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Final Report on Contract No. OST83-00136

"Aerodynamics and Construction of Lightweight Aircraft"

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Subject: Final Report for the Period 1 April 1983 to 31 March, 1984

Reference: Contract No. OST83-00136, entitled "Aerodynamics and Construction of High-altitude Lightweight Aircraft".

Scope:

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

(1) Propeller analyses, design and tests.

(2) Non-linear flight-dynamic analysis.

(3) Launch methods.

(4) Post-operational recovery of the SHARP airplane.

(5) Power failure analysis.

(6) Turns with Zero Bank Angle.

(7) SHARP demonstrator.

Progress:

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

PROPELLER DESIGN AND ANALYSIS

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The design of propellers for very low flight speeds (or more specifically, very low Reynolds numbers), as encountered with the SHARP aircraft, is still a relatively unexplored field, unlike propeller design at higher Reynolds numbers, which is a fairly advanced science. Success of the SHARP program depends heavily on the ability of the aircraft propulsion system to convert the microwave energy to power, and then to thrust; and the propeller is one vital link in that chain.

Recent work in the field of propellers has led to the development of three different design codes for propellers having minimum induced loss. Each of these codes is an improvement on the previous one(s); and at present, only the latest program, from Liebeck's AIAA paper (Ref. P-1), is used.

Following the successful development of the design codes, an analysis procedure was deemed to be the next logical step. Development of this program, based on an analysis algorithm outlined by Liebeck, yielded an iterative scheme that provided results for certain cases only. The problem was the non-convergence in the iteration procedure for a propeller operating away from the design point.

A search for a more general analysis, one that would work for all cases, ended when a vortex analysis in a Russian paper (Ref. P-2) was found. Development of the computer code was a lengthy affair, and outlined extensively in the previous progress reports (see November 1983 to January 1984 progress reports). The result of this work was a reasonably general program, suitable for propellers or rotors in axial motion, but extremely heavy in its demand for computing time. This drawback seriously limited the possibilities for the widespread use of this type of analysis.

As a result, the problems with the original Liebeck program were reexamined, and modifications in the iteration scheme led to successful convergence in all the cases tested. This program is orders-of-magnitude faster than the vortex analysis, and would appear to be the program of choice in any future propeller analyses.

As a final confirmation of all the theoretical work done to this point, actual testing of a propeller designed for the minimum induced loss condition would show how accurate, or inaccurate the theory would be. Construction of these propellers would pose a fairly tricky problem because the severe twist gradient (Fig. F-1), especially at the root of the blade, would be difficult to match. Lamination of balsa wood on a specially-made form was the method attempted, and the resulting propeller blades closely approximated the designed twist distribution. However, deviations in geometry were still present, and a better construction technique is still being sought. With this new propeller, wind-tunnel tests were conducted. Subsequent analysis of this propeller on the computer produced disagreeing results on the amount of thrust that should have been produced. The experimental results tended to be two to three times higher in the thrust values than the computer had predicted. Checks of both the computer programs and experimental setup/technique were conducted to determine the cause of error. (A photograph of the test setup is shown in Figure P-2.) It appears that the likely culprit at this stage is the six-component balance used, as a calibration check of this piece of equipment showed the existence of an interaction between the rolling moment and axial force; i.e. loading the balance with a measurable rolling moment tended to degrade the accuracy of the axial force. Work is now being undertaken to correct this problem with the six-component balance, and the propeller will be retested as soon as the problem has been resolved satisfactorily.

REFERENCES

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P-1) C.N. Adkins, & R.H. Liebeck, Design of Optimum Propellers, AIAA 21st Aerospace Sciences Meeting, Jan. 10-13, 1983, Reno, Nevada. AIAA-83-0190.

P-2) Baskin, V.E., Vil'dgrube, L.S., Vozhdayev, Ye.S., Maykapar, G.I., Theory of the Lifting Airscrew, NASA TT F-823, Feb. 1976.

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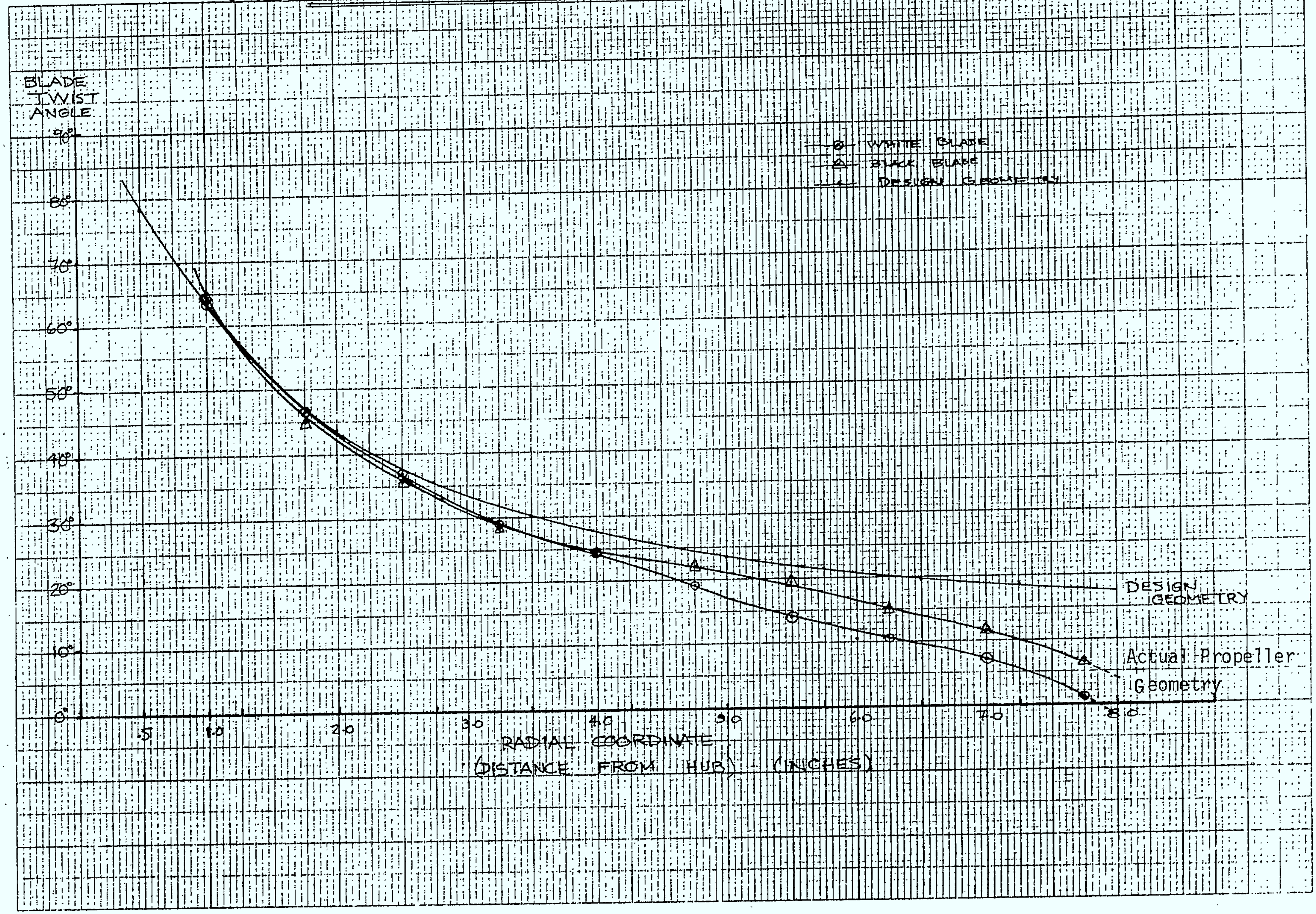
Fig. P-1 BLADE TWIST VS. RADIUS FOR DESIGN CASE & CONSTRUCTED BLADES.



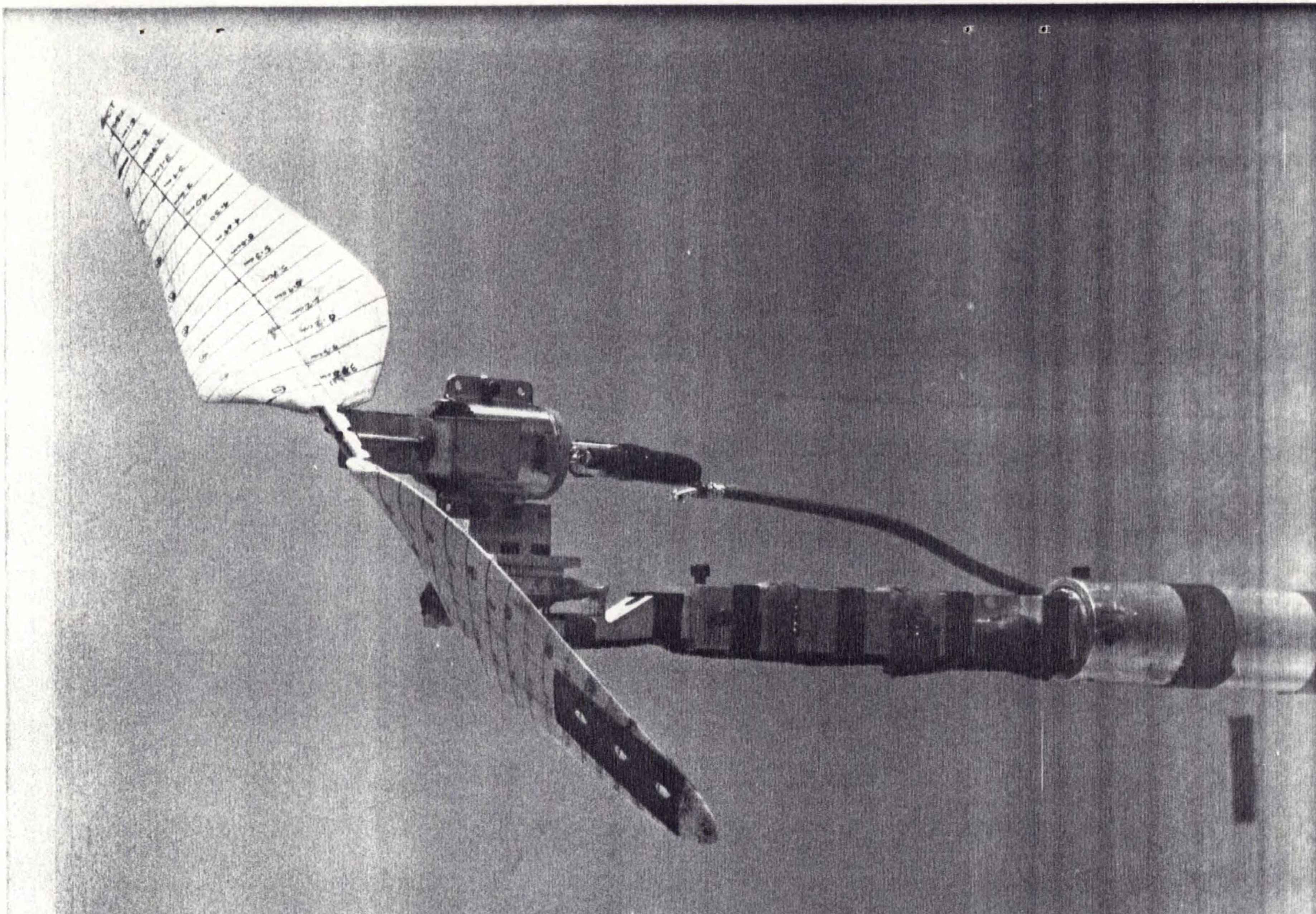


Fig. P-2 : Actual Photograph of Propeller Test Setup

Nonlinear Flight Simulation

A program to simulate flight of rigid aircraft has been developed and applied to the Slow Sharp vehicle in several manoevres. For example, Slow Sharp's minimum turning radius of approximately ten meters was determined by simulating flight with maximum (20 degree) rudder deflection.

A method of defining an arbitrary path in space so that the aircraft can, through appropriate control of the rudder, be caused to follow that path has been developed. This method has been used to simulate flight of Slow Sharp around the racetrack (oval), figure eight, and zigzag paths. Considerable work has been done on low energy stationkeeping strategies. Three approaches have been taken: The stationary microwave beam and racetrack path, the steerable beam and figure eight ground path, and the steerable beam and zigzag air path.

The stationary beam approach envisioned a fixed beam spot with the racetrack path crossing the beam on one straight section. Slow Sharp received power while in the beam spot, and glided over the rest of the path. In theory, enough altitude could be gained while Slow Sharp was in the beam to offset the altitude lost while gliding, however, the adverse reaction of Slow Sharp to application and loss of power at the beam edges was so severe the no altitude gain over one circuit of the racetrack was observed, even at high beam power-flux densities. (see the April-October, 1983 progress report)

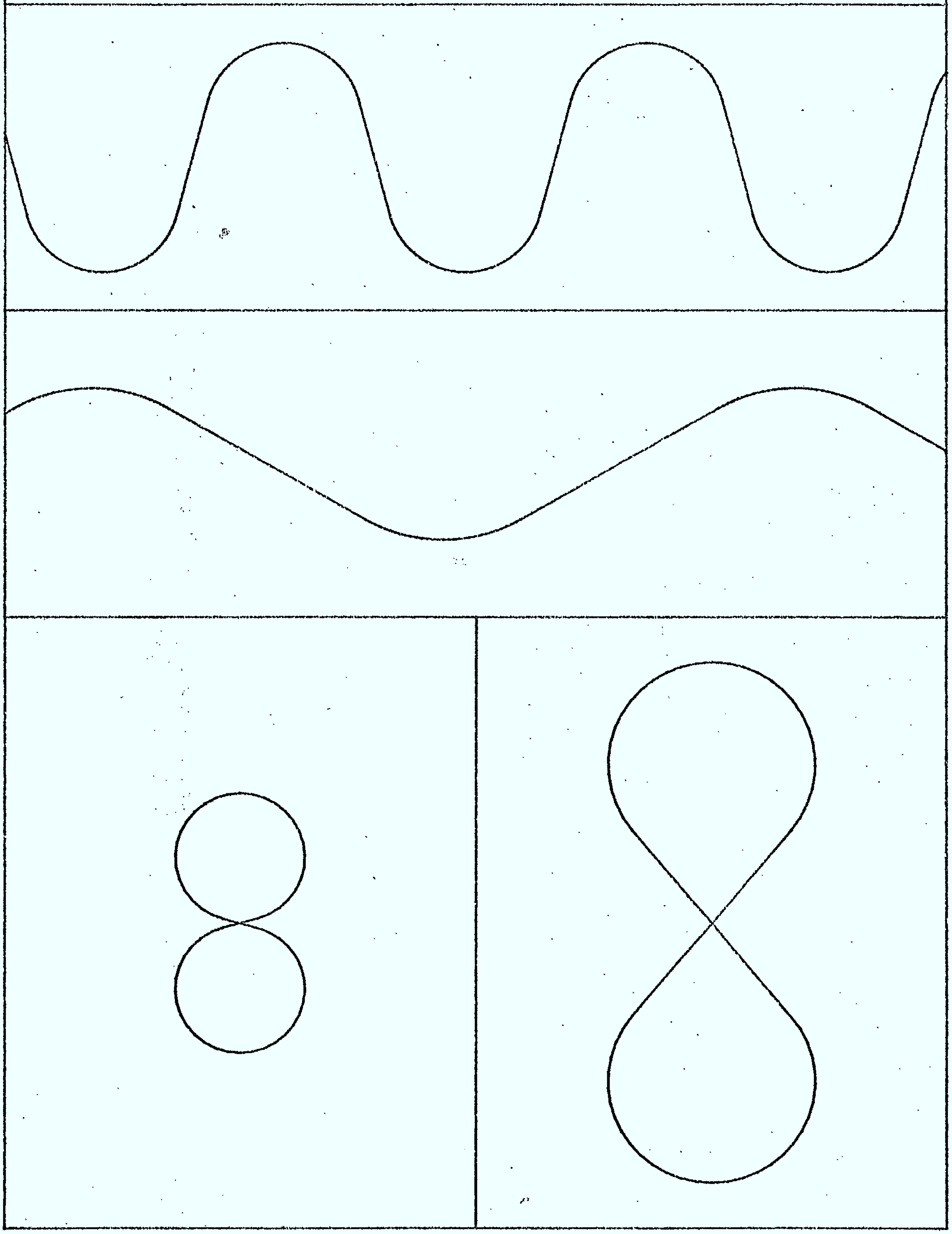
A steerable beam and rectenna were then simulated. Power received by the aircraft was determined by an empirical relation involving beam power-flux density, aircraft attitude, and motor impedance. Using the simulated rectenna, flight around the figure eight ground path (on which the aircraft appears to follow a figure eight when observed from the ground) in winds of varying strength, was investigated. As an alternate approach, the zigzag air path was considered as well. The zigzag is defined relative to still air, so in the presence of a wind of the correct direction and strength, the path of the aircraft over the ground will remain within the maximum allowable distance from the ground station. (see the February, 1984 progress report) Results of this investigation were:

(1) For any given wind speed and maximum distance allowable from the ground station, a zigzag path of lower energy than any figure eight path under the same conditions could be found. The smallest energy differences between the two types of paths occurred at low wind speeds.

(2) While zigzag paths could be followed in wind speeds up to the maximum speed of Slow Sharp, figure eight paths were increasingly difficult to follow as wind speeds increased.

(3) Energy increases of less than ten percent over straight and level flight requirements were necessary for stationkeeping using zigzag paths for all wind conditions simulated.

Sample Zigzag and Figure Eight Paths



LAUNCH_METHODS

Two launch methods to raise the SHARP airplane to its operational altitude were investigated (January, 84, progress report). It was expected that drift would be a problem; for this reason the winter wind profiles, with 1% probability of being exceeded, of Dayton, USA, and Yerevan, USSR, were used. The wind profiles of these two locations are the strongest of the two main types of profiles observed worldwide.

In the first launch method, a battery pack is used to provide power to the airplane while it climbs on its own. This battery pack is disposed of when the airplane reaches the operational box at 21 km altitude. This method was found to be unacceptable because the wind speed exceeds the maximum airspeed of the airplane by a significant amount at certain altitudes, causing large drifts (150 km at best in average winds). It was also found that the battery pack would be excessively heavy.

The second method uses a balloon to raise the airplane to an altitude greater than 21 km while drifting with the winds. At this altitude, the airplane is released from the balloon and glides to the operational box. The ground distance from the ground station at the release point is kept to a minimum by the fast rate of climb of the balloon (approximately 1000 ft/min). In all successful cases the ground distance was under 180 km. Airplanes with lift-to-drag ratios from 10 to 45 were used in the study. Successful launches were possible in more than average winds for all of them, with the exact wind level being dependent on the wind profile of the location and on the airplane. Figure

1 shows the ground-distance-versus-altitude plot of two representative launches.

RECOVERY

The recovery of the SHARP airplane after operation at 21 km was looked at. As described in the February 1984 progress report, it is desired that the airplane lands at the ground station in normal operation and at a small distance away in non-normal cases. For this study a computer program was used to simulate the descent of airplanes with lift-to-drag ratios ranging from 15 to 45. Winter wind profiles from Dayton, USA, and Yerevan, USSR, were used.

At first the airplanes were kept in their normal operational configurations during the glide. As a result, when glides in the strongests winds were simulated, none of the airplanes could land near to the ground station. This leads to a requirement for careful choice in the days when a descent might be initiated and/or to some modifications to the airplane. The use of spoilers during the descent (to increase the sink rate) and an increased maximum speed (to increase wind penetration) were investigated. Simulation showed that with the addition of small spoilers and an increase of 7.5 m/s in the equivalent maximum airspeed, it is possible for the airplane to land at the ground station in all wind conditions investigated as shown in figure 2.

The effects of wind direction inversion with altitude were also examined. At the present time the environmental data is not sufficient to permit any conclusive statements to be made, but, if the winds are monitored at the ground station, a strategy can be devised so as to use the inversion to advantage.

A method of recovery where the airplane is forced into a deep stall was also investigated. For landing, a parachute is used to slow the airplane and set it down without damage. The simulation demonstrated that the airplane would land within one hundred kilometers of the ground station. This method could be used when some failure has occurred and control of the airplane is no longer possible.

POWER_FAILURE

The case of a power failure while the airplane is in operation, has been studied and the results are included in the January, 84, progress report. Many reasons for such failures can be thought of: one example is an interruption in the electrical system at the ground station; putting the auxiliary power units in operation could take some time. During such a failure, the airplane would stay above the ground station by gliding down (use of potential energy). When power is regained, the airplane climbs back to the operational altitude as fast as possible. Since the operational altitude is above the jetstream, and the wind speed, in part of the jetstream, can exceed the maximum flight speed of the airplane, the permissible altitude loss is limited. If the airplane was to enter this high wind region it would be impossible for it to stay above its source of energy, the ground station. In such a case, the maximum duration of a power failure for which the airplane is to be designed for is very important. The sink rate of an airplane is proportional to its maximum lift-to-drag ratio. Therefore, if the design failure time is long, a high lift-to-drag ratio will be required. A second parameter of importance is the time until the airplane is returned to its operational box at 21 km. If a lot of altitude is lost during the failure and the airplane must climb to 21 km in a short time, a large climb rate will be required. This leads to the diversion of the telecommunication power to the motor, and a propulsion group (motor and propeller) greatly oversized for normal operation. As seen above, the design failure time and the design return time are prime parameters that need to be set before the airplane design phase. For some of the power failure cases these times can only be determined by CRC because they are related to the design of the ground station, and for some other cases they depend on both the airplane and the ground station. Since work on possible configurations is to start soon, it is important that UTIAS be provided with these parameters in the near future. A discusion is therefore required between CRC and UTIAS to organise this work

TURN_WITH_ZERO_BANK

The efficiency of a rectenna decreases with the angle between the microwave beam and the normal to the rectenna. Since, in the case of the SHARP airplane, banking in turns increases this angle, it was proposed that an airplane which turns with zero bank might be more efficient. For an airplane to turn, there must be a lateral force toward the center of the turn. The conventional method to create this force is to bank the airplane; a lateral component of the lift force, which is normal to the wing, is then created. For an airplane to turn with zero bank, a vertical wing must be added to generate this force. This wing then creates additional drag. A comparison, in terms of power requirements, of these two types of aircraft is described in the February 84 progress report. The vertical wing of the airplane with zero bank was designed with a somewhat unrealistic efficiency (weightless, aspect ratio 30, zero lift drag coefficient of .01 and an optimized area). Even with this bias toward the zero bank airplane, the study arrived at the conclusion that the conventional airplane required less power (7%, bias included).

SHARP DEMONSTRATOR

During the year, design work on a SHARP technology demonstrator continued. A first configuration was built, wind tunnel tested and flown, battery powered, during the summer of 1983. Although the flights were successful, the performances were insufficient for microwave powered flight, the reason being that there was not enough rectenna area to collect the energy required for flight. From that point on, the configuration was continuously iterated upon. Various rectenna-aircraft configurations were tried and excessively large drag or weight prevented most of these from becoming successful SHARP demonstrators. This difficulty in finding a configuration is caused by the low speed, which causes aerodynamic difficulties, and by the low efficiency of the propulsion group, encountered only at this small scale. A configuration known as "STAGGER SHARP", figure 3, is now being studied and present results indicate that this airplane will be able to fly under microwave power. This airplane is similar to the biplane flown during the summer of 83, but the wings were staggered so that a rectenna can be installed on both wings. Results of wind tunnel testing showed that a rectenna surface could be placed, without an exceedingly large drag penalty, at 3/4 of an inch from the wing's surface, which then served as a reflector plane. As a result, "STAGGER SHARP" has twice the rectenna area of the earlier biplane. This new airplane was wind tunnel tested in February 1984, and the results, described in the March progress report, are encouraging. A first model, which includes an improved propulsion group, is now ready for battery powered flight trials.

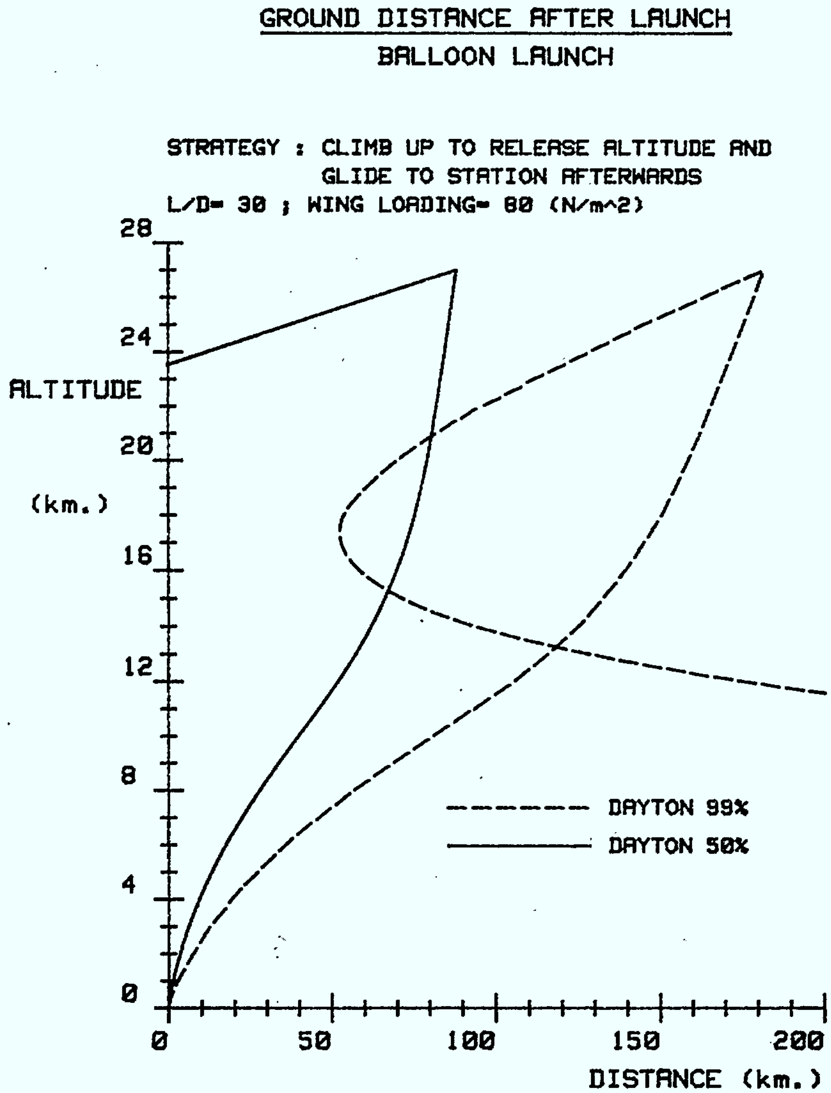


figure 1

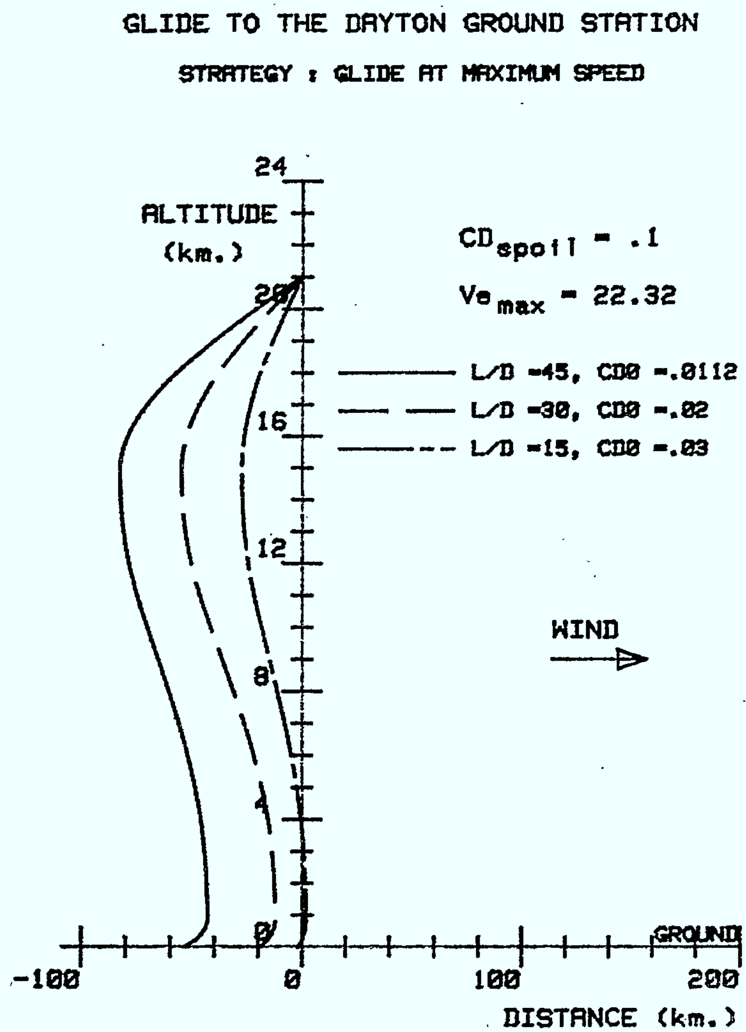
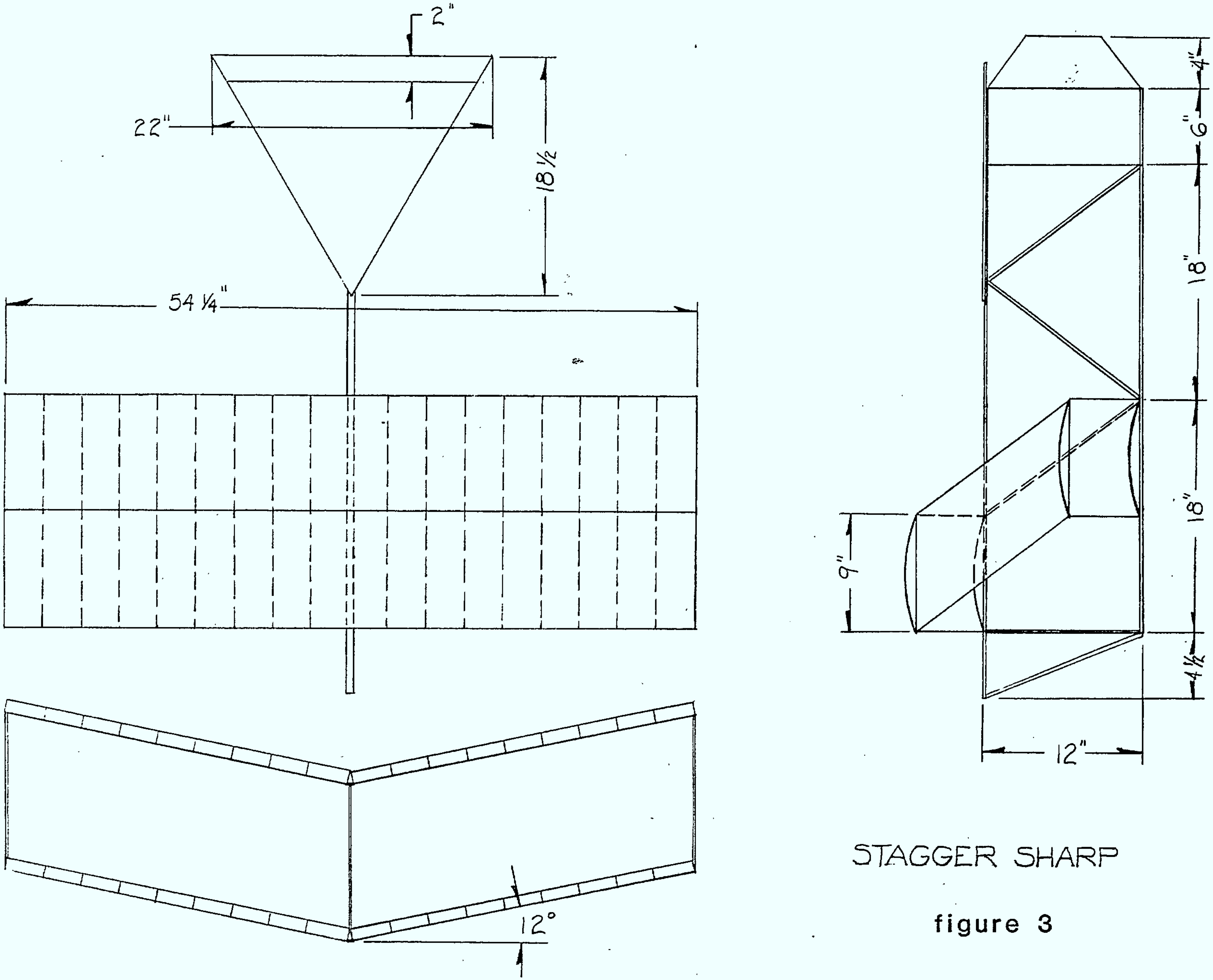


figure 2



STAGGER SHARP

figure 3