



INSTITUTE FOR AEROSPACE STUDIES

UNIVERSITY OF TORONTO

Final Report on Contract No. 12st-36000-4-4157

AERONAUTICAL RESEARCH ON SHARP AIRPLANES.

for

1984 and 1985

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Subject: Final Report for the Period covered by the referenced contract.

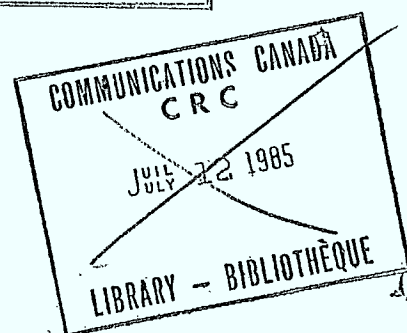
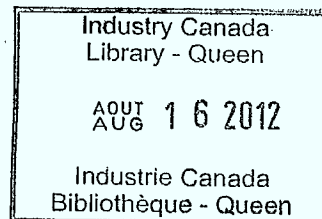
Reference: Contract No. 12ST.36000-4-4157, entitled "Aeronautical Research on SHARP Airplanes".

Scope:

The above referenced contract provided for the following tasks, pursued during the reporting period:

- 1) Slow SHARP and Stagger SHARP program.
- 2) SHARP Airplane Synthesis Program (SASP).
- 3) Airplane Configuration Research.
- 4) Propeller Research and Development.
- 5) Non-Linear Flight-Dynamics Program.
- 6) Flight Dynamics.
- 7) Flight Operations.
- 8) Future Research Activities.

Progress: The progress achieved during the reporting period is described as follows:



Rec'd from Dr. Jull July '85-

ABSTRACT

New lightweight aircraft structures, along with recent developments in efficient microwave-power transmission, have offered the possibility of high-altitude long-duration flying platforms. After initial consideration of balloons and helicopters, airplanes appear to be the most promising aircraft for this mission. Described in this paper is a theoretical study of suitable configurations, optimized between aerodynamic efficiency and microwave-power collection efficiency. A particularly promising design resulting from this utilizes an outsized stabilizer as a collecting area. Also described are the results from various launch and recovery scenarios through postulated "worse-case" wind profiles. Launching by balloon and recovering through a steep glide with "spoiled" flow appear to offer the best probability for success. Another theoretical study involves a non-linear flight-dynamic analysis, from which a zig-zag flight pattern is shown to give the most efficient mode for stationkeeping over a ground station, in relatively-high winds. Other work related to this program involve both analytical and experimental evaluation of optimum power-efficient propeller designs, and the design, construction, and test flying of a low-altitude slow-speed airplane, used for the demonstration of sustained microwave-powered flight.

INTRODUCTION

The purpose of this paper is to describe the research performed at the University of Toronto, Institute for Aerospace Studies (UTIAS), for the Communications Research Centre (CRC), on the development of an aeronautical platform for telecommunications-relay missions. This platform is required to fly in a station-keeping mode, for long duration (≈ 1 year), at a 21 km altitude. Specific mission details are described by Renaud and Martin¹; and in summary, the prescribed mission requires the vehicle to be remotely piloted and powered. Namely, an automatic flight-control system is needed to keep the vehicle in a defined "box" over its ground station. This system will have to incorporate the vehicle's flight-dynamic equations in a way which allows it to react to atmospheric perturbations with minimum propulsive-energy consumption.

Also, a major technological development has been the efficient transmission of microwave energy to light-weight rectennas. This development, detailed in Reference 1, has been the key factor in making the Stationary High-Altitude Relay Platform (SHARP) concept possible. The activities at UTIAS, since 1981, have been to define and study candidate vehicles which could best incorporate various rectenna designs and perform the SHARP mission with minimum propulsive power.

Initially studied were neutrally-buoyant vehicles, such as the high-altitude electric-powered airships described by Korn², and Mayer and Needleman³. The advantage of such craft is that power need not be expended to generate lift; so, for the low-wind environment which was assumed to exist at 21 km, sustained flight was possible for minimum power required. However, wind data from SED⁴ showed that 60 m/sec velocities are possible in Canadian latitudes during winter. With this as a

maximum-speed design constraint, airships were shown to be woefully unsuitable for all payloads considered (25 to 100 kg). "Wing-balloons" were also studied; but these offered no significant advantage over airplanes, and additionally raised helium-management questions.

Also, it should be mentioned that helicopters were studied, in 1983, for the SHARP mission. This research was not exhaustive; but the results obtained showed serious aerodynamic and stability limitations for a high-altitude rotary-wing craft. This direction was not pursued further, although the concept should not be completely dismissed for future work. Therefore airplanes, which generate their lift from forward flight, appear to be most suitable for this mission, and research has focused on identifying candidate configurations which could most efficiently incorporate the evolving rectenna designs from CRC.

Other researchers have also studied airplanes for SHARP-like missions. A comprehensive look at the suitability of all aircraft types was performed by Sinko,⁵ although the specific constraints and available technology for the SHARP program were not covered. Also, Lockheed Aircraft has developed, in detail, solar/battery-powered designs, the latest version of which is described by Hall.⁶ Brown's work on rectennas at Raytheon deserves particular attention, including his calculations in Reference 7 which showed the feasibility of microwave-powered airplane flight. Further, both solar and microwave-powered flight have been extensively studied by Youngblood and Jackson⁸ and Morris⁹ of NASA Langley. For most cases, point-to-point rectilinear flight has been assumed, and the candidate configuration is not exactly suited to the SHARP technology and mission; however, much of NASA's results and methodology have been most valuable to the SHARP program.

For the most part, however, the SHARP mission has evolved from different constraints and requirements than its American counterparts. This has resulted in research directions and accomplishments which differ significantly from other programs, as this paper shows. Namely, it has been considered important to balance theoretical work with wind-tunnel studies and proof-of-concept flight demonstrations. Therefore, this paper will describe a variety of activities, including a design-synthesis program, propeller research, non-linear flight-dynamic analyses, and a low-powered low-altitude microwave-powered demonstrator.

CURRENT RESEARCH ACTIVITIES

Slow SHARP and Stagger SHARP Program

In 1983, work was begun on a series of small flying model airplanes. The purpose of this program was to demonstrate the ability of a remotely-controlled airplane to fly on microwave power alone. Because of the low values of power-flux density available in 1983, it was required to develop a design which would minimize the power required for flight. Such an airplane would need a low wing loading, a broad capture area for the rectenna, an efficient propulsion system, including a gearbox and propeller, and a high value of "power factor", C_L^3/C_D^2 .

The first step in the design process was the choice of airfoil section. A thin, single-surface, highly-cambered airfoil (such as the 7.5% circular arc) was selected from DeLaurier¹⁰ to give good performance at low Reynolds numbers. This type of airfoil would also allow an external rectenna to be easily attached underneath.

This thin airfoil led to the choice of a biplane configuration. The wing box would provide torsional stiffness with a lower structural weight than a single wing with the same stiffness, and hence lower wing loading. A

more streamlined configuration would have had a higher value of maximum lift-to-drag ratio, but this was secondary to low wing loading. This is the same design philosophy that led to many early airplanes being biplanes. The biplane configuration could also incorporate vertical aerodynamic surfaces. These, coupled with high dihedral, would allow tight turns to be made with rudder control only.

The first airplane to be built was known as Slow SHARP, and is shown in Figure 1. This airplane evolved from a kite design which had low wing loading and was modular in construction (thus simplifying assembly and repairs). It had a span of 48", a chord of 9", and an overall length of 36". The first model was made from birch dowels and balsa wood, though for later models the dowels were replaced by balsa reinforced with carbon fibre. The wings, tail, and vertical surfaces were covered with 1/2 mil aluminized mylar. A Mabuchi motor was geared down to turn a balsa propeller, and power was supplied by Ni-Cad batteries. Controls and radio gear were conventional model airplane equipment.

The Slow SHARP model was tested in the wind tunnel, and the results are shown in Figure 2. This work, combined with flight tests, showed that level flight was possible on 3.7 Watts. The flight performance was only marginal however, and so a new design evolved.

The second flying model, shown in Figure 3, is known as Stagger SHARP, and incorporates a number of design changes. The major difference is a one-chord stagger of the wings, so that the lower surfaces of both wings are now exposed to the microwave beam, thus doubling the possible rectenna capture area. The aspect ratio was increased from 5.33 to 6.11 to improve aerodynamic efficiency, and a pod/skid was added under the nose, which houses the batteries and radio equipment. This enclosed pod produces less drag than the exposed equipment, and also protects the propeller when

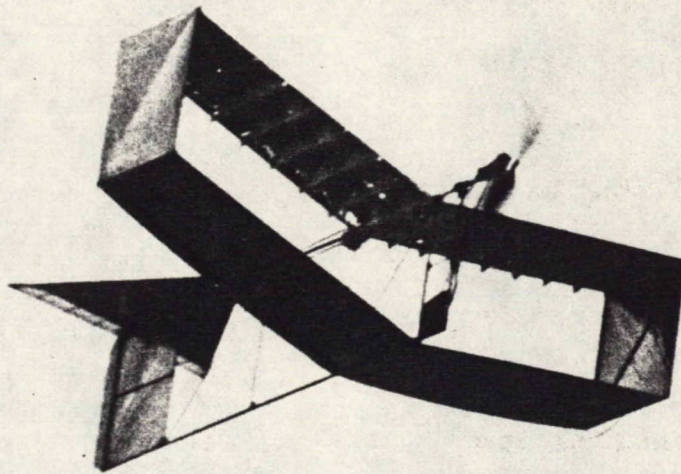


Figure 1: Slow SHARP during a test flight in 1983.

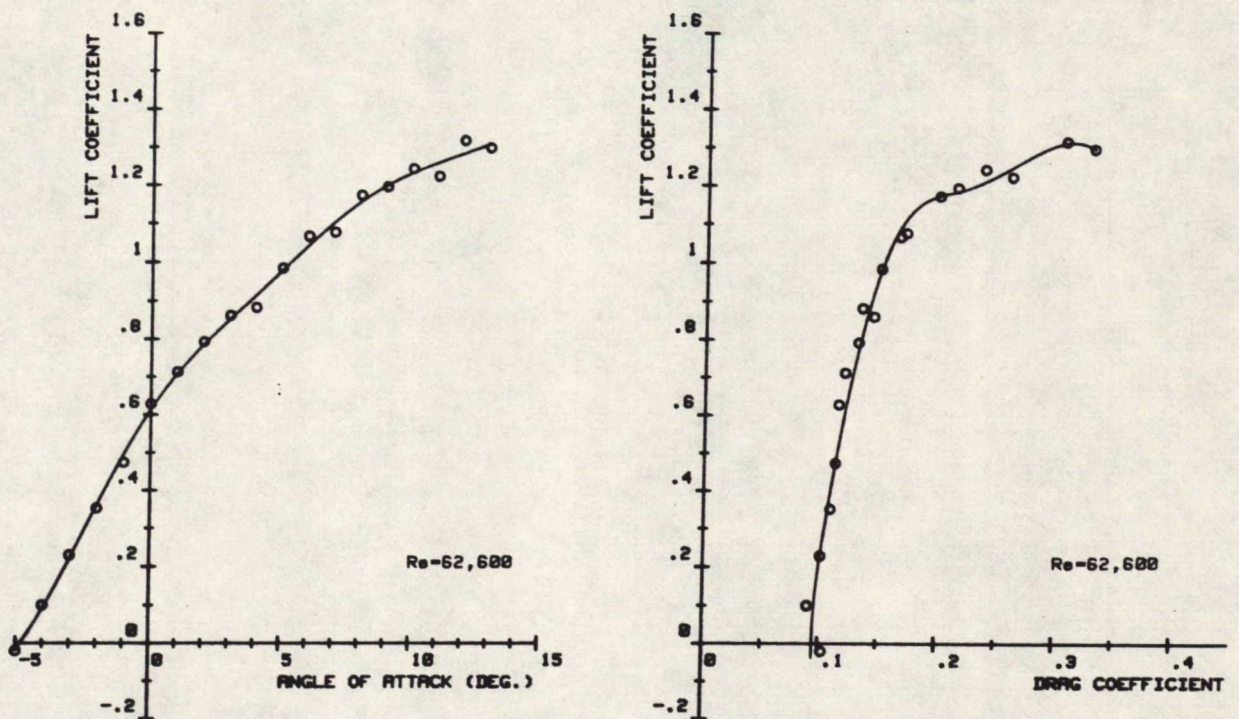


Figure 2: Results of wind tunnel test on Slow SHARP.

landing. Extensive use is made of carbon-fibre reinforcement. Finally, bracing wires were added from the wing trailing edges to the rear fuselage, to reduce flexing of the tail and hence eliminate control reversal of the rudder.

The results of wind tunnel-tests are shown in Figure 4. This work, combined with flight tests, showed that level flight was possible on 4.7 Watts. This slight increase in power required, when compared to Slow SHARP, is overcome by a more efficient gearbox and the increased rectenna surface. The flight performance of Stagger SHARP was also much improved. Flight duration is generally limited by battery life, but flights in excess of 5 minutes are regularly achieved, with altitudes of 100m frequently exceeded. The airplane is very stable, with a gentle stall. It is capable of very tight turns, and with fresh batteries had an impressive rate of climb. Figure 5 shows Stagger SHARP during a test flight.

Three models of Stagger SHARP are currently at the Communications Research Centre in Ottawa to undergo flight tests with microwave power. The strategy is to climb to altitude under battery power, then switch off the batteries and enter the beam for microwave-powered flight.

Although Stagger SHARP flies well, it has several limitations. Its low maximum speed of approximately 4 m/s requires calm weather. Also, the relatively fragile construction necessitates frequent repairs, as any bad landing produces some damage.

As will be further discussed, current work on the SHARP program involves the design of a second-generation flying model. This will be a low altitude microwave-powered demonstrator airplane, for flights over the existing ground station. It will be faster and more robust than Stagger SHARP, and will have greater payload capability.

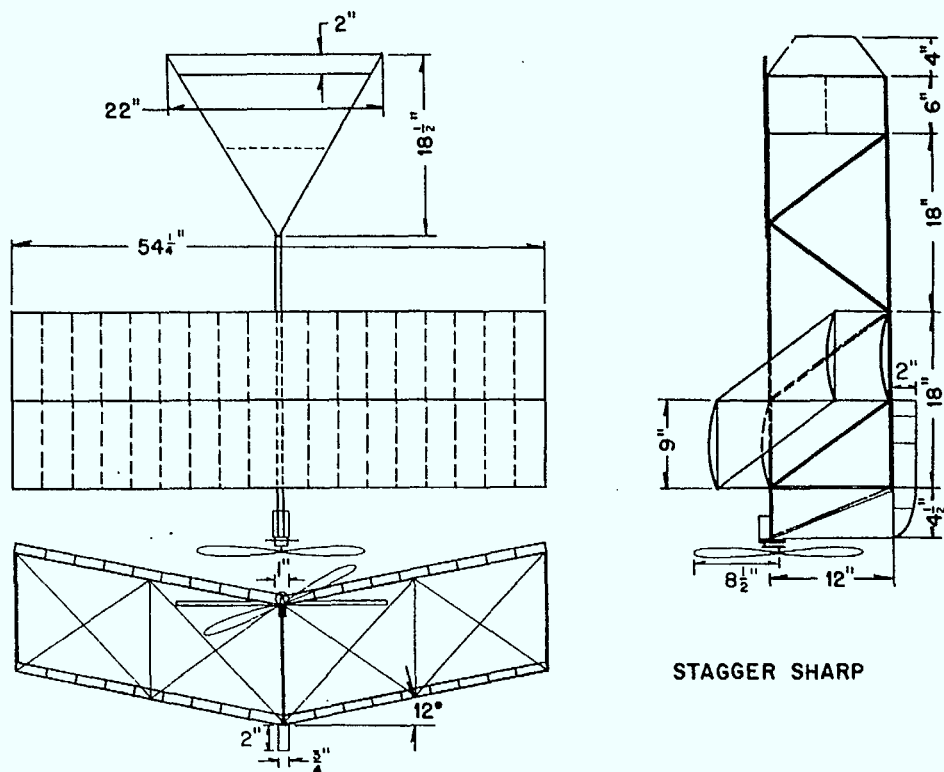


Figure 3: Stagger SHARP general layout.

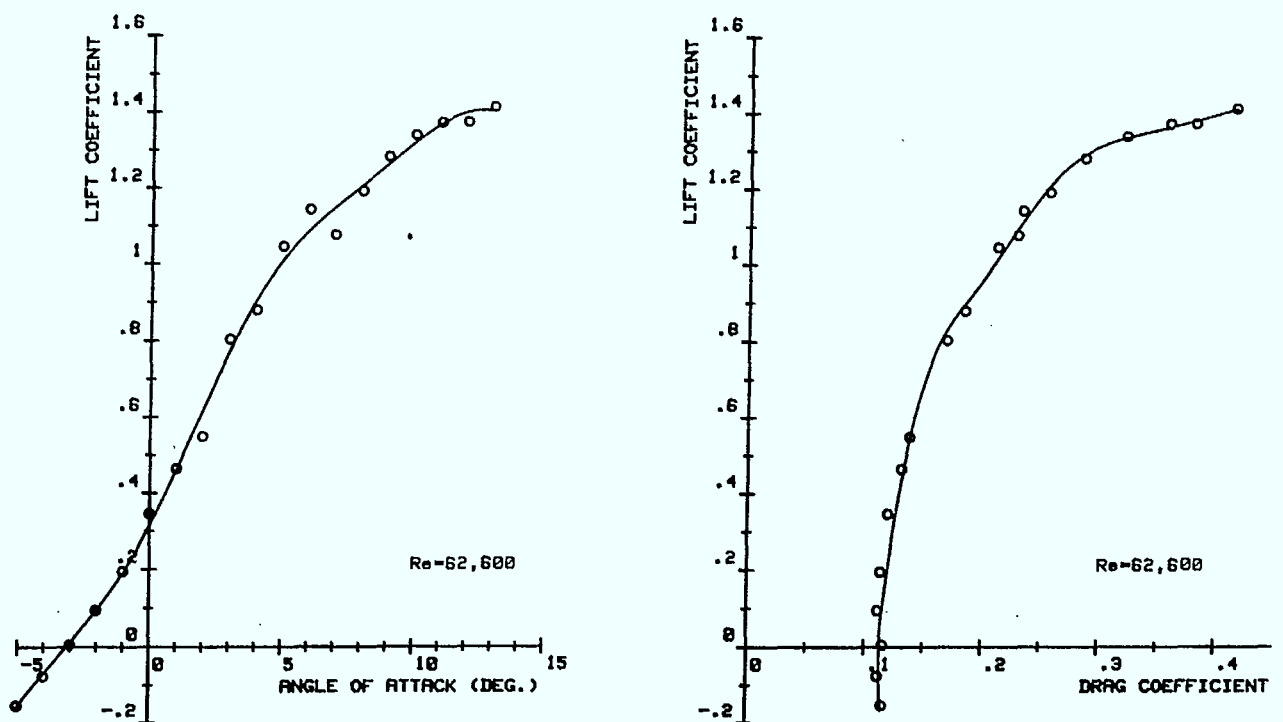


Figure 4: Results of wind tunnel tests on Stagger SHARP.

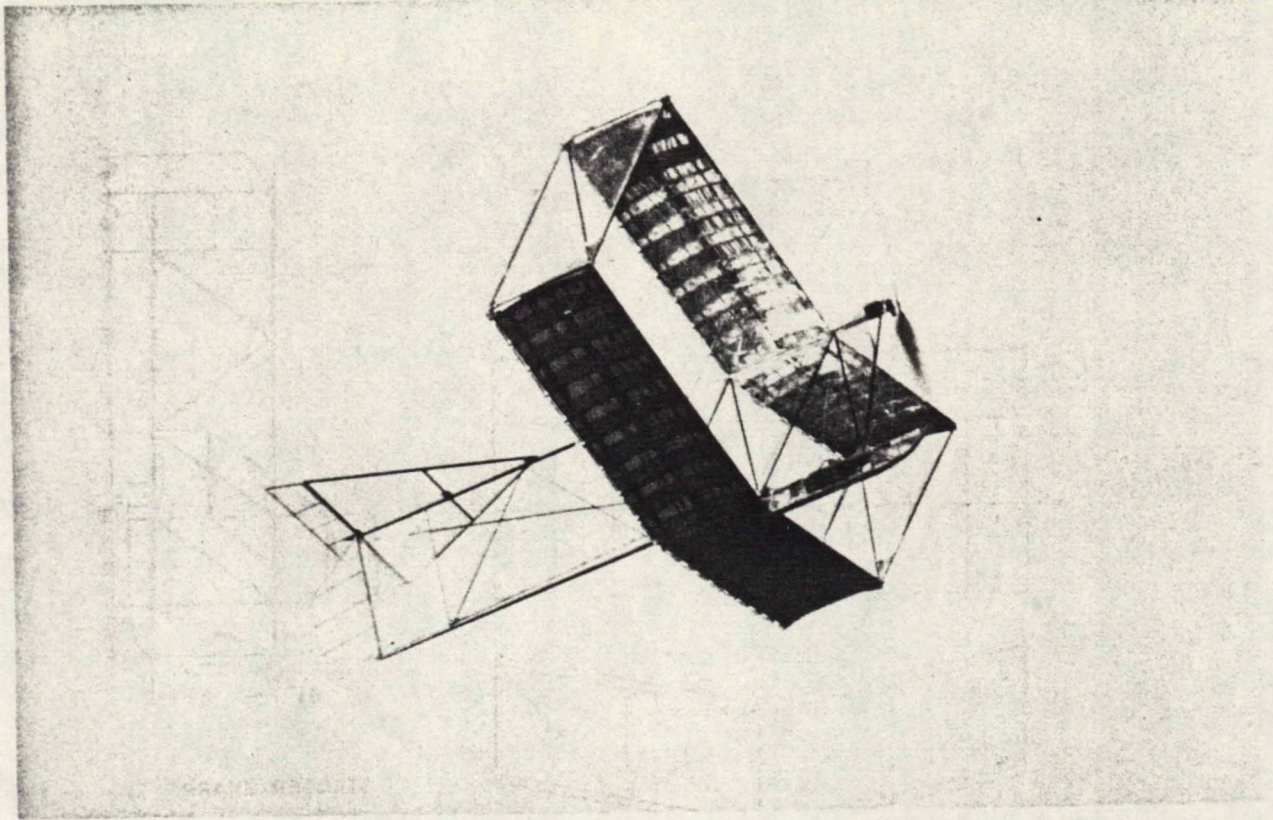


Figure 5: Stagger SHARP during a test flight in 1984.

SHARP Airplane Synthesis Program (SASP)

The problem of designing transport airplanes has been extensively studied. Configurations have polarized towards the now conventional wing-fuselage small-tail planform, and simple methods used in the initial design work have been developed for such airplanes. However, the design of a high-altitude relay-platform airplane, receiving its energy from the ground via a microwave beam, is a problem that has just recently been addressed. Simple methods for estimating performance parameters specific to this application, such as the power reception efficiency (a function of the airplane's geometry), do not yet exist. Also unknown is which airplane layout is best in this case. These facts led to the decision to develop an airplane synthesis computer program specialized for this application, which would incorporate estimation methods which are sufficiently elaborate to

accurately evaluate all the performance parameters required for the optimization of most of the possible configurations.

The methods included in this program, called the SHARP Airplane Synthesis Program (SASP), are as follows:

1) Aerodynamics:

- The induced drag: Weissinger's lifting-line theory is used to calculate the induced drag of each lifting surface at its proper lift coefficient for trimmed flight with a given static margin. Weissinger's method is also used to evaluate the spanwise lift distribution, lift-curve slope, and pitching moment due to sweep of each lifting surface.
- Airfoil drag: The airfoil drag of each lifting surface is evaluated by a spanwise integration of 2-dimensional wing section drag coefficients found, at the previously calculated local lift coefficient and Reynolds number, in a table of wind tunnel data. Interpolation between lift coefficients and Reynolds number is done linearly.
- Fuselage and boom drag: The conventional friction drag coefficient method is used to estimate the drag of fuselages and tail booms. A small correction is applied for the fuselage's angle of attack.
- Trim drag: The trim drag is implicitly included in the calculation of the induced drag and airfoil drag.
- Interference drag: The interference drag is estimated as 5% of the total drag.

2) Weight:

Structural component weights are calculated with a collection of statistical weight estimation equations for aluminum structures found in Torenbeek¹¹ and Nicolai.¹² A factor of 0.73 is used, as

recommended by Nicolai,¹² to correct for composite materials. Also, flight control systems weights are also calculated with equations from the above mentioned References. The many examples of high efficiency samarium-cobalt electric engines indicate that the motor weight is approximately 1 kg/kW. Further, the rectenna weight is estimated by CRC as .325 kg/m² and the payload weight is specified.

3) Engine power:

The engine power is initially set equal to that required to fly level at the maximum airspeed, at the operational altitude. Then, if required, the power is increased iteratively such that a preset climb-rate requirement is met at the maximum lift-to-drag speed. This process requires new weight and drag estimations for each iteration.

4) Power Flux Density:

The SHARP airplane receives its power from a microwave beam transmitted from the ground. The intensity (power-flux density) of this beam must be sufficient for the aircraft to be capable of continuous flight at speeds greater than, or equal to, the maximum wind speed at the

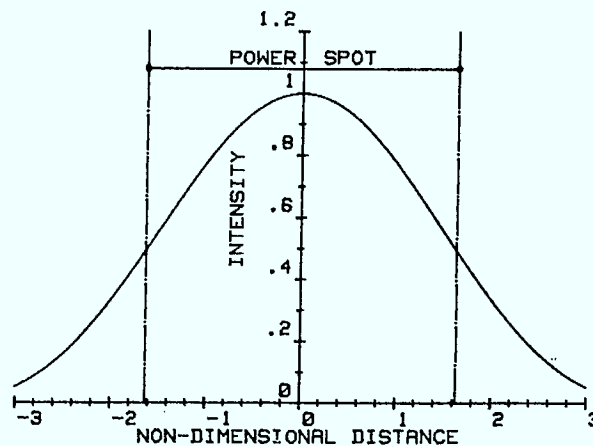


Figure 6: Normalized power-flux density distribution in the microwave beam.

operational altitude. Figure 6 shows that the distribution of the beam's intensity is not constant, and that rectenna surfaces near the centre of the beam should capture more energy than those further away, say at the tip of the wing. It then becomes important to calculate the efficiency of the airplane's planform for power reception. This efficiency is found by integrating the ratio of the local power-flux

density to that at the centre of the beam over the complete rectenna surface. This process is iterative because the best position of the beam's center on the aircraft must be found. The ground-station design power-flux density is then obtained from:

$$PFD_{\text{design}} = \frac{\text{Maximum Power}}{\text{Rectenna Area} * \text{Rectenna Planform Efficiency}}$$

where the Maximum Power is the payload and avionics power plus the maximum of:

- a) Power to fly straight and level at maximum airspeed.
- b) Power to climb at 100 ft/min (at maximum lift-to-drag velocity) divided by the minimum flight-pattern efficiency at that airspeed (discussed later).

5) Cost:

A cost estimate method put together by CRC is used to evaluate the Net Present Value (NPV) of the ground system and 10 years of operations. Nicolai's¹² airframe cost estimate method has been incorporated to take into account the effects of the size of the airplane. Two very important parameters in this method are the design power flux density and the power-flux density required at the maximum lift-to-drag speed. Usually, the first one is used to size the microwave beam transmission system and the second is the major factor in determining the energy expenditure.

The flow chart of this program is shown in Figure 7.

Airplane Configuration Research

The task facing the designer of a microwave-powered airplane is to find the perfect compromise between minimizing power requirements and maximizing the power reception. The first can be achieved by adopting a glider-type airframe with a high aspect-ratio wing. However, for power reception, a "flying disk" is best because it most effectively concentrates the rectenna around the microwave beam's maximum intensity region.

Some of the configurations proposed at the start of this research work are presented in Figure 8. Airplanes with the various types of wing gloves have now been discarded because of a peak in local lift distribution that leads to early stall at the break. All efforts to alleviate this problem have led to large induced-drag penalties.

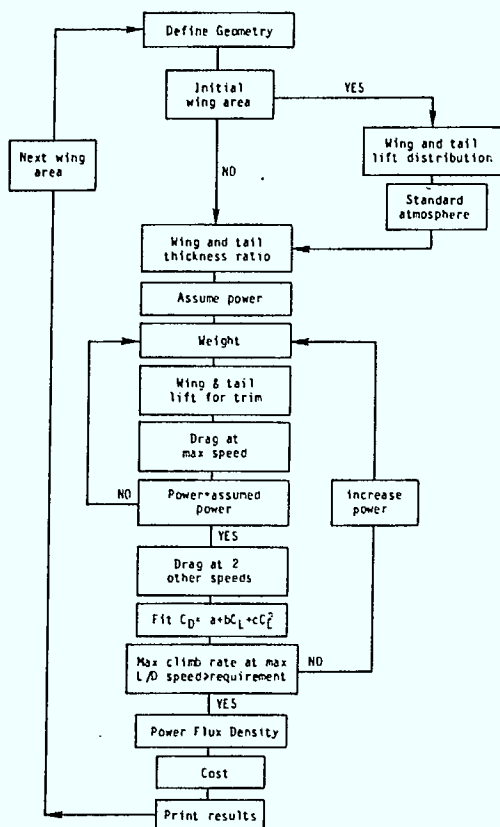


Figure 7: Flow chart of the SHARP Airplane Synthesis Program (SASP).

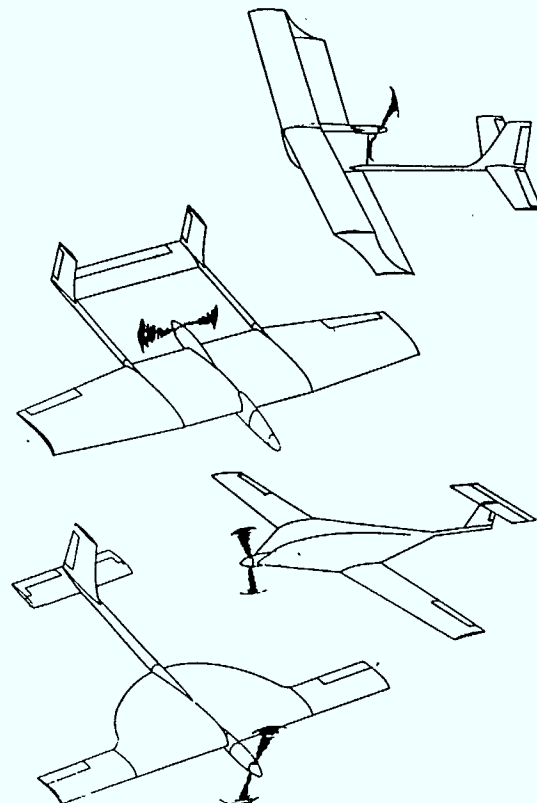


Figure 8: Some of the configurations initially proposed.

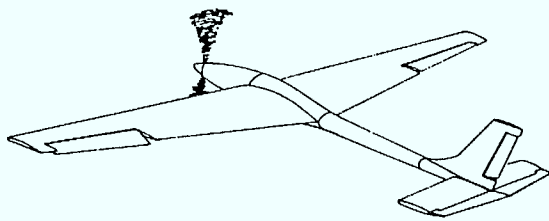
For this configuration research, CRC has selected a baseline payload of 100 kg and microwave beam radius at the half-intensity point of 15 meters. SASP results for the candidate airplanes are presented in Figures 9 to 11 (note that the airplanes are not shown to scale). For site cost comparison the glider-type airplane of Figure 9 has been selected as the baseline. It has a wing area of 100 m^2 , an aspect ratio of 10, a weight of approximately 950 kg, and its cost has been designated as the 100% mark. The rectenna surface is located in the wing and tail. Figure 9(c) shows that its maximum power-flux density required is 299 Watts/m^2 .

Early in this study it was realized that the microwave power reception efficiency of the horizontal tail could be improved by moving it near the wing, where the microwave beam intensity is greatest. The tail volume was kept at 0.6, as for the glider-type airplane, and this resulted in an increase in the tail area and weight. Aerodynamic interference problems between wing and tail were reduced by positioning them with a large vertical gap.

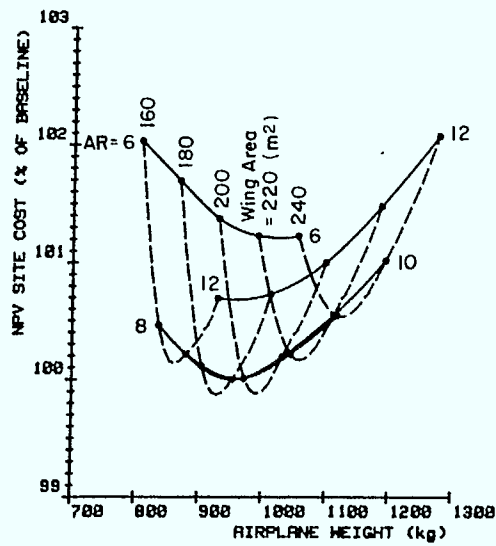
The results in Figure 10 show that site cost and power-flux density reductions can be obtained with this configuration. In percentage, the site cost variations appear small, however these reductions can represent millions of dollars.

This success with the close-coupled tail led to the idea that it might be advantageous to further increase its size. The resulting configuration is shown in Figure 11(a). Tail volumes from 0.6 to 2.2 were studied and the optimum was found to be 1.80. The results are shown in Figure 11(b) and (c). This configuration also offers other advantages which are:

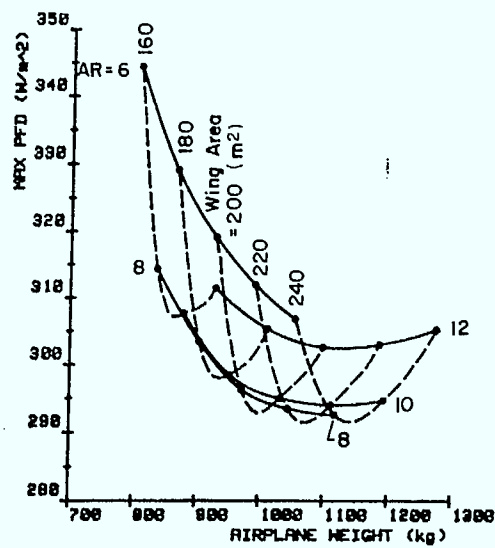
- (1) Drag reduction due to the pusher propeller, which can allow laminar flow over the central part of the wing.



(a)

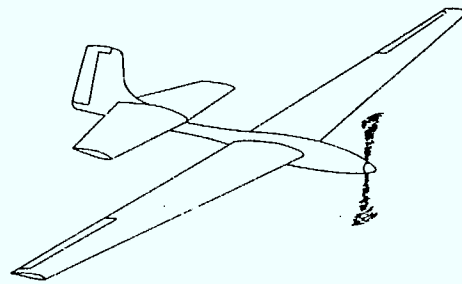


(b)

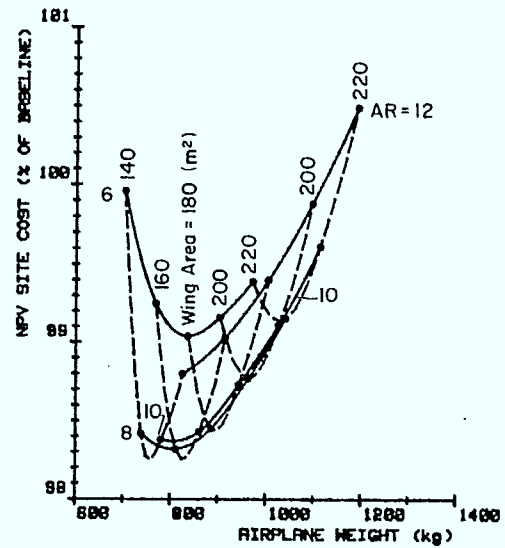


(c)

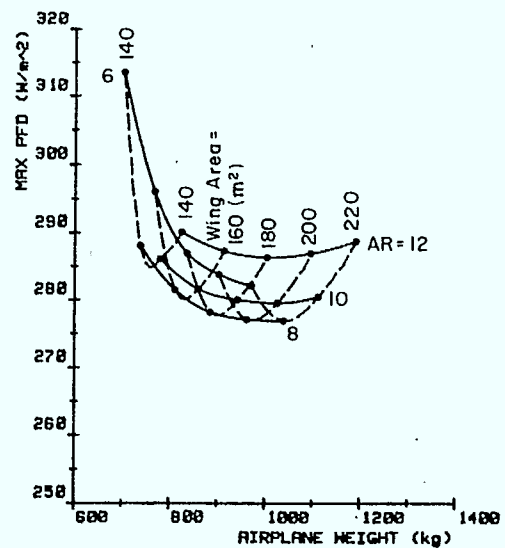
Figure 9: Baseline airplane.



(a)



(b)



(c)

Figure 10: Close-coupled tail layout.

- (2) The propeller can be folded rearward over the tail during a glide or landing, and is therefore protected from damage.
- (3) The neutral point is located far enough aft so that large flat antennas can be carried in the tail without upsetting the balance of the airplane.
- (4) The use of a payload-carrying pod mounted on a strut below the wing ensures that, during a turn, the inboard wing tip does not obstruct the telecommunication package's "view" of the earth.

Propeller Research and Development

The development of the SHARP airplane, with its long-duration mission, led to the requirement for a highly-efficient propeller as part of an optimized propulsion group. As with all propeller-driven aircraft, efficient propellers can lead to substantial reductions in the energy required to fly the airplane, whether it be fuel for piston or turbine engines, or electrical energy for electrically-powered aircraft.

Optimization of the motor and gearbox combination was primarily limited to a careful choice of motor and precise construction of the gearbox. The propeller, however, could be designed to be at an optimum for a given operating condition. Also, prediction of its performance in the region around that design point would be essential in the estimation of the airplane's performance.

The design of propellers having minimum induced loss is based extensively on the theory developed by Albert Betz and Ludwig Prandtl¹³ in 1919, who showed that, for minimum energy loss, the displacement velocity of the wake left by the propeller is constant over the radius of the propeller. This is analogous to the constant downwash condition for a wing having minimum induced drag. The design equations that were developed for the

minimum energy loss condition, however, lay unused by the aeronautical community until E. E. Larrabee¹⁴ put them into a straightforward procedure in 1979. Subsequently, Adkins and Liebeck¹⁵ made certain refinements to this work.

The performance prediction of propellers operating at off-design points is essential information for aircraft performance estimation, and two analytical methods were examined by Wong.¹⁶ The first procedure, which makes extensive use of the momentum and blade-element theory (also used for the design of propellers), is by far the simpler of the two. Basically, this method uses an iterative scheme to solve for the local flow angles along the propeller blade. Larrabee¹⁴ and Adkins and Liebeck¹⁵ suggest variations of this which are slightly different from each other, but both were found to give essentially the same results. The second method makes use of vortex theory, where the propeller was assumed to be a lifting line with a sheet of vortices trailing off in a helical wake. The induced velocities were calculated along the radius of the blade and hence the performance of the propeller could be determined. This approach resulted in a far more complicated analysis, which is reflected by the requirement for much more computing time. Agreement between both methods was good, but since the simpler momentum and blade-element analysis was significantly faster with comparable accuracy, it has become the preferred method.

Currently, wind-tunnel experiments are being prepared in order to obtain comparisons with the theories mentioned. The measured flight performance of the Slow and Stagger SHARP aircraft confirm the high efficiency of their propellers, designed from the Larrabee method. However, a wind-tunnel test will allow greater precision in the measured performance parameters, as well as giving a wider range of variables. Figure 12 shows an example propeller with its strain-gage balance, and Fig. 13 shows the wind-tunnel setup.

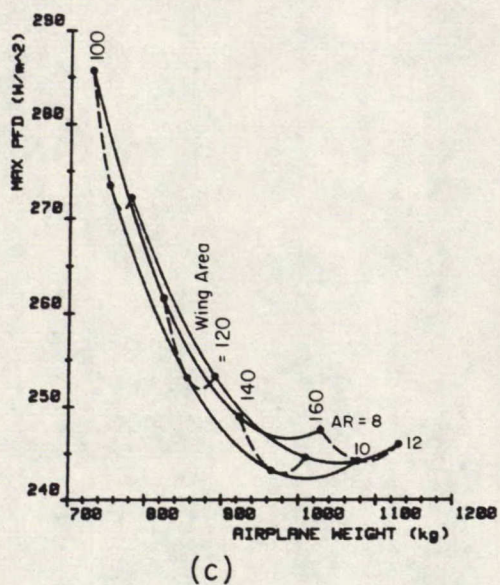
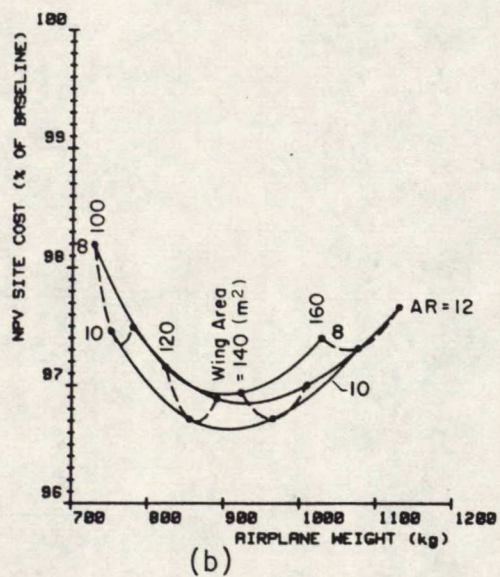
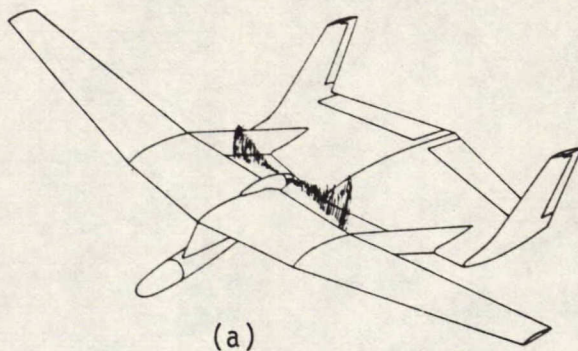


Figure 11: Large-tail configuration.

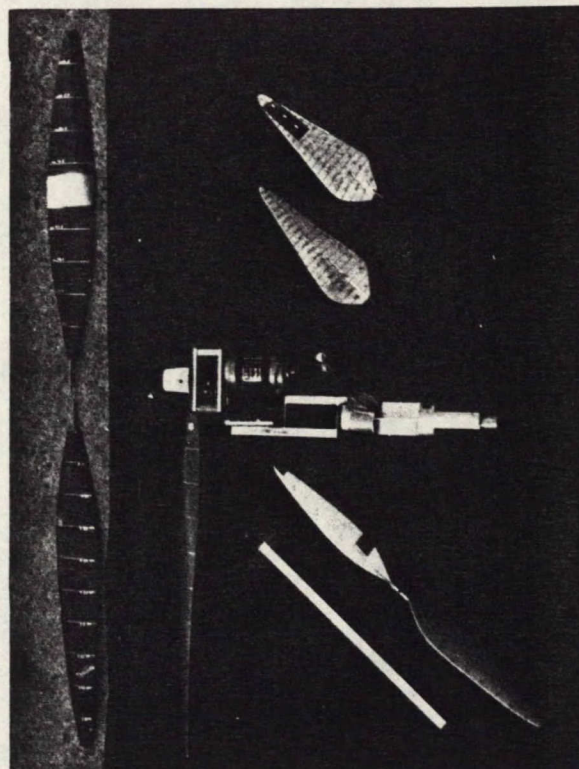


Figure 12: Example propellers and strain-gauge balance.

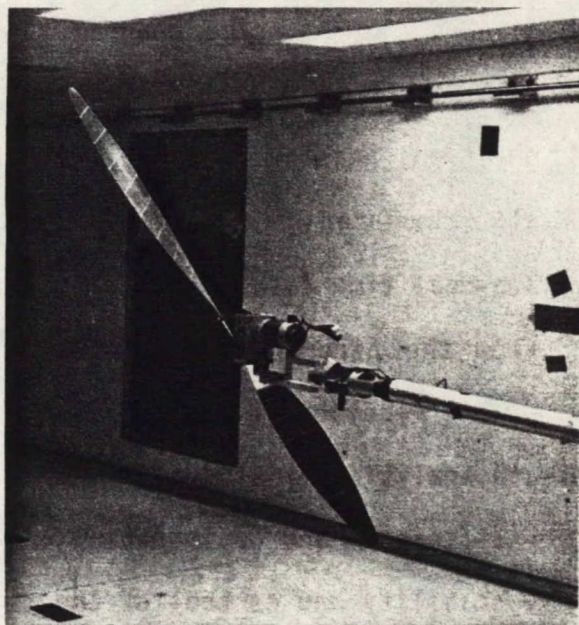


Figure 13: Wind tunnel setup for propeller tests.

Non-Linear Flight-Dynamics Program

Due to the tracking limitations of the microwave beam, the aircraft is constrained to fly within certain boundaries, described by a circular containment box. Several typical containment boxes are shown in Figure 14, including the maximum circle with radius 2200 meters (21 km altitude), corresponding to a maximum beam angle of 6° . The path that the aircraft

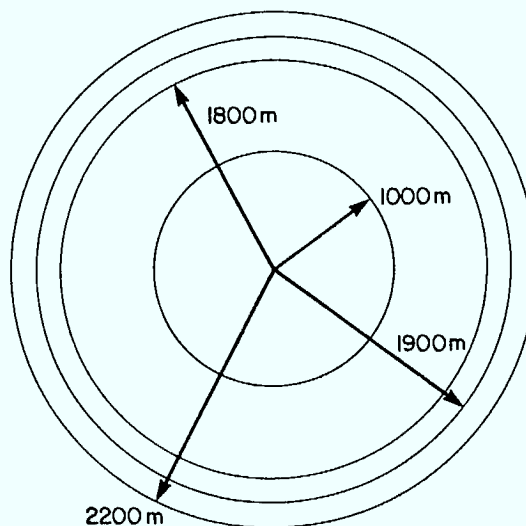


Figure 14: Flight path containment boxes.

flies must be within this box, and be optimal with respect to power consumption and reception. In order to aid in the investigation of candidate aircraft and to study possible flight paths, a computer program was developed by Eert¹⁷ which provides a non-linear flight simulation of a given aircraft. The program allows for easy definition of an aircraft as well as its desired flight path. The aircraft's attitudinal motion, position, heading, control system, and power (i.e., the rectenna system) are all simulated. Thus the program 'flies' the candidate aircraft in a non-real time fashion.

From the aircraft's position, speed and attitude outputs, as well as the power 'received' by the aircraft through the simulated rectenna system, one can analytically study:

- efficiency and optimization of flight paths
- stability and control of the aircraft
- system characteristics and tradeoffs
- the control actions required to enter and maintain a prescribed flight pattern

One application of this simulation program has been the analysis and optimization of flight patterns based on the time average of the power reception efficiency. In this analysis only the rectenna efficiency was studied, this being a function of the attitude of the rectenna surface with respect to the microwave beam. The two flight paths compared were the figure 'D' and the figure 'Z'. Figure 15 shows these patterns as defined in the frame of reference moving with the wind vector (the air frame), and as defined in the ground frame of reference.

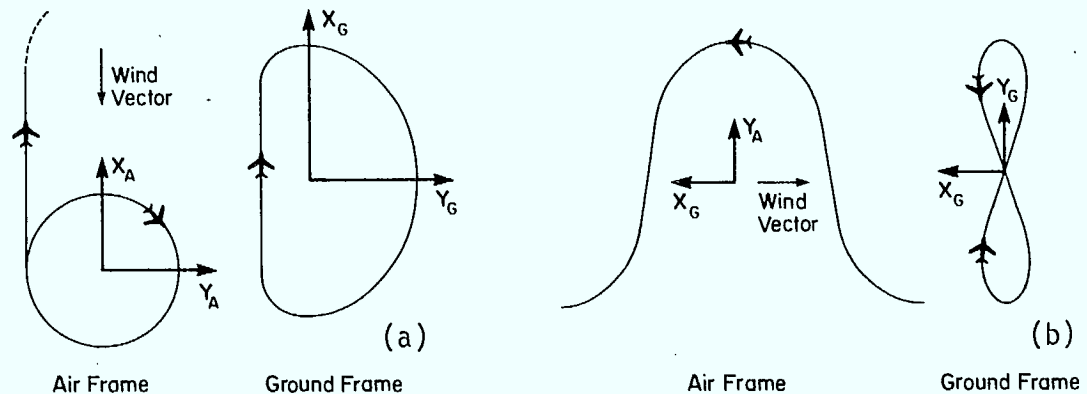


Figure 15: (a) Figure "D" flight path.
(b) Figure "Z" flight path.

The results showed that, at low wind speeds, figure 'D' patterns are generally better from a power-reception efficiency point of view, and at high wind speeds, the figure 'Z' patterns are better (see Figure 16). For example, the figure 'D' path is best only when the wind speed is less than 0.4 times the airspeed in the 1900 meter box. This is due to the fact that as the velocity of the

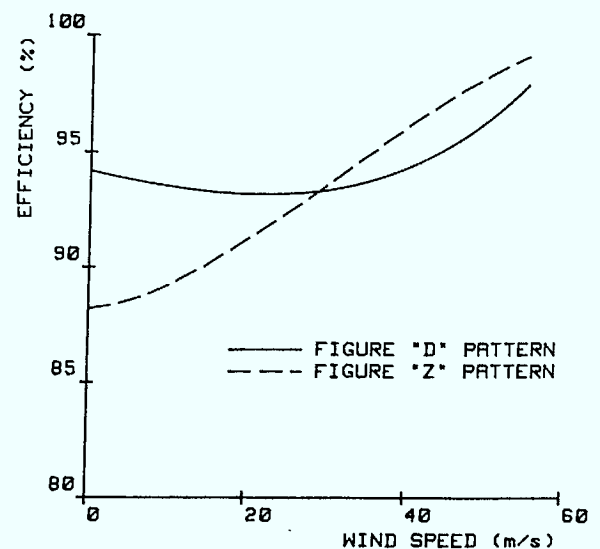


Figure 16: Flight pattern efficiency versus wind speed. Airspeed = 60 m/s, box radius = 1900m, altitude = 21 km.

aircraft in the air reference frame approaches that of the wind velocity, the figure 'Z' pattern degenerates to a straight line (in the air frame), i.e., the aircraft simply hovers over the ground station. The computer simulation also showed that for lower microwave beam tracking rates and accelerations, the figure 'Z' patterns are better.

Note that once the aircraft has entered the pattern, in steady winds, Gagnon¹⁸ has shown that these results can also be obtained with a much simpler analysis. Namely, the aircraft may be assumed to act in a quasi-steady fashion, so that steady-state equations may be used to describe its equilibrium attitude. The results generally match those from the non-linear analysis to a high degree of accuracy. This provides a cost effective way for initially assessing flight patterns with many variations in parameters.

Flight Dynamics

In order to achieve a successful SHARP demonstration, work is required on a stability-augmentation and control package. This is needed mainly for two reasons: (1) the aircraft can experience variation in stability modes with altitude as it climbs to station, possibly becoming less stable, and (2) if the aircraft is controlled in a remotely-piloted mode, the time lag between an aircraft's (perhaps unstable) motion and the operator's detection of this motion often will not allow corrective action to be carried out in time.

As currently envisaged, the control system for the demonstrator will consist of a simple attitude and air data determination system, based on the successful motion-sensing package developed by de Leeuw and Kung¹⁹ at UTIAS for the USAF Geophysics Laboratory's free balloon studies. The aircraft's

position in space will be assumed to be known from a ground-based system. In order to develop the required system, further work is needed in the areas of:

- (i) hardware requirements/capabilities/cost
- (ii) demonstrator stability analysis
- (iii) computer simulation

The computer-simulation work is intended to provide the capability of studying in more detail the sensor, control, and actuator sub-systems, and their interactions with each other and the overall aircraft stability. The program will also allow for simulation of 'man-in-the-loop' scenarios.

Flight Operations

The subject of flight operations deals in part with the launch and recovery phases of a SHARP mission. These differ from the operational phase in two important respects. First, there may be no microwave energy available to power the aircraft. During an ascent in which aircraft #1 is flying up to replace aircraft #2, which is due to return for routine maintenance, it is undesirable to have an interruption in the telecommunication service. However, the microwave beam may be unable to support two aircraft at once. Also, a sudden failure of either the microwave transmitter or the rectenna (or power train) on the SHARP aircraft would necessitate an unpowered descent. The second difference is that at intermediate altitudes, the winds are generally much stronger than those at the operational altitude (Figure 17). If the wind speed is higher than the flight speed, the airplane cannot fly in the flight path used at the operational altitude. Instead, it must head straight into the wind, while drifting downwind.

It has been assumed that a SHARP ground station would consist not only of the microwave transmitter, but also of the launching facilities and post-operational maintenance facilities, all within a few kilometres of each other. If the launch site was some distance away from the transmitter, it would only be useful for a limited range of wind directions. The same is true of the recovery site. The maximum usefulness would be achieved if the sites were arranged so that the prevailing winds blow from the launch site towards the transmitter, and from the transmitter towards the recovery site. But because SHARP is intended to be a commercial telecommunication system, it probably cannot afford to be non-operational for days simply because the wind is not blowing in the prevailing direction. A ring of launch and recovery sites around the transmitter would accommodate all wind directions, but may be very costly.

Performing all three functions at a single site reduces the cost, but introduces the following constraint. An ascent must terminate in a location as nearly overhead of the ground station as possible, and a descent must terminate on the station.

The ascent or descent duration must be as brief as possible in order to reduce the time spent at altitudes with high winds (and hence minimize the downwind drift), and also to reduce the length of time the system is non-operational during the emergency replacement of a failed SHARP aircraft.

With these difficulties in mind, the problems of launch and recovery have been addressed by Gagnon.^{20,21} Two methods of launch and one method of recovery have been studied in detail, using computer simulations of various cases. Each new case is defined by a wind profile, values of lift-to-drag ratio (L/D), zero-lift drag coefficient C_{D0} , and maximum speed for a proposed SHARP airplane. In each case, the weight of the airplane was fixed

and the wing-loading was optimized for minimum power required at a speed of 50 m/s and altitude of 21 km. (Initially the wing loading was also varied, but this was found to have little effect on the results of the simulations in the range of practical wing loadings for this application.) The simulation program calculates climb or sink rates, airspeeds, ascent or descent duration, and ground distance, producing a plot of altitude versus ground distance for each case.

The wind profiles used were taken from Reference 22. This Reference contains seasonal plots of wind speed, not exceeded a given percentage of the time, versus altitude. The two locations chosen for this study had different profile shapes, and each had the strongest winds of all locations with that particular type of profile shape. Dayton, Ohio, USA, has a strong jetstream and lighter winds at 21 km, while Yerevan, USSR, has a light jetstream and stronger winds at 21 km. These two profiles are shown in Figure 17. The winter season was chosen for having the strongest winds. Note that if the wind speed is greater

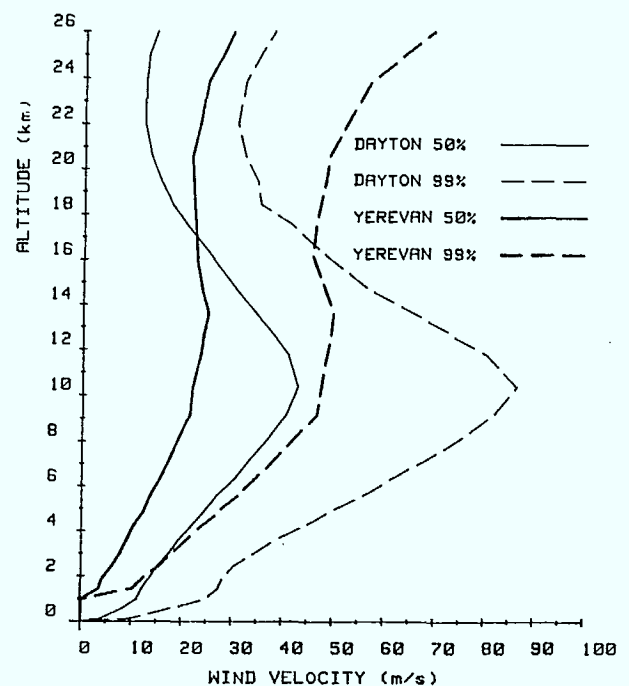


Figure 17: Winter wind profiles for Dayton, Ohio, and Yerevan, USSR (from Ref. 22).

than the 99% profile at one altitude, it is not necessarily greater at all altitudes at the same time. A profile that exceeded the 99% profile at all altitudes would be extremely rare. Therefore the 99% winter profile is a much worse case than a single winter day with strong winds. Wind data for Canadian sites could not be used because at present only raw data exist; no statistical information is available. Also, the wind direction was assumed

constant in the studies. This is not realistic; it is known that the direction varies with altitude, but very little information is available in a suitable form.

The first launching method investigated required the SHARP airplane to climb from the ground to the operational altitude using power from a disposable battery pack. It was suspected from the start, however, that this method would be difficult due to the weight of the batteries required. A number of cases were simulated, using the unrealistic assumption that the battery pack weighed nothing. If the method was unsatisfactory in this very optimistic case, then it would certainly be unacceptable in a more realistic case in which the battery weight was included.

The suspicion was confirmed by the long climb durations which resulted. Even when the maximum rate-of-climb speed was used, climb durations were as high as 17 hours. Also, the airplane was not always over the ground station by the time it reached the operational altitude, having drifted some distance downwind.

Using the highest energy-density batteries available, the battery pack would have to weigh up to 40% of the aircraft weight in order to supply sufficient energy for the long ascent. The extra battery weight would reduce the climb rate and increase the climb duration, which would then require more batteries. The heavy battery pack would also require extra structure on the airplane to support it, which, of course, would weigh more. Also, the total additional weight would increase the wing loading, which would cause the speed for maximum lift-to-drag ratio to increase above the maximum wind speed. This would increase the power required considerably (since power varies as the cube of the speed), which, in turn, would necessitate a beam with higher power-flux density, and hence a larger and more expensive ground station. The increase in speed could be reduced by

increasing the wing area to decrease the wing loading, but the resulting larger airplane would then require more power so the size and cost of the system would still escalate. This, along with the problem of jettisoning the battery pack and having it parachute safely to earth, caused this launching method to be abandoned entirely.

The second launching method investigated involved suspending the SHARP airplane under a large balloon, which would carry it aloft while drifting downwind. At an altitude above operational, the airplane would be released, and would glide back upwind until it was over the ground station. The balloon was sized to ascend at 5 m/s at sea level, and release altitudes from 26 to 32 km were investigated. Airplanes with lower lift-to-drag ratios required higher release altitudes; but in average wind conditions, all the airplanes could return upwind and be over the ground station at the operational altitude. Figure 18 shows the variation of release altitude with lift-to-drag ratio, for three successful launches.

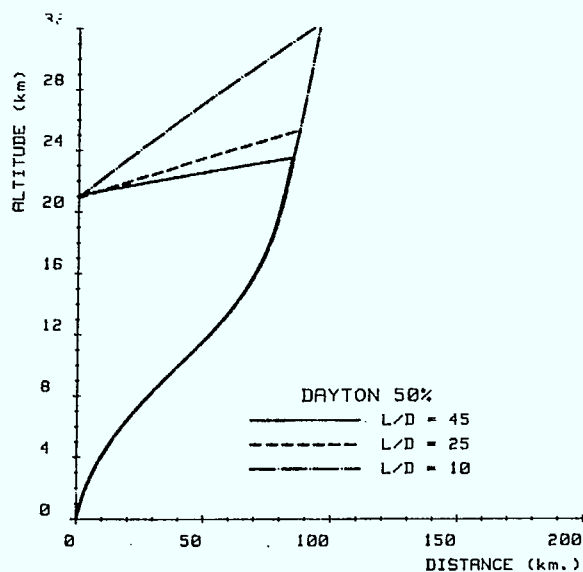


Figure 18: Altitude versus ground distance for simulated balloon-launches of three SHARP airplanes, using the Dayton 50% wind profile.

The method was not so successful in strong winds, however. Using the Dayton 99% profile, an airplane with $L/D = 35$ returned to a point above the ground station, but at an altitude of only 19.5 km; and using the Yerevan 99% profile, the same airplane was blown away and never returned.

Although this method could not be used under all wind conditions, it was much more suitable than the first method. Neither the airplane nor the ground station had to be modified, and in all the successful launches

simulated, the total climb duration was less than two hours. Also, the balloon launch method should prove even more successful under "real" wind conditions.

The only recovery method which has been studied in detail is that of a simple glide down to the ground. The airplane flies upwind at the maximum equivalent airspeed, so as to minimize the downwind drift.

In the first cases studied, the airplane was flown down in the same clean configuration that was used at the operational altitude. This was not satisfactory in high winds, because the airplane was blown away and never returned to the ground station. An example is shown in Figure 19. The downwind drift at landing was as high as 1000 km, with less drift for lower lift-to-drag ratios. This is because the higher sink rate of an airplane with a lower lift-to-drag ratio causes it to spend less time at altitudes where the winds are strong.

Based on these results, the simulations were repeated, this time using spoilers along the wing to increase the drag, and hence the sink rate. These were deployed only when the wind speed was greater than the flight speed. The maximum equivalent airspeed was also increased in order to reduce the drift speed (wind speed minus airspeed), and hence, the downwind drift. These measures improved the results considerably. Figure 20 shows a descent using spoilers along roughly 20% of the wing span, and a maximum equivalent airspeed of 22.32 m/s (90 m/s at 21 km), as opposed to 14.88 m/s (60 m/s at 21 km) used previously. In all the successful descents, the descent duration varied from 1.5 to 4.5 hours.

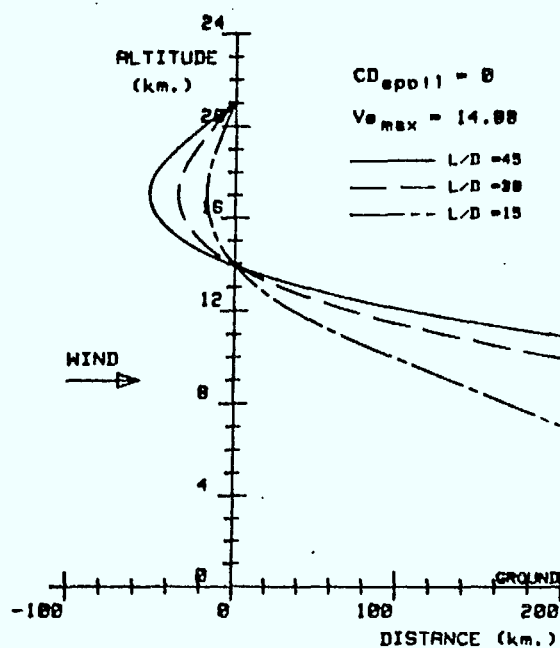


Figure 19: Simulated recoveries of three SHARP airplanes, using a simple glide and the Dayton 99% wind profile.

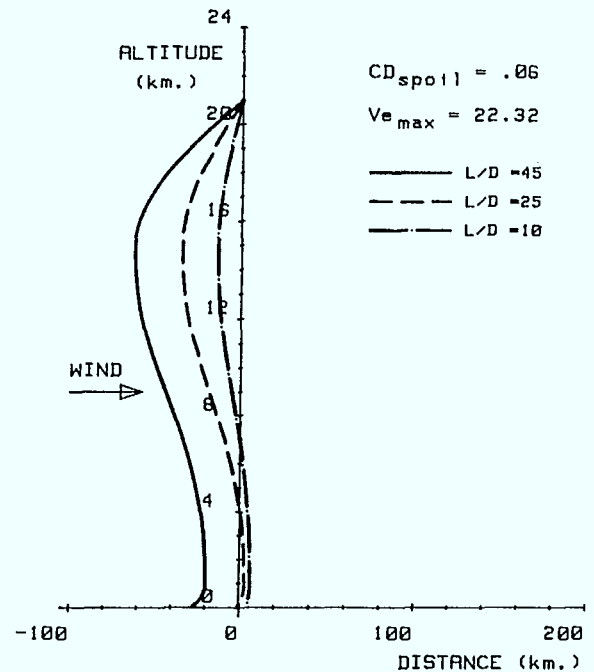


Figure 20: Simulated recoveries of three SHARP airplanes, using a steep glide with spoilers at high speed, and the Dayton 99% wind profile.

Both spoilers and a higher maximum equivalent airspeed carry some small weight penalty, but this is not expected to be restrictive.

FUTURE RESEARCH ACTIVITIES

The Stagger SHARP program has been an important first step in demonstrating that a freely-flying airplane can be sustained with microwave power alone. The integration of this with the microwave source and tracking apparatus is providing valuable directions for subsequent SHARP hardware development. However, as previously mentioned, the primary design constraint for Stagger SHARP was that it should fly with the lowest practical power-flux density. This resulted in an aircraft which is slow (4.0 m/s), lightweight, and essentially a calm-weather flyer. Subsequent development by CRC of rectennas and the demonstration ground station now offers higher power-flux densities and the possibility of flight with a faster and more robust vehicle with a certain payload capability for instruments and flight-control systems.

This aircraft, called the "Mini-SHARP", will be a small low-altitude analog to the projected full-sized vehicle, in that its configuration and ultimate demonstration flights are planned to closely resemble those of the operational SHARP. That is, the airplane will be designed for high values of lift-to-drag ratio, L/D , in addition to high values of "power factor", C_L^3/C_D^2 . This leads to the selection of a high aspect-ratio monoplane with a finite-thickness airfoil. Further, it appears advantageous to have a dedicated capture area for the rectenna, in addition to the wing. One attractive solution, previously discussed, is to house part of the rectenna inside an outsized stabilizer. This has been proposed and extensively studied by B. Gagnon, as described previously in this paper.

Another solution to housing the rectenna has been proposed in Reference 1. This consists of a separate AWACS-type lenticular structure affixed to the fuselage of the airplane. At one given flight condition, this disk would be oriented to give zero lift. Thus its drag contribution would be primarily due to skin friction.

The Mini-SHARP's higher speed will allow flight in stronger winds than those for Stagger SHARP. Therefore, it will have a much higher percentage of availability. Also, its payload capability will allow the installation of a simple motion-sensing package. This can act, initially, to obtain flight-dynamic data for comparison with theoretical predictions; but ultimately, the motion-sensing package will be a component of an automatic flight-control system.

The limitations of the Mini-SHARP are readily acknowledged, in that this is a small-scale system to be simulated in a cost-effective and easily-modified fashion. It has been found, throughout this project, that complementing theoretical studies with experiments and demonstration flights

has greatly enhanced the progress made towards the definition of the operational SHARP system.

CONCLUDING REMARKS

Although this research shows the considerable promise for the SHARP airplane, several significant tasks remain to be accomplished before the mission can be achieved. Among these is a study of materials at 21 km. The feasibility of a SHARP airplane depends greatly on the use of modern plastics, composites, and adhesives; and their long-term behaviour at the atmospheric pressures and UV radiation at 21 km must be carefully studied in simulated and actual conditions. The same requirement also applies to the electric propulsion motors in order to assess any potential problems with brushes and bearings. In many cases, results from space-technology research will be particularly valuable.

Navigation is also a major research requirement. The station-keeping flight strategy must be completely automatic except for emergency situations. The vehicle's location may be sensed by a ground station, and its orientation and accelerations by an on-board motion-sensing package. This information, fed into a program incorporating the airplane's flight-dynamic equations, may provide the control motions necessary to execute the flight-path strategy required to stay on station for minimum energy required. Some of the key elements needed for constructing this navigation system, such as the non-linear flight-dynamic analysis and the motion-sensing package, have already been researched, as described in this paper, but much remains to be done before this synthesis is complete.

Along with the new materials previously mentioned, much thought must be given to the way in which these can be fabricated into large, light airframes. The Solar Challenger showed how foam, Mylar, and carbon fibre

can be assembled into a traditional structure of ribs and spars with an exceptional strength/weight ratio. However, these new materials offer exciting possibilities for unique structures specifically tailored to their fabrication capabilities, such as molding the carbon-fibre cloth into wing, body, and tail shapes. Such airframes have considerable promise for the long-term success of the SHARP concept.

As shown in this paper, many design constraints and flight scenarios have been based on assumed most-severe wind profiles. A major component of this project has been to study and assess available high-altitude wind data, and it has become clear that much more information is required. For example, the profiles used, to date, tell nothing about wind-direction changes with altitude. This would significantly affect the launch and recovery scenarios, which have mostly assumed a worse-case constant-direction profile. Also, the profiles give no information about duration of these worst winds. If the 60 m/s encounter is fairly brief, a major design constraint could be relaxed, to the vehicle's considerable benefit. Currently, detailed upper-altitude wind data from Environment Canada's balloon ascents are being organized and studied for the SHARP program.

Finally, much thought must be given to flight operations, both for the initial demonstration phases of the program, and for the ultimate operational system. Mention has been made of balloon launching. Also, piggy-back launching with another airplane has been proposed by W. Roderick of NAE; and although both techniques have some precedent in aviation history, this particular high-altitude application may require considerable research effort for their implementation, especially for the piggy-back case. Also, recovery, both scheduled and unscheduled, must be carefully considered. Successful recovery means that the airframe and payload are

safely brought down into a prescribed area. However, as this paper shows, achievement of this requires careful planning and timing. The initial flights will be crucial in revealing the real magnitude of these problems.

However, despite the perceived challenge of these current and future research tasks, no results, to date, show the SHARP mission to be unachievable. Rather, a fortunate confluence of new technologies have brought the SHARP concept into clear possibility, with its availability coinciding with growing telecommunications requirements.

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