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by
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SUMMARY

The study indicates that a microwave-powered sailplane could be a reasonable substitute for a satellite in some missions requiring only limited coverage of the surface of the Earth. A mode of operation in which the aircraft cyclically climbs to high altitude in the beam, and then glides for several hundred kilometers, is feasible and takes advantage of the inherent forward speed of the sailplane at high altitude. Substantial research and development would be necessary to insure success within a reasonable period of time.

INTRODUCTION

Satellites have proven the value of high altitude platforms in many applications such as communications, mapping, and resource monitoring. The benefits of orbital platforms are obvious when a major portion of the Earth's surface must be covered. When the region of interest is limited, a satellite may not be the optimum solution since its coverage can not be limited; either the small region is covered intermittantly from a low orbit, or continuous coverage of an excessively great area is obtained from the extreme altitude of a stationary orbit.

In many cases, coverage of a limited region can be obtained from an aircraft at relatively modest altitudes. Unfortunately, if the coverage must be nearly continuous, the relatively short duration of airplane flight may lead to large operational costs. The use of a pilot is one factor contributing to short flight duration since human fatigue limits useful flight duration. In addition, the need to provide a livable environment for a human pilot necessitates major increases in the cost and complexity of the aircraft. Thus, the present study considers only automatically controlled pilotless flight.

A second, and more fundamental, reason for short flight duration is the need to carry fuel for the aircraft propulsion system. This restraint may be eliminated by providing a remote source of power. A number of remote sources are possible. The source considered herein is power transmission from the ground by means of a microwave beam. Such transmission has been demonstrated in the laboratory with an overall efficiency, including rectification, in excess of 50 percent (ref. 1). Large-scale tests have transmitted 30 kw over a distance of 1.6 km (1 mile) (ref. 2). Model-scale flight of a microwave powered helicopter has also been demonstrated (ref. 3). Thus, microwave transmission of the levels of power over the distances required in the present study appear to be a rational extrapolation of current technology to an aircraft with an initial operating date in the 1990's.

This study is based on a single preliminary aircraft design intended to operate at altitudes of 15 to 23 km (approximately 50 000 to 75 000 ft). These altitudes are chosen to provide wide sensor and transmitter coverage as well as to avoid severe wind velocities and velocity gradients. Aerodynamic characteristics, weight, power, mode of operation, and mission performance are considered and presented. The results indicate that the system should be feasible; however, significant research and development effort would be required to insure success.

This paper is partially based upon the results of an unpublished study conducted under contract to NASA by the Vought Corporation Hampton Technical Center.

RESULTS AND DISCUSSION

Requirements

In keeping with the preliminary nature of the current study, no specific payload was chosen for the present vehicle. A survey of a number of satellite missions indicated payload masses ranging from a few kilograms to several megagrams. At least for the present purposes, an arbitrary payload mass of 500 kg (1100 lbm) was assigned.

The altitude range of 15 to 23 km (50 000 to 75 000 ft) was chosen to provide a relatively wide field of coverage. It also coincides with a relative lull in prevailing winds at altitude which should result in some simplification in flight path control.

Mode of Operation

The initial inclination in studying an aircraft to substitute for a satellite is to assume that the airplane should circle above a point on the Earth. A recent study (ref. 4) indicates that the flight path is not that simple; instead, the optimum path becomes either "D" shaped or "8" shaped according to the direction and magnitude of the winds aloft. These differing paths impose penalties on the ground-based microwave transmitter, which must be capable of tracking the aircraft in two dimensions. The transmitter must also produce a polarized beam so as to provide power to the aircraft at all possible relative angular alignments of transmitter and receiver antennas. Both two-dimensional tracking and circular polarization add cost and complexity to the transmitter system.

The use of circling flight results in an additional, and not immediately apparent, penalty. The atmospheric density is low at high altitude; thus, in order to maintain flight, the aircraft must have a significant forward speed. Even a very lightly loaded aircraft may require true airspeeds in excess of 77 m/s (150 knots) at that altitude. This speed could serve a useful purpose in linear flight; in circling flight, it is totally wasted.

Linear flight offers an interesting alternative. In this mode, the airplane would climb rapidly while within reach of the microwave beam. After reaching some maximum altitude, it would then glide until it reached the next microwave beam, at which point the cycle would be repeated. This mode offers full utility of forward speed which is the main attribute of airplanes. It also simplifies the transmitter antenna which no longer requires circular polarization and which only needs to be steered in one direction to home on the aircraft. Mapping payloads may also be simplified since sensors need not scan in two dimensions. One direction, across the flight path, is adequate; the other dimension will be filled in by the airplane's forward motion. These advantages are not totally free. The aircraft must carry rechargable batteries to accommodate the payload during those portions of the flight between microwave beams.

The advantages of linear flight are large, and this mode of operation has been chosen for the present study. Circling flight, if necessary, is possible; however, the aircraft configuration might differ somewhat from that developed herein.

Aircraft Configuration

The aircraft configuration is dictated largely by the mode of operation. It must climb rapidly with small power; thus, it must be light. It must attain high altitudes with an available power that is directly proportional to the wing area (which is covered with the receiving antenna); therefore, it must have low wing loading. Finally, it must glide for long distances between beams; thus, it must achieve extreme aerodynamic efficiency by means of large aspect ratio and small friction drag. These requirements lead immediately to a high-efficiency powered sailplane (fig. 1).

Size. - The aircraft is large, having a wingspan of 57.5 m (190 ft), an aspect ratio of 30, and a wing area of 110 m^2 (1200 ft^2). Despite the light payload, the wing span is almost as great as a Boeing 747 wide-body air transport.

Wings. - The airfoils used on the wing are NACA 65_3-621 at the wing root and NACA 65_3-618 at the wing tip. These sections were chosen in anticipation of extensive amounts of laminar flow at the low Reynolds numbers and low unit Reynolds numbers encountered in the projected flight envelope. Adequate wind tunnel data does not exist for these conditions; the extent of laminar flow and the maximum lift coefficient were extrapolated from test data at greater Reynolds numbers (ref. 5).

At low Reynolds number, the selected airfoils have relatively low maximum lift coefficients. To avoid stall, the aircraft is operated at a constant lift coefficient of 0.9 at all times after having reached operational altitudes. This constant lift coefficient results in a constant equivalent airspeed of 15.9 m/sec (30.9 knots). This speed is close to that required to fly at maximum lift-drag ratio while gliding. It is somewhat faster than required while climbing; however, the increase in required power because of the fixed speed is not great.

The lower surfaces of the wings are covered with an advanced microwave rectenna (fig. 2, from fig. 9 of ref. 6). This antenna consists of an array of half-wave dipoles and conductors vapor deposited on a sheet of Kapton film. At each intersection, a rectifier bridge is bonded to the film so that direct-current power is drawn at voltages determined by the series-parallel connection of the dipoles. The entire assembly permits a smooth external contour allowing laminar flow. Within the airfoil contour, the Kapton film is backed by 2.5 cm (1 in) of lightweight plastic foam. The foam, in turn, is backed by a layer of 0.0025 mm (0.1 mil) Mylar with a vapor deposit of aluminum. This last layer serves as a reflector for the rectenna.

Motors. - The direct current from the rectenna is delivered to two 67 kw (90 HP) motors. The motors are samarium-cobalt brushless direct-current motors of the type described in reference 7. These are wound-stator motors with electronic commutation. The brushless design avoids the high-altitude arcing problems common to more conventional motors. Motor efficiency on current motors of this type ranges between 90 and 95 percent. Current motors weigh approximately 6 N/kw (1 lbf/HP).

Motors of the required size and weight are not yet available; however, this class of motor is being developed rapidly (ref. 8). It is estimated that motors of the correct power and greatly reduced weight should be available within the time required to develop the aircraft.

Propellers. - The motors drive three-blade pusher propellers of 7.3 m (24 ft) diameter. The blades have an activity factor of 80 and a design lift coefficient of 0.3. The aircraft operates at essentially a constant equivalent airspeed; however, the large variation of altitude results in a wide range of true airspeed and advance ratio (from 0.3 to 1.3). To maximize efficiency, the propellers are provided with constant-speed hubs having two selectable rotational speeds. The greater speed, 47 rad/sec (450 rpm) is used throughout most of the mission and results in a tip speed of 172 m/sec (565 ft/sec). The lower speed, 37 rad/sec (350 rpm), is used only during the initial climb to operational altitudes and results in a tip speed of 134 m/sec (440 ft/sec). Overall installed propeller efficiency was calculated to be 87 to 92 percent at altitudes of 15 to 21 km (50 000 to 70 000 ft) and 70 to 77 percent at altitudes of 3 to 6 km (10 000 to 20 000 ft).

The pusher propeller configuration was dictated by two considerations. First, at the operational altitudes and speeds, both the Reynolds number and the Reynolds per unit length are small. Significant runs of laminar flow are required and are possible in the absence of external disturbances. The pusher configuration minimizes flow disturbances over the wing surface. Second, a major portion of the flight consists of gliding without power between microwave beams. To maximize the glide range, the propellers not only feather fully, but also "flap" rearward from central pivots to trail behind the aircraft. In this trailed position, the propeller should add only 0.0006 to the aircraft drag coefficient.

Fuselage. - The fuselage is small compared to the wing in order to reduce drag by minimizing wetted area. No detailed payloads were studied; it was presumed that the payload would be of a size commensurate with small satellites and that it could be accommodated within the fuselage. Antennas were assumed to be flush mounted or to be located within the fuselage behind radio-frequency transparent panels.

No landing gear is provided. The aircraft is towed from the ground while mounted on a light dolly. The dolly is released after attaining flight speed. Ground clearance can be reduced during takeoff by setting the propeller blades in their inactive trailing position.

Weight. - A brief weight statement for the aircraft is presented in table I. The structural weight, based upon a load factor of 2.5 and on the use of graphite-fiber composites throughout, is only 8.8 kN (1980 lbf). Because of the light weight of the samarium-cobalt motors and the light loading of the graphite-fiber composite blades, the propulsion system is estimated to weigh 0.8 kN (180 lbf). Systems and equipment includes controls, antenna, and a small allowance for batteries to supply control functions during glide. The payload weight of 4.9 kg (1100 lbf) is assumed to include batteries for payload operation during glide. The resulting gross weight is 15.6 kN (3500 lbf). The resulting wing loading is 140 Pa (2.92 lbf/ft^2). Wing loadings of this low order of magnitude are necessary to obtain adequate power from the microwave beam with reasonably low transmitted microwave beam intensities.

A brief study was made of the change in aircraft gross weight caused by increased payload weight. Using a geometrically similar configuration, gross weight increased by about 90 percent when doubling the payload. Therefore, the larger aircraft would have approximately the same, or even slightly better performance than the aircraft studied herein, provided that the overall beamed energy was also doubled.

Aerodynamic characteristics. - The aerodynamic performance of the aircraft was estimated using conventional techniques. Figure 3 shows the estimated lift-drag ratios. These ratios are a function of altitude because of the variation of Reynolds number with altitude and because of the extent of laminar flow achieved. Two curves are shown in figure 2. The lift-drag ratio is different in climbing and gliding flight. When gliding, the folded propeller produces a small increment in profile drag and lowers the lift-drag ratio slightly. In climb, the blades still have drag, but the blade drag is absorbed in the propeller efficiency. In either event, the lift-drag ratios at operational altitudes are very large, ranging from 42 to 47.

Ground Stations

The microwave beam transmission stations are located at intervals along the flight path. The design condition for these stations is that they must provide a power density of 1.1 kw/m^2 (100 w/ft^2) at an altitude of 21 km (70 000 ft) and a downrange distance of 46 km (25 n.mi.).

The antenna is a flat array, which is electronically steered in one direction. The beam cross-sectional pattern is designed to be elliptical to accommodate the long, narrow, receiving antenna on the lower surface of the high apsect ratio wings. The beam is steered to home on a weak microwave beam transmitted from the aircraft, which, in turn, is programmed to search for the ground station. The signal from the airborne-beam steering is used to control the flight path of the aircraft.

The microwave power supply is from banks of microwave-oven magnetrons which are available at low cost because of volume production. The antenna is assumed to use low-cost wave guides which are currently under development. With these technologies, the cost per station should be on the order of only about two million dollars. Several such permanent stations could be constructed for the cost of a single satellite launch.

Some concern might be expressed over the environmental consequences (or the perception thereof) of such prolific use of microwave energy. No definitive estimate of such possible problems can be made at present; however, for some missions, such as coastal monitoring, the transmitters could be located on offshore platforms. This solution would minimize any microwave exposure of populated areas and, at the same time, allow a wide sea area (to both sides of the aircraft) to be surveyed.

Operation

Aircraft launch. - As noted earlier, the aircraft has no landing gear. It is mounted on a light dolly and towed into the air by another aircraft. An agricultural aircraft would be a suitable choice for the tow-plane since such aircraft tend to be designed for low-speed flight and to have substantial excess thrust. The aircraft is towed until it is at an altitude in excess of 3 km (10 000 ft) and in reasonable proximity to the microwave beam. At this point, the aircraft is released, and it commences a climbing race-track pattern through the beam until it reaches an altitude of about 15 km (50 000 ft).

Mission performance. - Once having achieved minimum operational altitude, the aircraft begins operation along the flight path shown in figures 4 and 5. While within the range of the microwave beam, the aircraft climbs rapidly to an altitude of about 23 km (75 000 ft). During this climb, the aircraft absorbs approximately 6 kw-hrs of energy in excess of that required to climb. This excess energy is used to charge the batteries used to provide power to the payload during the subsequent glide phase.

Upon reaching maximum altitude, the propellers stop, feather, and fold into the trailed position. The aircraft then glides until it intercepts the microwave beam from the next transmitter station. At this point, the cycle repeats until the final station in the chain is reached. After passing through the beam of the last station, the aircraft executes a 180 degree turn and returns along the same line of stations.

Because the energy for propulsion is transmitted from the ground rather than carried as fuel, the endurance of the aircraft is, to all intents, eternal. It is limited only by the possibility of mechanical or electrical failure. Range along the ground is limited only by the number of transmitter stations in the chain. Range through the air, considering the return portion of the flight, is essentially infinite.

Figures 3 and 4 shows a maximum performance system with no wind. In this case, adjacent stations may be located as much as 435 km (235 n.mi.) apart. Consideration of possible head winds would reduce the maximum distance between stations. Observe that the beam is utilized less than full time when a single aircraft is used between stations. Thus, more than one aircraft could occupy a single leg, and the multiplicity of aircraft would decrease the time between observations. A study of scheduling outbound and inbound aircraft along the chain of stations has not been conducted.

Other considerations could also affect the spacing chosen between stations. The flight shown in figures 4 and 5 provides 6 kw/hr of energy to operate the payload. If more energy was required, it could be obtained by shortening the distance between stations. With a shorter distance, the glide would lose less altitude, the climb would require less distance, and part of the powered phase could be accomplished in level flight. The excess power received in level flight greatly exceeds that in climb; thus, more energy would be available for storage. A second alternative would be to augment the microwave power with solar cells installed flush with the upper surface of the wing.

If a transmitter is disabled, or if the aircraft misses a beam, the mission is not necessarily lost. As shown in figures 4 and 5, the aircraft can continue its glide to reach the next beam. The loss of altitude is relatively large; the next beam is encountered at an altitude of about 5.5 km (18 000 ft). More than a single passage through the next beam would be required to regain the full altitude to glide to the following beam. Timing might become critical if numerous aircraft were supported. Not only would time be lost because of the longer climb, but the long glide itself would require much more time because of the slower true airspeeds at low altitude (fig. 5). Execution of this maneuver probably would require a radio-link to command suitable course corrections so as to insure capture of the second beam. Consideration of such "station-lost" exigencies might be the limiting factor in determining the maximum capacity of the overall system.

Required Research and Development

The system described herein is intended for operation starting sometime after 1990. Numerous items of research and development would be required in the intervening time to insure success. Improvements in the microwave transmission and reception systems are already being made. Lightweight rare-earth motors are already in intensive development. A comprehensive study of airfoils at low Reynolds numbers and low Reynolds number per unit length would be necessary to allow the selection of more nearly optimum airfoils for the wing. Continued development of filamentary composite structures would be required in order to provide the low structural weight postulated herein. Finally, a large-scale flight demonstration, over practical altitudes and distances, would be necessary to uncover possible operational problems at a sufficiently early stage to permit the study of rational solutions to those problems.

CONCLUDING REMARKS

The study indicates that a microwave-powered sailplane could provide a reasonable substitute for a satellite in some missions requiring only limited coverage of the surface of the Earth. A mode of operation in which the aircraft cyclically climbs to high altitude in the beam, and then glides for several hundred kilometers, is feasible and takes advantage of the inherent forward speed of the sailplane at high altitude. Substantial research and development would be necessary to insure success within a reasonable period of time.

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TABLE I.- WEIGHT SUMMARY

	kN	lbf
Structure	8.807	1980
Propulsion	.801	180
Systems and equipment	1.068	240
Total empty weight	10.676	2400
Payload	4.903	1100
Gross weight	15.579	3500

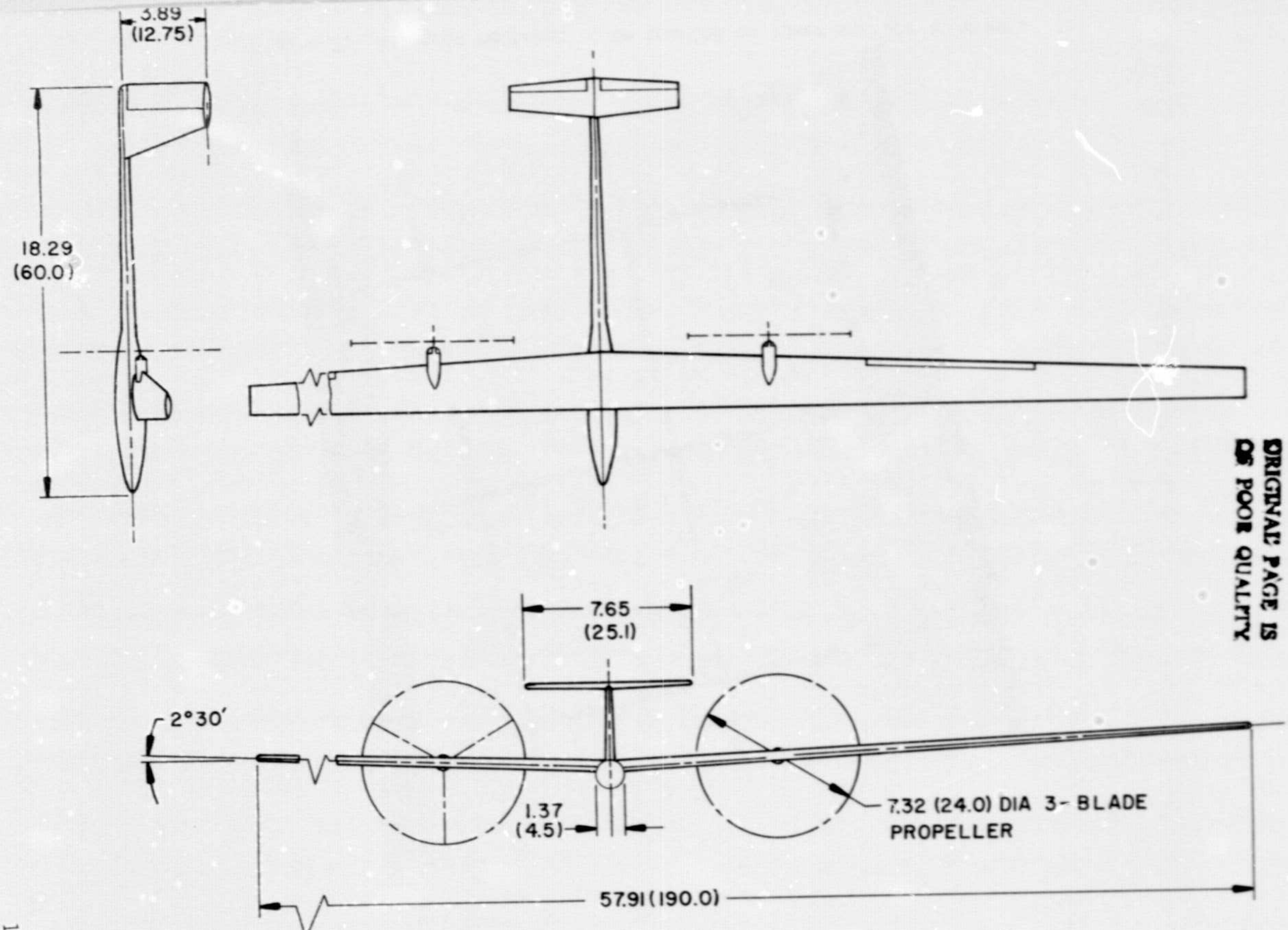

Figure 1.- Geometric characteristics of the microwave-powered aircraft.
Dimensions are in meters (feet).

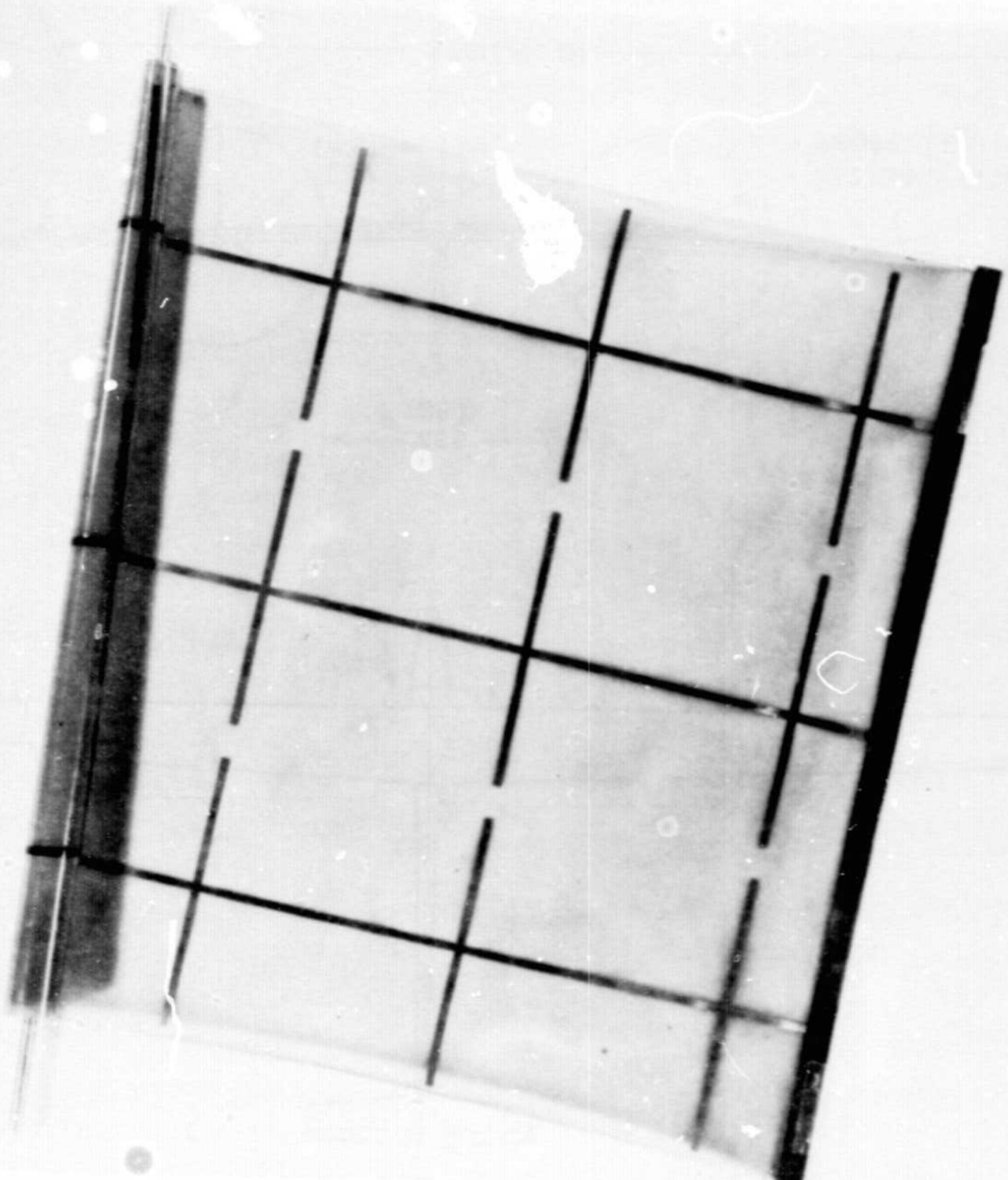

Figure 2.- Advanced rectenna to be mounted on lower surface of wings.

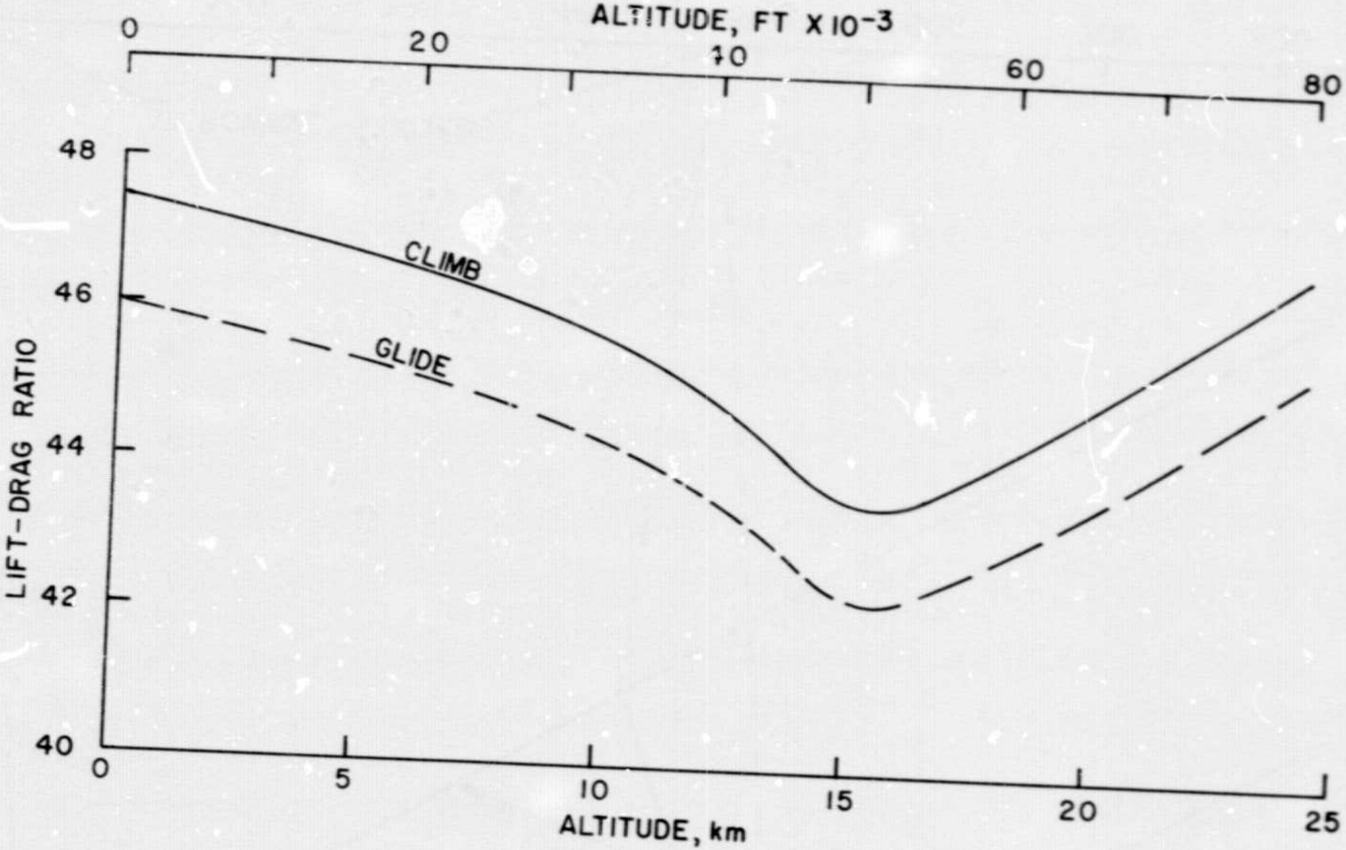

Figure 3.- Estimated lift-drag ratio as a function of altitude.

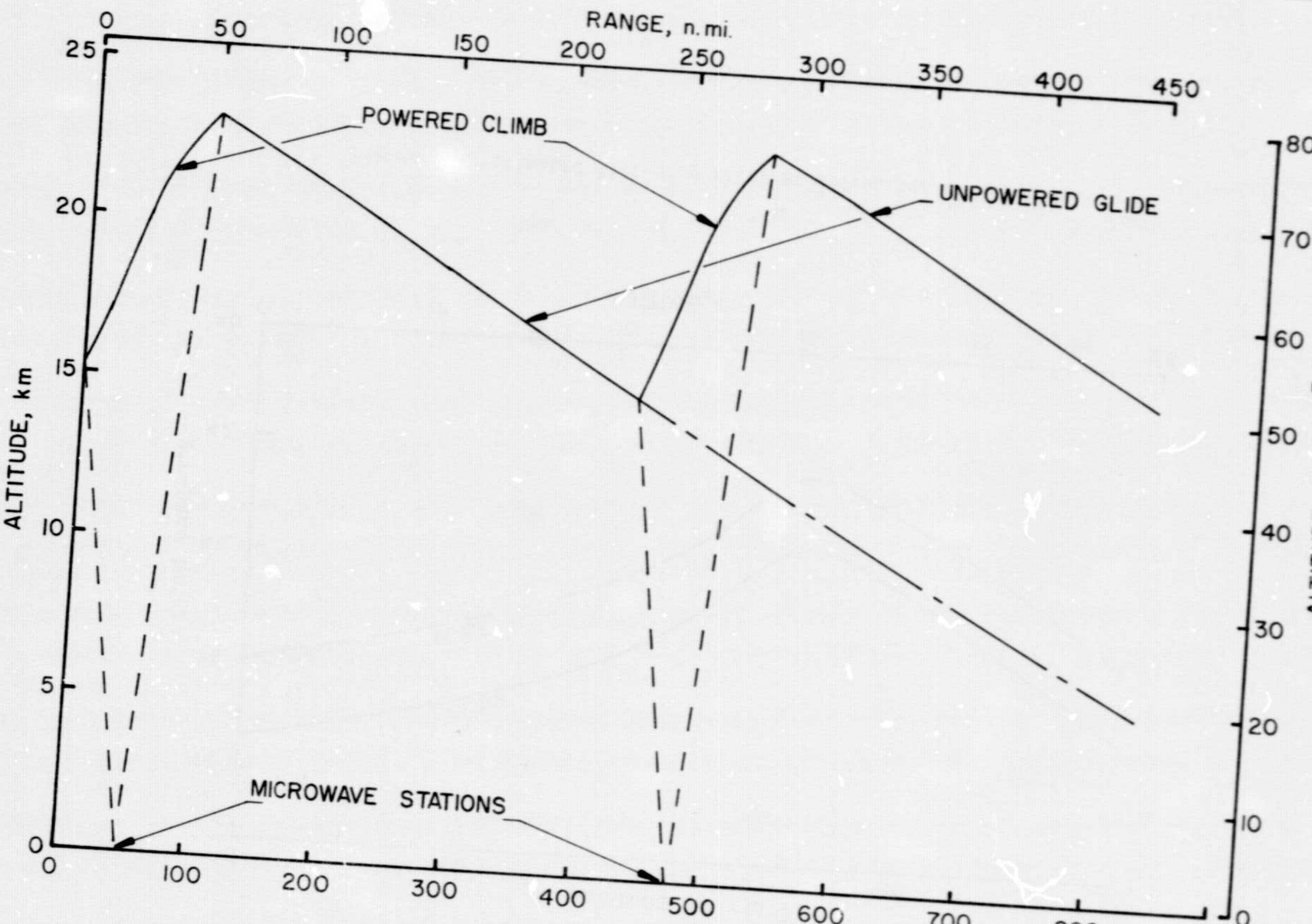

Figure 4.- Maximum performance mission of the microwave aircraft as a function of distance from the start of the climb cycle.

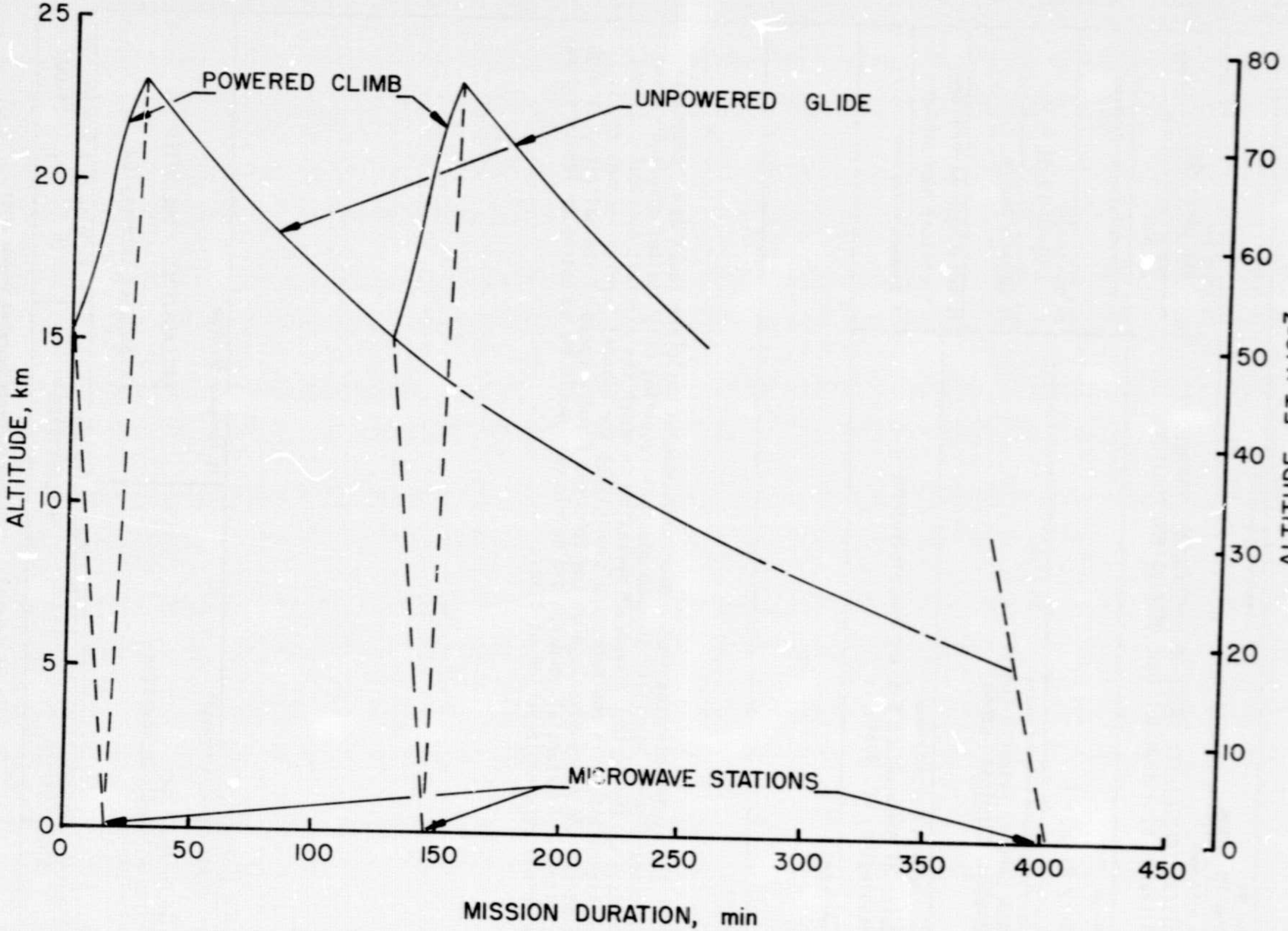

Figure 5.- Maximum performance mission of the microwave aircraft as a function of time from the start of the climb cycle.