Microwave-Powered, Unmanned, High-Altitude Airplanes

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Performance analysis and sizing studies have been conducted for unmanned, microwave powered, low speed airplanes that must fly with long endurance at high altitude The necessity of locating the receiving antenna in the vehicle wing couples both vehicle sizing and flight mechanics with power transmission This leads to un conventional performance equations for flight modes using either continuous power transmission or boost glide flight paths Vehicle size is a direct function of payload weight and power requirements Analytic results indicate that a variety of strategies can be employed to enhance vehicle performance for a range of mission requirements and wind conditions

Nomenclature

F_{sw}	= ratio of structural plus control and navigation system weight to total vehicle weight
k	= coefficients in Eqs (2) and (3)
P_{pay}	= payload power requirement W
P_{prop}	= propulsion power requirement W
P_R	= required beam power on wing W
S	= wing area, ft^2
T	= battery endurance, h
V_e	= equivalent airspeed, ft/s
W	= vehicle weight, lb
ρ_0	= air mass density at sea level, slug/ft^3

Introduction

A NEW class of aircraft has been proposed to conduct long endurance missions at high altitude [1] These vehicles would be unmanned and powered by microwave beams from ground based transmitters [2 4] The resulting endurance would be limited only by factors such as systems reliability and fatigue load effects They would complement the use of satellites and conventional aircraft in a variety of tasks In comparison to satellites, these high altitude airplane plan forms (HAAP) would offer better observational resolution, local persistence, and the capability of reuse They surpass conventionally powered vehicles in their ability to provide continuity of operation with a minimum number of aircraft The list of missions for which HAAP are well suited includes communications relay, Earth resource monitoring atmo spheric sampling, and surveillance

The vehicle and associated power system of this study have several unique components [2 6] A ground station with a transmitting antenna is required to track the vehicle and focus a microwave beam on the wings A rectenna, an integrated combination of a receiving antenna and rectifying circuitry is built into the wings This rectenna converts the microwave power to direct current electrical power for all of the vehicle systems Propulson is provided by propellers driven by electric motors

The microwave airplane configuration was selected for this design study on the basis of its ability to operate with a minimum of constraints at any given site Although lighter than air vehicles use less power when wind speeds are low they are less capable of operating in high wind en vironments [7 8] Photovoltaic power has also been studied for HAAP[9 10]; this eliminates all constraints associated with a ground based power supply However, the operation of solar powered vehicles is contrained by the seasonal and geographic availability of adequate sunlight In addition, the currently available energy storage systems required for flight at night are prohibitively heavy

Studies of microwave powered high altitude airplanes have analyzed both boost glide flight[3 11 13] and continuously powered flight [2 5 6] In each cycle of boost glide flight, the vehicle climbs while powered, then glides back to its original altitude The climb occurs in a vertical plane to allow for efficient tracking by the transmitter Continuously powered flight is constrained to the conical volume swept out by the ground station beam The effects of winds on both boost-glide and continuous flight can be countered by various strategies involving adjustments to cruise altitude, aerodynamic trim, and vehicle flight path

The objectives of this study are to indicate some limits of feasibility of microwave powered HAAP design and to contribute to the formulation of vehicle design guidelines Analytical methods for conceptual design and performance prediction are exercised for representative payload/mission requirements to develop the design guidelines

Microwave Power System

The technological base for microwave power transmission has been developed over several decades [4 14 16] Initial rec tennae provided more than 80% efficiency in the conversion of microwave power to direct current electrical power [16] Large scale tests demonstrated the transmission of 30 kW over a one mile range Theoretical and experimental studies have defined the relationships of the variables affecting the transmission of microwave power All work to date has used frequencies of 2 4 to 2 5 GHz This frequency band has been reserved for industrial, scientific, and medical use and provides for virtually no attenuation due to atmospheric conditions [6]

Lightweight rectennae can be constructed with three layers [3 5] The foreplane consists of antenna and rectifier elements attached to a sheet of Kapton with thin film, printed circuitry methods A sheet of lightweight spacing material separates the foreplane from the third layer, a thin metallic reflecting plane This rectenna can be built as an integral part of the lower surface of an airplane wing Flow under the wing provides convective cooling

Numerous configurations of transmitting antenna have been studied [4 6] Analyses have shown that radar dish con figurations are impractically large and costly Array antennae

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appear to allow greater ease of construction and operation Each array element is a simple, fixed frequency transmitter Electronic phasing of the array elements controls focusing and pointing of the total beam Increasing the number of these elements increases both initial costs and tracking efficiency

The allowable flight paths are influenced by the con figuration of the transmitting antenna [2 6 11 13] Some array configurations can track in three dimensions The conical volume that is swept out by such a ground station is limited by the effect of beam pointing on power transmission ef ficiency [2 6] Array antenna can sweep efficiency through much larger deflections if they are designed to track only in a vertical plane This is the tracking pattern proposed for boost glide configurations that fly a linear ground track [11 13]

Several other factors influence the efficiency of microwave power transmission [17] Both the relative orientation and the separation between the transmitter and rectenna are im portant Power reception is proportional to the projected area of the rectenna visible to the tracking transmitter; power intensity varies inversely as the square of range Signal polarization is also significant: for linear polarization, transmission efficiency varies approximately as the square of the cosine of the angle between the transmitter and rectenna phase alignments [2 17] The use of a double set of rectenna foreplanes, one orthogonal to the order, may alleviate this problem.

Safety must also be a designed consideration [8,18] Trans mitter radiation levels are expected to be less severe than some currently operating systems, including conventional radars and ground stations for satellite communications networks The large disparity between various national safety standards for microwave radiation reflects the uncertainty in knowledge on this matter [8] This study used 100 W/ft^2 as a limiting value of beam power intensity at the rectenna Values at the transmitter are much lower

Cost is an important factor not treated in the following analyses The investment for power transmission equipment has been estimated to constitute up to 80% of the possible total cost of a million dollar system This suggests that ac cepting complexity in the vehicles themselves may be reasonable if that significantly decreases complexity and cost at the transmitter

Microwave-Powered Airplane

Vehicle design is influenced by the need to achieve good aerodynamic performance and to meet the special requirements of a long endurance, microwave powered system As an example of the need to compromise, reducing the aspect ratio of the wing reduces aerodynamic efficiency but produces a rectenna shape that couples more efficiently with the microwave beam The need to fly as long as months between inspection and maintenance is significant: it leads to design conservatism and emphasis on reliability In addition the vehicle must be able to operate over an extreme range of altitude during the relatively brief periods of climb and descent

The prediction of aerodynamic characteristics must account for the effects of low Reynolds numbers A representative vehicle flying at 60 000 ft could have full chord Reynolds numbers as low as 400 000 at the wing and half that for the empennage surfaces and the propeller However, success in low Reynolds number aerodynamic design in the past 15 years has shown that these are acceptable values [19 20] Many of these airfoils exhibit relative invariance of profile drag with changes in lift coefficient; this allows the use of a simple, two term polar for drag

The propulsive system consists of electric motors gear boxes, and variable pitch propellers This combination of components has already been demonstrated on the Solar Challenger [21] The electronically commutated motors can use rare earth (samarium cobalt) magnets to achieve efficiencies of greater than 90% [22] The brushless design of these motors eliminates the arcing problems of conventional motors operating in a rarefield atmosphere The specific power of the motors is approximately 1 hp/lb

Winds and turbulence at high altitudes have a strong effect on HAAP design Data presented by Waco[23] and others indicate that turbulence is much lower at high altitudes However, the techniques used to acquire that data may have filtered out the shorter wavelength gusts that could have a strong effect on vehicles as slow as HAAP Consequently structural design may need to be conservative with respect to fatigue loads The need to remain within range of a ground station during extremely long periods of flight means that statistically improbable winds must be considered Wind data from Ref 24 are used as part of design criteria for this study (Fig 1) The resulting requirement for achieving a given equivalent air speed determines the dynamic pressure for structural design and helps to size the propulsion system

This study uses a simple structural model It was assumed that initial HAAP would resemble conventional gliders A structural weight fraction of 0 6 was selected on the basis of appropriate data [25] The fraction includes not only airframe structure but also controls and navigation systems; the remainder of the vehicle consists of payload, propulsion system, power processing equipment, and energy storage systems The simplistic approach should result in adequate design conservation for conventional glider-size vehicles

Analysis and Discussion

The evaluation of system performance has required the development of equations unique to microwave powered HAAP Vehicle weight remains constant, and motor power is unaffected by altitude variation As noted previously, power availability is influenced by factors such as both the separation and relative orientation between the rectenna and transmitting antenna Onboard energy storage is heavy but essential for either boost glide systems or emergency operations The resulting sets of unique sizing and performance equations are applied to a series of design cases

Simplified Vehicle Sizing Method

A highly simplified design and sizing method has been developed for continuously powered, microwave HAAP The method consists of several equations and a set of design criteria combined into very simple design algorithms

The method determines structural weight fraction and beam power intensity (required at the rectenna) by incrementing wing loading from a minimum value

$$W/S = C_L \rho_0 V_e^2/2 \qquad (1)$$

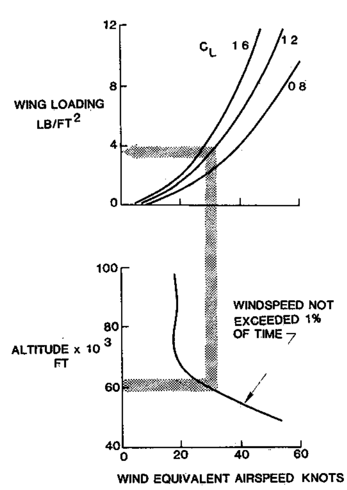

Fig 1 Effect of statistically expected winds[24] on vehicle design

$$F_{sw} = 1 - [k_1 P_{\text{pay}} + k_2 P_{\text{prop}} + k_3 T(P_{\text{pay}} + P_{\text{prop}})]$$
$$\div S(W/S) \qquad (2)$$

$$P_R/S = k_4 (P_{\text{pay}} + P_{\text{prop}})/S \qquad (3)$$

Values for weight/power ratios (k_1 k_2, and k_3) are obtained from Ref. 8; k_4 is the constant of proportionality that accounts for the wing/rectenna area ratio rectenna efficiency, the power drain to storage, and oversizing the rectenna to provide some redundancy This initial equation considers power requirements at the rectenna and excludes factors such as the attenuation of transmitted power

Application of a series of design criteria produces a vehicle sizing method. The method of this study requires the specification of span, wing aspect ratio, lift coefficient profile drag coefficient, operating altitude, payload weight, and payload power Data shown in Fig 1 define a minimum wing loading W/S to overcome a head wind with prescribed probability of occurrence The method next requires the calculation of structural weight fraction with Eq (2) and its comparison to the minimum value of 0 6. If structural weight fraction is too low, wing loading is increased (up to a limit of 10 lb/ft^2) The method finally determines the required beam power intensity P_R/S for a structurally feasible configuration

A simple set of vehicle/mission specifications constitute the baseline for the simplified sizing studies The chosen mission requires a 1000-W, 100 lb payload to operate at 60,000 ft A vehicle span of 50 ft reflects concern for minimizing difficulties in ground transportation and in launch site selection Lift coefficient and profile drag coefficients are 1 0 and 0 02, respectively

Results of Simplified Sizing Method

The data of Figs 2 and 3 illustrate the effect of incorporating limiting criteria into the sizing methodology Three basic trends are shown in Fig 2 for the case of no battery requirement First, wing area for the fixed-span vehicle varies inversely with aspect ratio Second, at sufficiently high aspect ratio (and low wing area), the structural weight fraction reaches a minimum value, and wing loading must be increased Third the increase in wing loading produces increases in requirements for both propulsive power and beam power intensity. Increasing the period of time to be sustained on stored energy simply increases the nonstructural weight (required by the battery); this reduces the aspect ratio at which the structural weight fraction becomes a dominant criterion The discontinuities in the curves of Fig. 3 are also produced by the same criterion for structural weight fraction.

Analyses of results presented in Figs 2 and 3 show that the design criteria have a strong effect on vehicle sizing Lower acceptable values of structural weight fraction and wind speed should lead to lower requirements for beam power density This, in turn, has a significant effect on the size and cost of the ground station

The limits of system feasibility can be defined in terms of payload requirements and vehicle constraints If structural-weight fraction and wing loading are specified constants, the equations yield results such as those shown in Fig 4 The limitations defined in Fig 4 reflect constraints on vehicle and ground station size and provide crude, optimistic guidelines Further constraints due to considerations of flight path, transmitter power, and overall cost will produce more severe limitations.

Continous Power and Zero Wind Speed

A more sophisticated sizing algorithm must account for the effect of vehicle motion These effects include power at

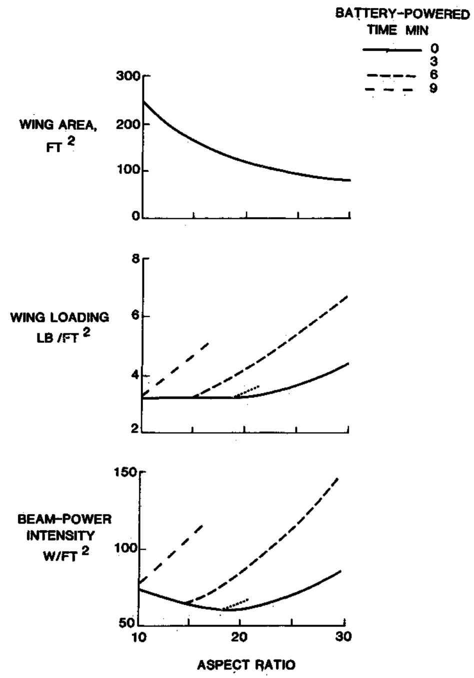

Fig 2 Effect of wing design and energy storage requirements on systems characteristics; continuous power for constant span, representative airplane

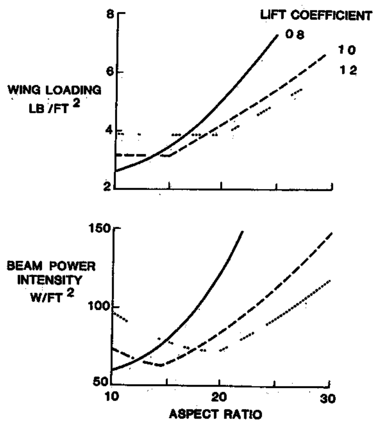

Fig 3 Effect of varying aspect ratio and lift coefficient on system characteristics for continuous power, constant span, representative airplane

tenuation due to spatial relationships between the moving rectenna and the ground station Figure 5 presents data for the simplified case of a HAAP circling above the ground station with no winds; the center of that circle lies directly above the transmitting array antenna (This vehicle has a 100 lb 400 W payload, a span of 60 ft, an aspect ratio of 20, and a wing loading of 3 lb/ft^2 Air speed is a constant 30 knots)

Results show that power requirements of ground station transmitters can be minimized as a function of turn radius Small turn radii produce higher bank angles; this increases drag and reduces the apparent size of the rectenna visible to the transmitting antenna Large turn radii can required higher power transmission due to beam pointing attenuation (associated with a limited number of phase array elements)

Continuous Power and Wind

Various adjustments to the vehicle flight path can minimize the adverse effects of wind on HAAP continuously powered by microwave beams. One strategy requires the vehicle to

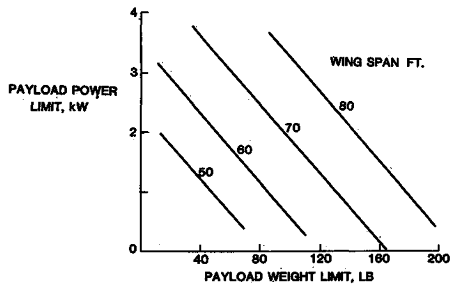

Fig. 4 Payload limitations for continuous power baseline con figuration

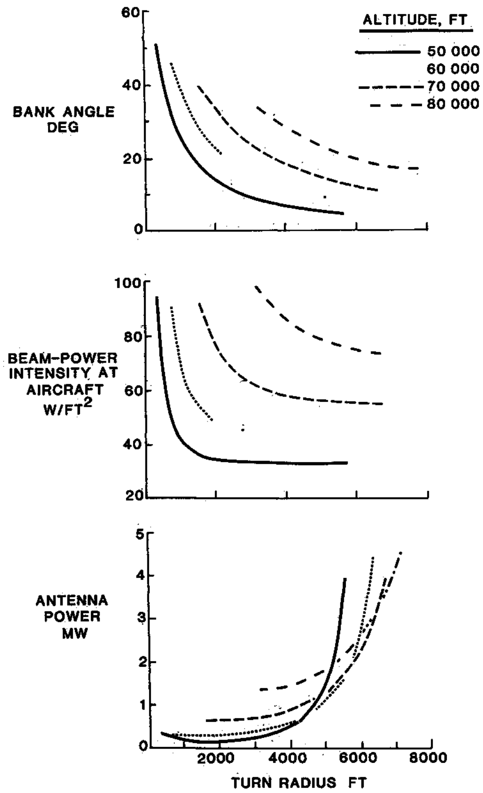

Fig 5 Effect of variation in turn radius on vehicle with continuous power transmission; one representative configuration with 100 lb, 400 W payload and zero wind speed

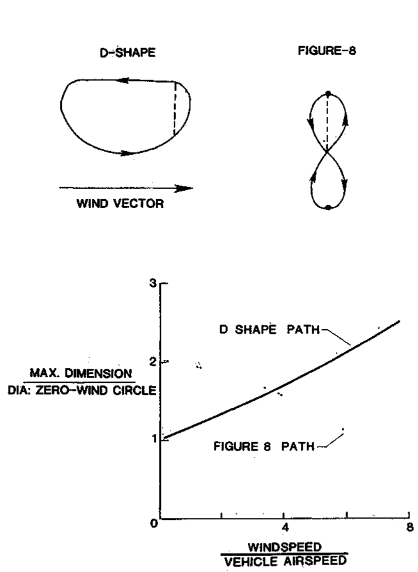

Fig 6 Effect of wind speed on size of flight path shapes for con tinuous-power, constant-altitude vehicle

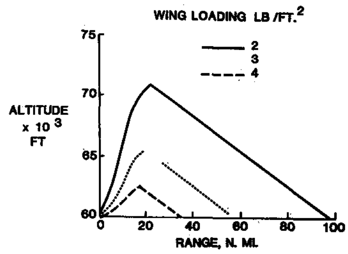

Fig 7 Flight profiles of representative, boost glide, microwave powered airplanes.

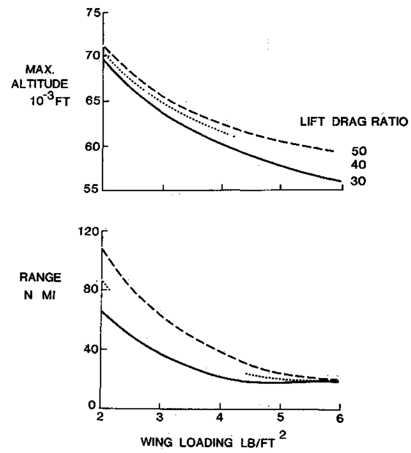

Fig 8 Effect of wing loading and lift drag ratio on performance of representative, boost-glide, microwave powered airplane

climb to seek a compromise between minimum wind and the attenuation of beam power with range In moderate winds, an appropriate strategy may be to increase lift coefficient to reduce air speed to equal wind speed; this allows the vehicle to remain virtually stationary above the transmitter In all cases, payload/mission requirements may rigidly define the set of acceptable strategies

Sinko[2] reported on several flight paths that minimize wind effects for vehicles constrained to fly at constant altitude A "D shaped" path can be developed from what is simply a constant bank angle circle at zero wind speed. At any given wind speed, the vehicle completes a steady turn that begins and ends with the vehicle pointed into the wind The wind deforms the circular path into a cycloidal ground track a shape similar to the curve of a "D" A second flight segment, straight and level flight into the wind, returns the vehicle to its starting point for another cycle (Fig 6)

An alternate flight path describes a pair of contiguous circles at zero wind speed. These are achieved with alter nating, full circle turns to port and starboard As wind speed increases, the vehicle continues to alternate its bank angle to fly a "figure 8" ground track (Fig 6) This pattern shrinks to a point when wind speed increases to equal air speed

The ratio of wind speed to air speed determines which constant altitude pattern should be flown As shown in Fig 6, a smaller pattern is achieved with the "figure 8" flight path if the wind speed air speed ratio is above approximately 0 35 Vehicles flying these patterns do not have constant power requirements due to variations in rectenna pointing, beam pointing, and other factors Power transmission efficiency is generally inversely proportional to the size of the pattern, hence the "D shaped" pattern is more efficient at low wind speeds [2]

Boost Glide Flight

A boost glide profile can simplify transmitter operations while significantly constraining the boost portion of flight

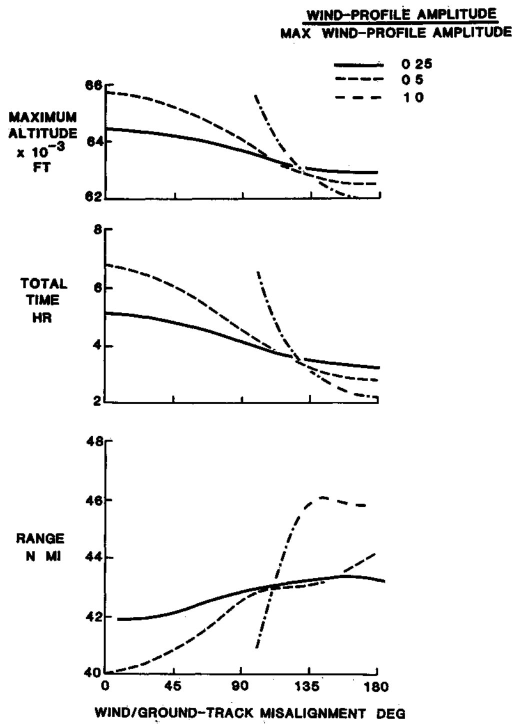

Fig 9 Performance of representative, boost glide, microwave powered aircraft as affected by wind magnitude and misalignment with required ground track (0 deg misalignment corresponds to a head wind).

Although the beam can tract only within a narrow vertical corridor, the beam can sweep efficiently over a ±45 deg deviation from the local vertical As indicated in Fig 7, a representative microwave HAAP can be tracked for about 20 n mi and glide well beyond that point Less conservative estimates of the effects of tracking accuracy yield significantly greater range

Figure 8 illustrates several basic characteristics of boost glide performance for zero wind conditions Maximum achievable altitude is inversely proportional to wing loading and is affected more by wing loading than by lift drag ratio Range, however is strongly affected by aerodynamic per formance, particularly at low values of wing loading

Wind profiles also affect the performance of boost glide systems Analytical results are presented in Fig 9 for a representative vehicle (It has a lift drag ratio of 40, a wing loading of 3 lb/ft^2 and a beam intercept point at 60 000 ft of altitude and 10 n mi range from the transmitter) A given wind azimuth is assumed constant at all altitudes The reference wind profile is the same one shown in Fig 1 In creasing the ground track/wind angle from a simple head wind condition reduces the time in the beam and con sequently reduces attainable altitude Large misalignment corresponding to tail winds, produce small increases in range In the case of the maximum wind profile amplitude, flight into the headwind is infeasible due to inadequate vehicle air speed

The analytical methods for performance analysis of boost glide systems are documented in Ref 13 There is no simple design algorithm for this mode of flight; an interative design process is currently required Existing study results indicate that changes in operating altitude should be an efficient way to minimize wind effects [13]

Concluding Remarks

Unmanned high altitude airplanes that receive their power from a microwave beam have unique capabilities for long endurance missions The characteristics of these vehicles also require the formulation of unconventional sets of sizing and performance analysis equations Highly simplified equations can size vehicles as a function of payload power and weight More complete analyses for sizing and performance can be formulated for continuously powered and boost glide modes of flight Analytic results indicate that a variety of strategies can be employed to enhance vehicle performance for a range of mission requirements and wind conditions

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