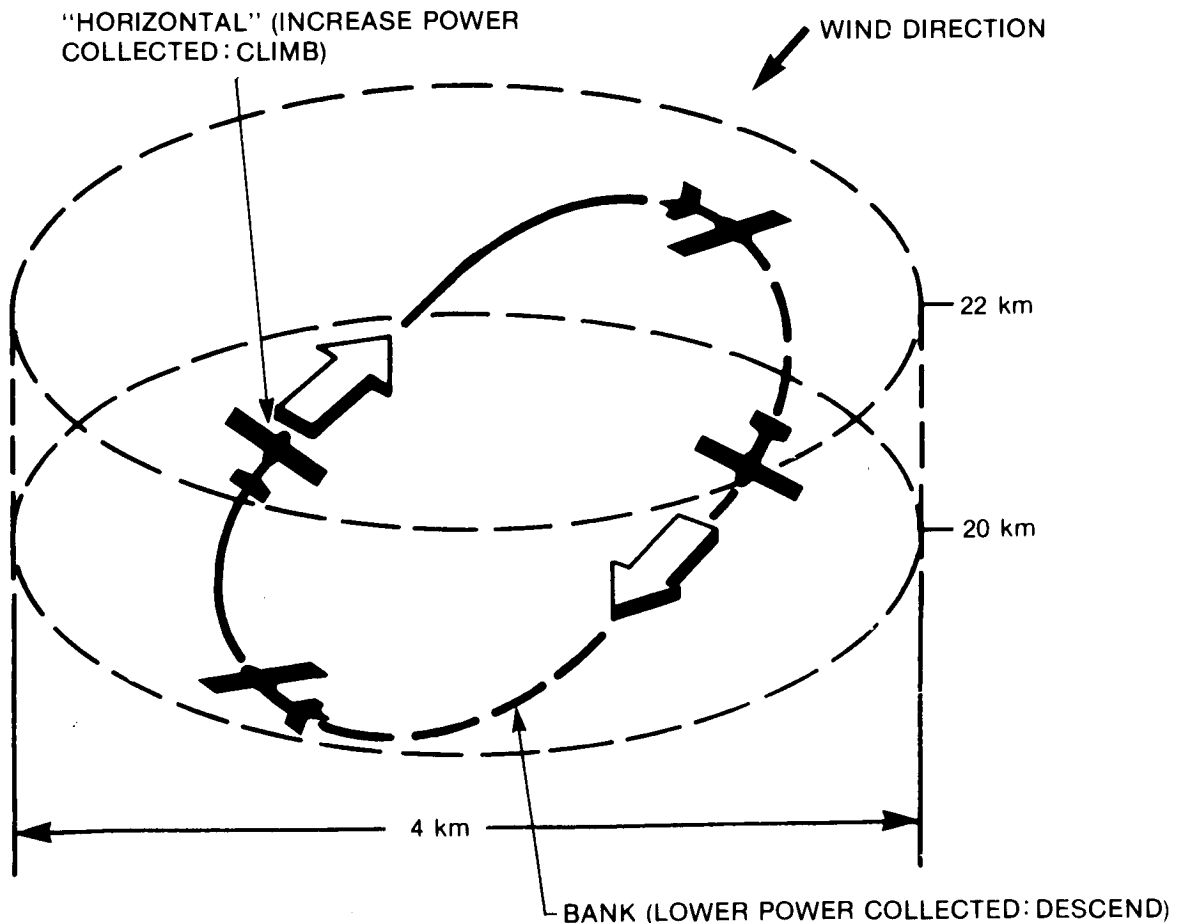
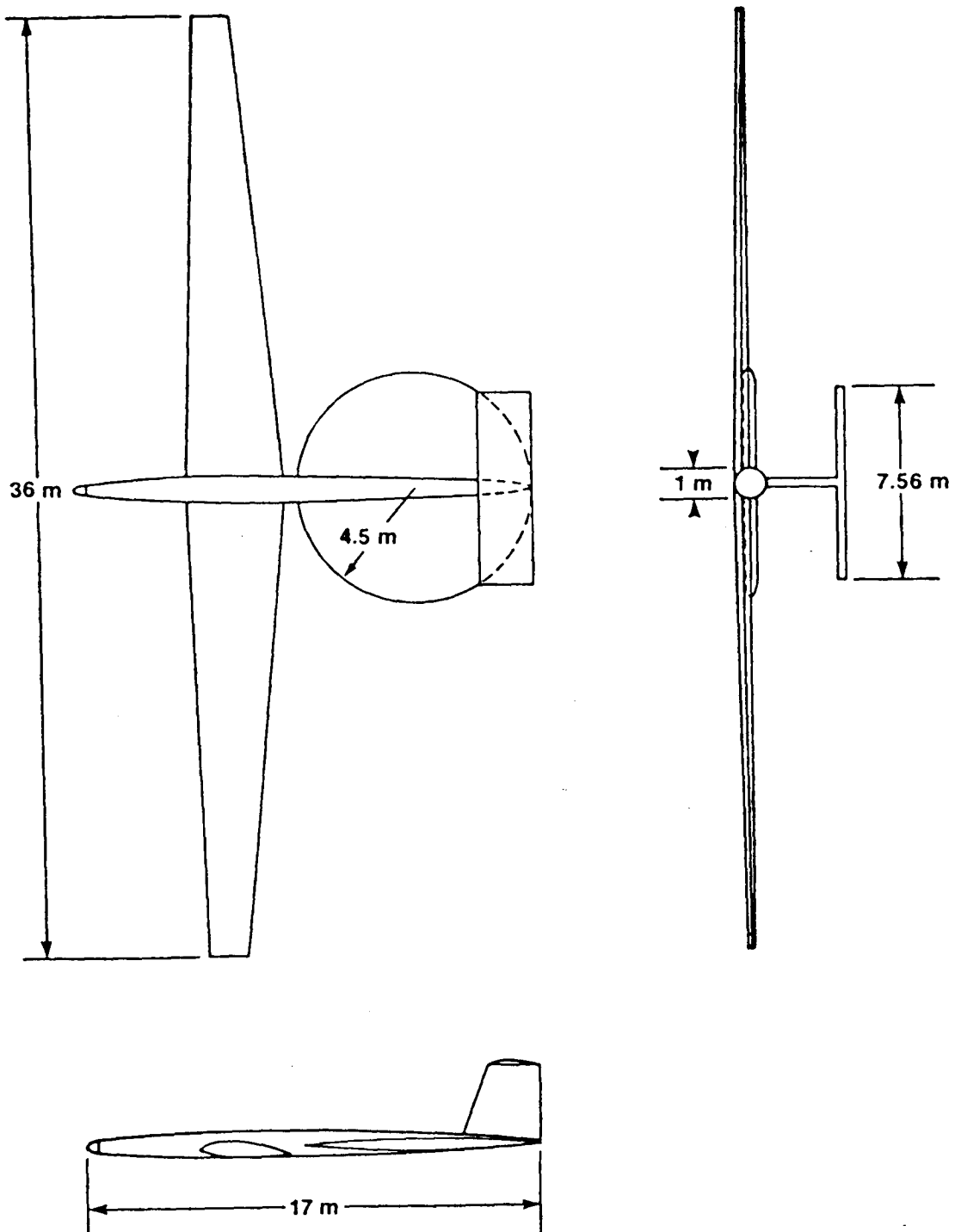


Fig.3- Figure "D" Flight Pattern for Constant Tx Power

Kinetic energy/potential energy tradeoffs could also be used to meet other short time power variations during systems operations. For example, should another airplane fly near the beam, the **MPTS** could be shut down for a few seconds or minutes with no appreciable effect on operations. On the other hand, if the **MPTS** were to be shut off for periods of greater than about ten minutes, the airplane would descend to the jet stream wind altitude, with the consequence that normal operations could not be easily restored.



ASPECT RATIO	14
WEIGHT	1260 lb
NORMAL OPERATING SPEED	162 ft/sec (49.5 m/s)
POWER FLUX DENSITY	216 w/m ²

Fig. 4- ISIS Airplane

3. AIRPLANE

To meet telecommunications mission requirements, the **SHARP** airplane is required to support a payload of 100 kg requiring 2 kW of dc power. The peak power flux density (**PFD**) at 21 km has been set at 500W/m^2 , within a half power (diffraction-limited) beamwidth of 30m.

A necessary condition for high efficiency of power transfer from ground to airplane is that the power collecting area of the airplane should closely match the cross sectional area of the focussed power beam itself. Figure 1 shows the virtual impossibility of achieving this with practical sizes and shapes of airplanes and typical diffraction-limited beamwidths. Aerodynamically-efficient airplanes have long thin glider-like wings and these would intercept only a small fraction of the power contained within a circular cross-section powerbeam.

DeLaurier and his research colleagues at **UTIAS**⁹ and J.F. Martin¹⁰ have investigated a variety of airplane configurations with power collection areas which are more closely matched to a circular cross-section, diffraction-limited power beam. One promising candidate is the configuration illustrated in Figure 4. This type of airplane combines aerodynamically-efficient long thin wings with a large circular disc for efficient power collection. (Because of its Sun-like shape, it is called "**ISIS**" after the Egyptian god.) This 9m diameter disc has an elliptical cross-section with a maximum thickness of 1m and is mounted on the fuselage of the airplane. The disc contributes no aerodynamic lift and would house rectennas.

Characteristics of this airplane are compared with those of a conventional airplane in Table 2. Calculations show that the **PFD** requirements for the **ISIS SHARP** are significantly lower than those of the conventional airplane, in spite of having 20% more weight and requiring almost 50% more propulsive power. The decrease in **PFD** arises from the improved efficiency of power transfer for the **ISIS** configuration.

*Table 11- A/C Characteristics**

	CONVENTIONAL (GLIDER-LIKE)	ISIS (GLIDER + DISC)
PAYLOAD/AVIONICS	100 kg/2kw	100kg/2kw
TOTAL WEIGHT	472 kg	572 kg
DESIGN PFD	428 w/m ²	330 w/m ²
NORMAL PFD	262 w/m ²	220 w/m ²
MAX.BRAKE HP	22 HP	32 HP
MAX.DC POWER**	20 kw	29 kw

* A.H. REYNAUD AND J.F. MARTIN

** INCLUDES 2 kw FOR PAYLOAD/AVIONICS

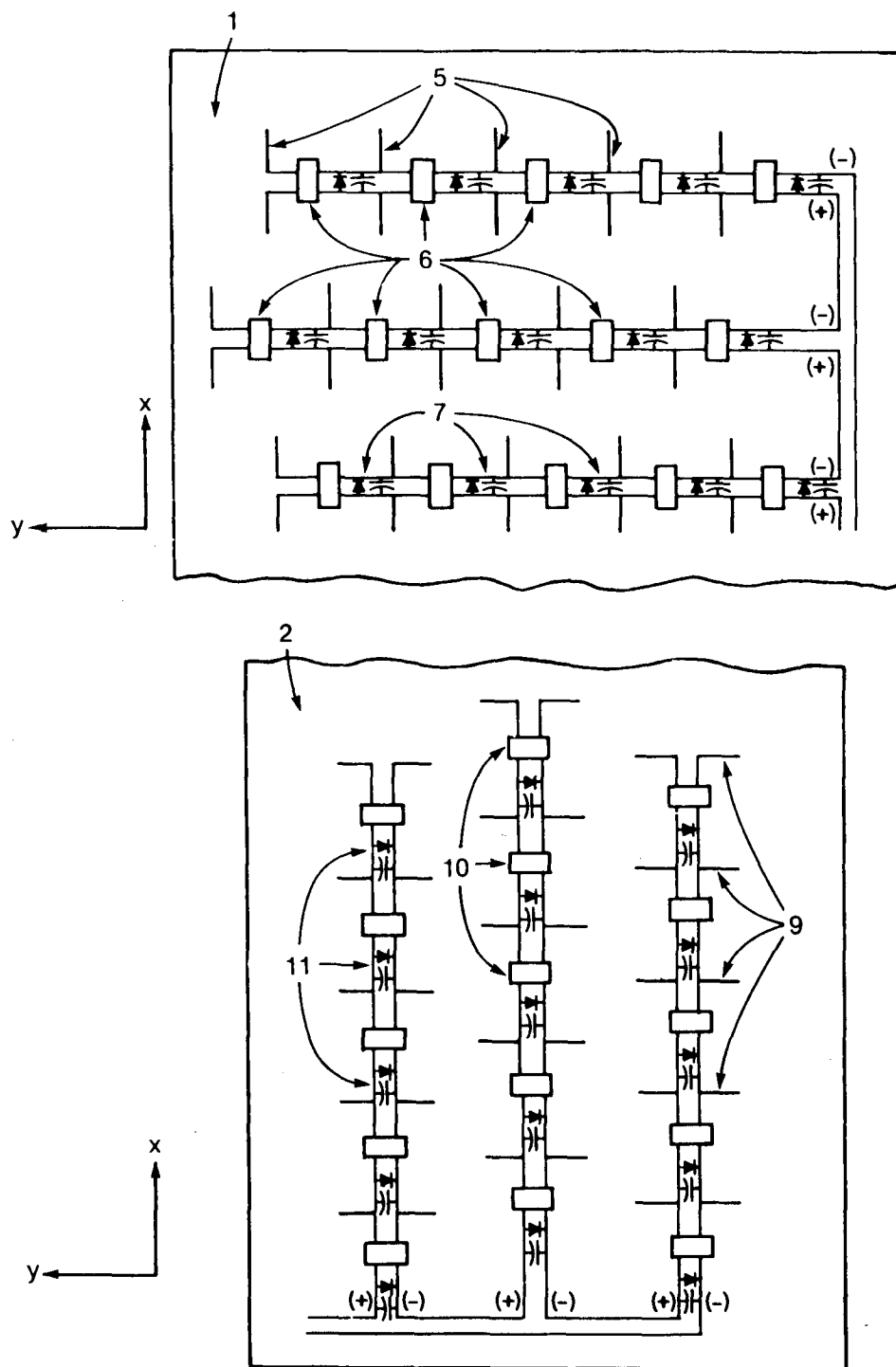


Fig. 5A- Foreplanes of Dual-Polarization Rectenna

4. RECTENNA

In a recent history of power transmission by radio waves, W.C. Brown described the evolution of the rectenna from a hand-crafted array of dipoles and diodes in the 1960s to the film printed circuit format of today.¹¹ This new type of rectenna, which was developed by Brown, is well suited to aerospace applications. Its low weight (only a small fraction of a kg per square m), and printed circuit format (which lends itself to mass production), are required for application to **SHARP**.

Figure 5A illustrates the two foreplanes of a CRC-designed dual-polarization version of this rectenna. This type of rectenna is capable of receiving and rectifying either circularly polarized waves or linearly polarized waves, with relatively high efficiency (as discussed below). Each foreplane consists of an array of half wave dipoles, and power collecting bus lines which have been photoetched onto a Kapton substrate. These have a density of about 200 dipoles per square meter at 2.45 GHz. Rectifying diodes and filter sections are associated with each dipole. By terminating each dipole with a diode, the dipoles are essentially isolated from each other at microwave frequencies (except for secondary coupling effects). Therefore, the array exhibits a directivity which is essentially that of a single halfwave dipole.

Figure 5B illustrates the positioning of the two orthogonally-polarized foreplanes 1 and 2 and a reflector plane 4, of the dual-polarization rectenna. One foreplane overlays the other, but they are electrically isolated. The reflector plane is about a quarter wavelength behind the foreplanes.

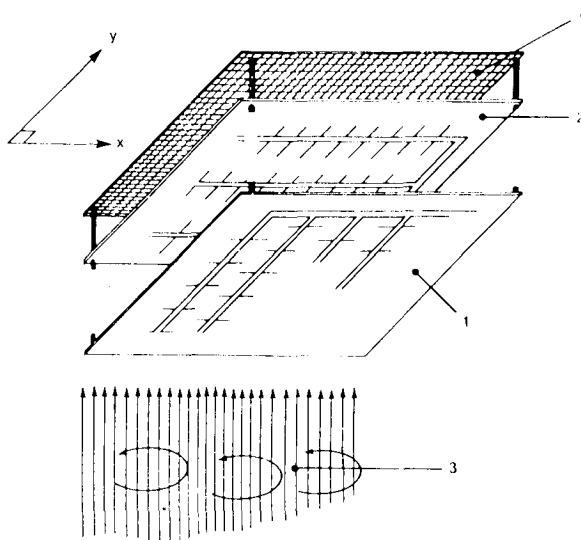


Fig. 5B-Positioning of Foreplanes of Dual Polarization Rectenna

Results of evaluation tests for various types of 2.45 GHz, thin film rectennas, are presented in Table 3-I and Table 3-II. The first type evaluated was a one square metre linearly-polarized rectenna designed and supplied by Raytheon, Waltham. It was constructed with high power Schottky **IMPATT** diodes. The performance of this rectenna was tested over a microwave **PFD** range from 100W/m^2 to 450W/m^2 . The rectenna was convection-cooled in a manner to simulate flight at operating altitudes. For several tests, the **PFD** was raised to produce a dc output of 700W/m^2 . The dual-polarized rectenna designed by **CRC** was constructed with lower power **HP2900** Schottky diodes supplied by Hewlett Packard. This type of rectenna was found capable of delivering a dc output power of 100W/m^2 . Table 3-I also presents the required peak dc power loading for a 21 km airplane platform, and "**Stagger SHARP**" (30W/m^2). (Stagger SHARP is a low altitude demonstrator airplane discussed below).

*Table 3-I 2.45 GHz Thin Film Rectennas**

DIODE TYPE		RAYTHEON IMPATT (W.C. BROWN)		HP 2900 (CRC)	
MAX. DC POWER/DIODE		3.5 W		0.25W	
ARRAY POLARIZATION		LIN.	CIRC	LIN.	CIRC
DIODE DENSITY		200/m ²	400/m ²	200/m ²	400/m ²
MEAS. DC POWER/m ²	FULL SCALE	700W/m ²		50W/m ²	100W/m ²
	SIMUL.				
BASELINE DC POWER/m ²	21 km PLATFORM	450W/m ²			
	STAGGER SHARP			30W/m ²	

**Unpublished results of Alden, Ohno, King, Nishizaki*

Table 3-II presents results of preliminary measurements of conversion efficiency and electromagnetic interference levels generated by these rectennas. For the Raytheon-supplied rectennas, simulated tests of a small array found that conversion efficiencies of up to 83% could be achieved, in agreement with earlier measurements by Brown. However, J.King and T.Nishizaki found that this rectenna reradiated out-of-band signals at high levels. These signals arose from use of the **IMPATT** diodes, and appeared to be reradiation of cross-modulation products. The levels of these were between 20 and 30dB below the reflected 2.45 GHz. In addition, second harmonic signals were found to be about 40 dB below the reflected **PFD**. By way of comparison, rectennas, using **HP2900** diodes, were found to have conversion efficiencies of only up to 72% (for linearly-polarized waves incident on the linearly-polarized rectenna). On the other hand, no out-of-band cross modulation spurious signals were measured for these rectennas.

*Table 3-11 2.45 GHz Thin Film Rectennas- 11**

DIODE TYPE		RAYTHEON IMPATT (W.C. BROWN)	HP 2900 (CRC)
MAX. RECT. EFF.	FULL SCALE	81%	
	SIMUL.	83% (LIN)	72% (LIN)
EMI LEVEL WRT REF. 2.45	X-MOD	- 20 TO - 30 dB	< -60 dB
	2ND HARM	- 40 dB	- 50 dB

**Unpublished results of Alden, Ohno, King, Nishizaki*

At the same time, the levels of second harmonic reradiation were found to be about 50 dB below reflected 2.45 GHz, as for the rectenna using **IMPATT** diodes. These measurements lead to the conclusion that, as of the present, we have not identified a thin film rectenna configuration which can meet baseline characteristics.

5. MICROWAVE POWER TRANSMISSION SYSTEM (MPTS)

In 1983, Miller Communications carried out studies on the performance of low cost oven magnetrons as power sources for a large **MPTS** array operating at 2.45 GHz. A **PFD** of 500W/m² at 21 km would require an array of 200 elements, each element consisting of a 5m diameter antenna fed by a 5kW source. This approach to meeting powering requirements appears attractive for medium term system implementation. Other approaches, using readily-available klystron sources, have been examined for near term implementation. The characteristics of some near term options, examined by R. Milne and R.M. Turner, are presented in Table 4.

*Table 4 Microwave Power Transmission Options**

ISM POWERING FREQUENCY	ANTENNA		POWER SOURCE	
2.45 GHz	NO.	APERTURE	NO.	POWER
	7	32 m	7	150 kw
5.8 GHz	7	12 m	7	150 kw
5.8 GHz	1	32 m	7	150 kw

**R. Milne, R.M. Turner*

It was found that there is a clear technical and cost preference to use the **ISM** frequency of 5.8 rather than 2.45 GHz for power transmission. Capital and operating cost reductions of between 25% and 50% of the **MPTS** could result from a choice of 5.8 GHz. These savings arise mainly because of the significant reduction in antenna aperture (a factor of greater than two), to meet the 30m power beam aperture requirement at 21 km. Studies of various methods of phasing the output power from each array element are now in progress. Interferometric and retrodirectional techniques are under investigation.

6. LOW ALTITUDE FLIGHT TESTS

Experience with microwave-powering of airplanes is being gained through a series of experimental flight tests, starting with a small airplane flying at low altitude. The initial requirement was for an easily-controlled model airplane which could fly on low microwave power levels. Researchers at **UTIAS**, working in collaboration with **CRC**, designed and constructed the 1.3m wing span airplane* illustrated in Figure 6. At first glance, this biplane configuration is reminiscent of airplanes flown over 75 years ago by the Wright brothers at Kitty Hawk and McCurdy at Baddeck, Nova Scotia. Its biplane configuration is very stiff and lightweight, and so it is able to fly on low propulsive power (as did early biplanes). Inspection of the wings reveals the essential differences from earlier airplanes. Open-structured, dual-polarization rectennas are mounted on the lower surface of the wings. The upper surfaces of the wings are made of aluminized **Mylar** and act as reflector planes, located one quarter wavelength behind the foreplanes. The upper and lower wings are staggered with respect to each other by one wing chord so that rectennas on both wings can be exposed to the microwave beam. (Because of the stagger of the wings, the airplane has come to be called "**Stagger Sharp**").

The maximum **PFD** required to fly **Stagger Sharp** is within the power handling capability of the low power 2.45 GHz dual-polarized rectenna, which is used. Various configurations of arrays and single element power transmission systems will be tested. Initially the system will consist of a 6 kW power source feeding a steerable 4.5m diameter antenna. The system is illustrated in Figure 7. Video cameras will be used to determine the location of the airplane and signals from these cameras will be processed to provide input signals to steer the antenna onto the airplane.

In operation, the airplane will be flown up to its operating altitude, using onboard batteries for powering its motor. Then, after the batteries have been switched off and

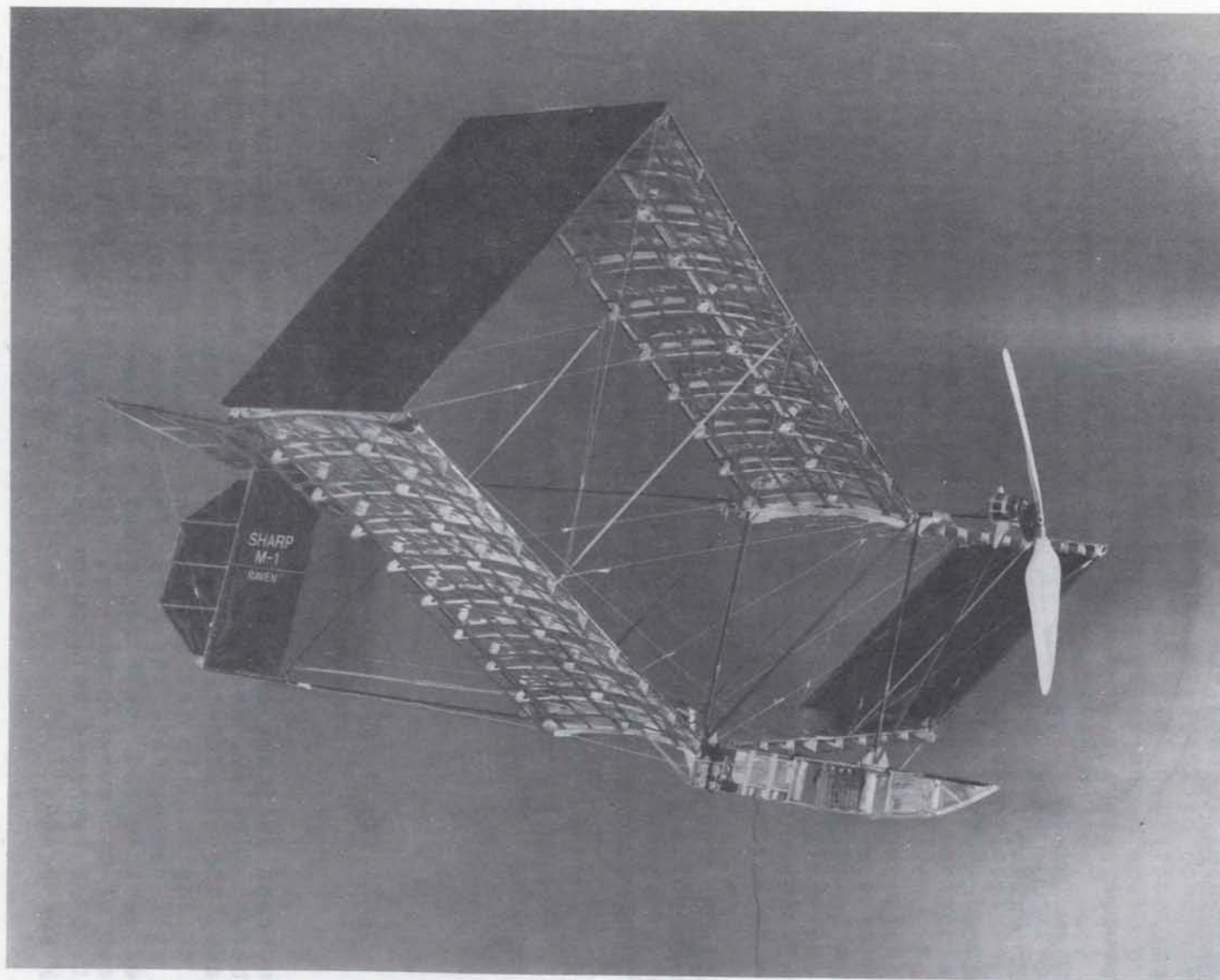


Fig. 6- Stagger SHARP Airplane Model

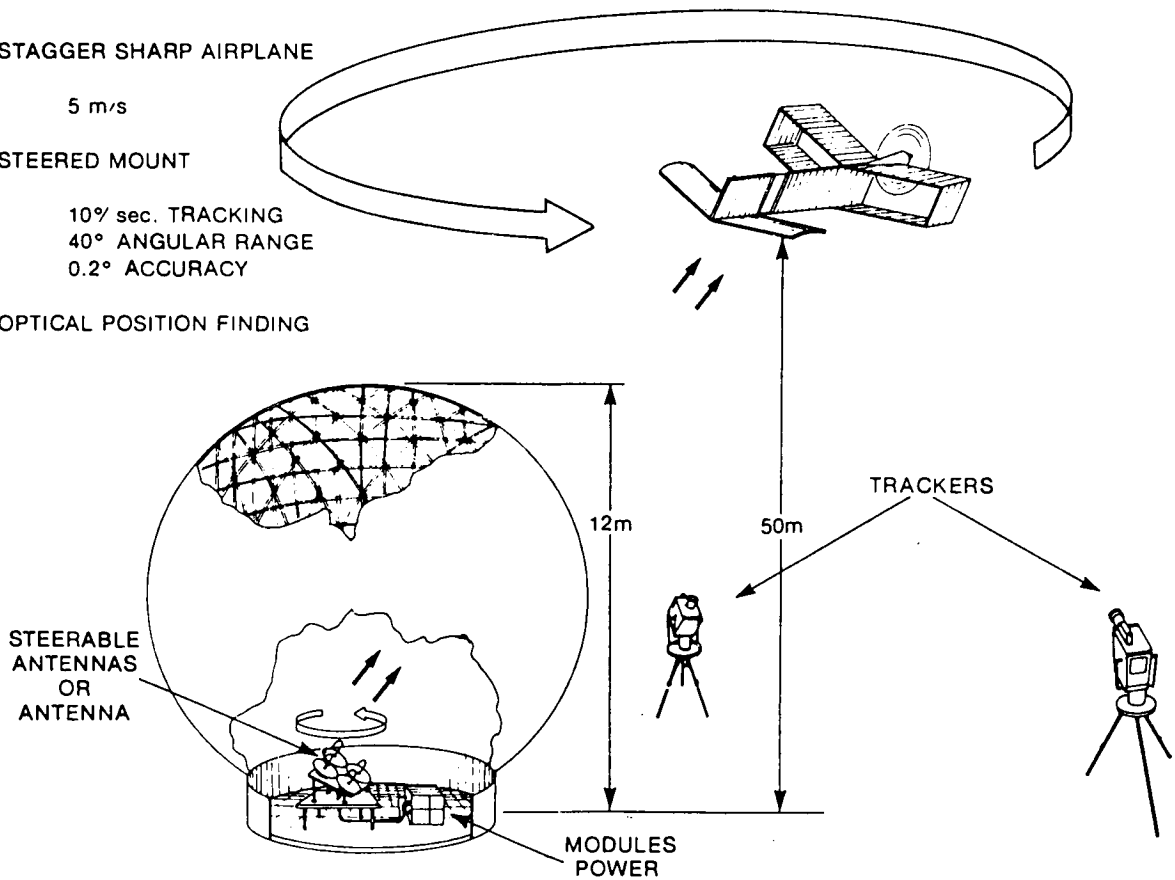
- STAGGER SHARP AIRPLANE

5 m/s

- STEERED MOUNT

10% sec. TRACKING
40° ANGULAR RANGE
0.2° ACCURACY

- OPTICAL POSITION FINDING



*J.J. SCHLESACK, CRC/DOC

Fig. 7 System to Demonstrate Free Flight of Microwave Powered SHARP Airplane

the rectenna switched on, the airplane will glide into the microwave beam. Finally, when the microwave beam has acquired the airplane, the airplane will be flown and tracked over a $\pm 20^\circ$ range of angles. To the best of our knowledge, these flight tests will demonstrate the first free flight of any microwave-powered vehicle and would represent a further milestone in the progress of microwave-powering. They will follow initial flights of a tethered helicopter carried out by Brown, some twenty years ago.¹¹

7. CONCLUSION

In conclusion, we return to the question raised at the beginning of this paper: **"Is the SHARP concept technically feasible"**? The DOC studies, to date, lead us to conclude that the answer is **"YES"**, with several important qualifications. There are no identified technical barriers which would preclude achieving microwave-powered flight within the next few years. In particular, the airplane and ground station for power transmission do not present insuperable problems. On the other hand, the concept is still at an embryonic state of the development. A variety of technical and operational questions must be answered before the relay platform concept is shown to be effective for various mission applications. In particular, the **EMI** characteristics of the rectenna must be improved. Further, there are a number of uncertainties related to operational aspects of flight at 21 km. Finally, there are uncertainties related to the performance of structural materials and motors over extended durations of flight at altitude. With some confidence, it can be predicted that these current uncertainties could be satisfactorily resolved within the next few years.

It will also be necessary to assess impact of wide scale use of microwave power transmission on use of the frequency spectrum. Finally, it will be necessary to resolve legitimate concerns related to health and environmental impacts of microwave powering.

8. ACKNOWLEDGEMENTS

The author acknowledges contributions by many **DOC** colleagues to this paper. Principal contributors have been identified in various references, figures and tables, and also in Table 5. Of particular importance, was the contribution of Dr. E.J. Hayes of the Space Technology and Applications Branch, who was leader of a project to assess the feasibility of the concept during 1984/85. Also, discussions over the past few years with Mr. W.C. Brown of Raytheon, Waltham, Mass., have helped spur progress in power transmission research in **DOC**. Finally, contributions by staff of **UTIAS**, Toronto; **SED Systems**, Saskatoon; Miller Communications, Ottawa and **CAL**, Ottawa, are acknowledged.

Table 5- ACKNOWLEDGEMENTS

STUDIES —	PREPHASE A FEASIBILITY	— E.J. HAYES (LEADER)
	PAYLOAD	— J. PALMER AND STAFF
	A/C	— H. REYNAUD AND STAFF
	POWER	— R. MILNE AND STAFF
	RECTENNA	— R. BONN YCASTLE AND STAFF
RESEARCH —	LOW ALTITUDE TRIALS	— J. SCHLESACK AND STAFF
	RECTENNAS	— A. ALDEN AND STAFF
	POWER Tx	— R. TURNER AND STAFF
	SYSTEMS	— A. LILLEMARCK AND STAFF

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