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DESIGN CONSIDERATIONS FOR REMOTELY PILOTED, HIGH-ALTITUDE AIRPLANES POWERED BY MICROWAVE ENERGY

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SUMMARY

A design study has been conducted for unmanned, microwave-powered airplanes that must fly with long endurance at high altitude. They are proposed to conduct communications-relay, observation, or various scientific missions above approximately 55,000 feet altitude. The special characteristics of the microwave-power system and high-altitude, low-speed vehicle are reviewed. Examples of both sizing and performance analysis are used to suggest design procedure guidelines.

INTRODUCTION

A new class of aircraft has been proposed to conduct long-endurance missions at high altitude (ref. 1). These vehicles would be unmanned and powered by microwave beams from ground-based transmitters (refs. 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 platforms (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, atmospheric sampling, and surveillance.

The vehicle and associated power system of this study have several unique components (refs. 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. Propulsion 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 environments (refs. 7 and 8). Photovoltaic power has also been studied for HAAP (refs. 9 and 10); this eliminates all constraints associated with a ground-based power supply. However, the operation of solar-powered vehicles is constrained 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 (refs. 3, 11, 12, and 13) and continuously powered (refs. 2, 5, and 6) flight.

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In each cycle of boost-glide flight, the vehicle climbs while powered, then glides back to its original altitude. The climb is assumed to occur in a vertical plane to allow for efficient tracking by the transmitter. Continuously powered flight is constrained to a conical volume swept out by the ground-station beam. The effects of winds 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 design guidelines. Analytical methods for conceptual design and performance prediction are exercised for representative payload/mission requirements to develop the design guidelines. Emphasis is placed on the relationship between vehicle design parameters and system performance for the vehicle at high altitude.

SYMBOLS

F_{sw}	ratio of structural plus control-and-navigation system weight to total vehicle weight
k	coefficients in equations (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, hr.
V_e	equivalent airspeed, ft/s
W	vehicle weight, lb.
ρ_o	air mass density, $slug/ft^3$

MICROWAVE POWER SYSTEM

The technological base for microwave power transmission has been developed over several decades (refs. 4, 14, 15, and 16). Initial rectennae provided more than 80 percent efficiency in the conversion of microwave power to direct-current electrical power (ref. 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 band has been assigned to such use and provides for virtually no attenuation by atmospheric conditions (ref. 6).

Lightweight rectennae can be constructed with three layers (refs. 3 and 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 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 (refs. 4-6). Analysis have shown that radar-disk configurations are impractically large and costly. Array antennae 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 focussing 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 configuration of the transmitting antenna (refs. 2, 6, 11, and 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 efficiency. As shown in figure 1, efficiency decreases as the vehicle flies farther from the center of the cone (refs. 2 and 6). Array antenna can sweep efficiently 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 (refs. 11-13).

Several other factors influence the efficiency of microwave power transmission (ref. 17). Both the relative orientation and the separation between the transmitter and rectenna are important. Power reception is proportional to the projected area of the rectenna visible to the tracking transmitter; power intensity is also an inverse function 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 (refs. 2 and 17). The use of a double set of rectenna foreplanes, one orthogonal to the other, may alleviate this problem.

Safety must also be a design consideration (refs. 8 and 18). Transmitter 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 (ref. 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 percent of the total cost of several million dollars. This suggests that accepting 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 is easier to track. 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 feet 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 (refs. 19 and 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 (ref. 21). The electronically commutated motors use rare-earth (Samarium-Cobalt) magnets to achieve efficiencies of greater than 90 percent (ref. 22). The brushless design eliminates the arcing problems of conventional motors operating in a rarefied 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 (ref. 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 wave-length 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 reference 24 are used as part of design criteria for this study (fig. 2). The resulting requirement for achieving a given equivalent airspeed 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 (ref. 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 conservatism.

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. On-board energy storage is heavy but can alleviate temporary attenuation of power transmission. The resulting sets of unique sizing and performance equations are applied to a series of design cases.

Simplified Vehicle-Sizing Method

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

The method utilizes simple equations for determining an initial guess on wing loading, structural weight fraction, and beam-power intensity required at the rectenna.

$$W/S = C_L \rho_o V_e^2/2 \tag{1}$$

$$F_{sw} = 1 - (k_1 P_{pay} + k_2 P_{prop} + k_3 T (P_{pay} + P_{prop}))/S\ (W/S) \tag{2}$$

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

Values for weight/power ratios (k_1, k_2 and k_3) are obtained from reference 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 figure 2 define a minimum wing loading, W/S, to overcome a headwind with prescribed probability of occurrence. The method next requires the calculation of structural weight fraction with equation (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 feet. A vehicle span of 50 feet 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 figures 3 and 4 illustrate the effect of incorporating limiting criteria into the sizing methodology. Increasing aspect ratio at fixed span decreases wing area (fig. 3). Three basic trends are shown in figure 3 for the case of no battery requirement. First, wing area for the fixed-span vehicle varies inversely with aspect ratio. Second, at sufficently 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 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 figure 4 are also produced by the same criterion for structural-weight fraction.

Analyses of results presented in figures 3 and 4 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. The limitations defined in figure 5 reflect constraints on vehicle and ground-station size. These results provide crude, optimistic guidelines. Further constraints due to considerations of transmitter power and cost will produce more severe limitations.

Continuous Power and Zero Windspeed

The requirement for continual airplane motion leads to power attenuation due to spatial relationships between the moving rectenna and the ground station. Figure 6 presents data for the simplified case of a HAAP circling above a 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 feet, an aspect ratio of 20, and a wing loading of 3 lb/ft^2. Airspeed is a constant 29.8 kts.)

Results show that power requirements of ideal, 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 require higher power transmission due to beam-pointing attenuation.

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 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 airspeed to equal windspeed; 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 reported on flight paths that minimize wind effects for vehicles constrained to fly at constant altitude (ref. 2). A "D-shaped" path can be developed from what is simply a constant-bank-angle circle at zero windspeed. At any given windspeed, 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. 7).

An alternate flight path describes a pair of contiguous circles at zero wind speed. These are achieved with alternating, full-circle turns to port and starboard. It is necessary for the major axis of this figure to be perpendicular to the wind. As windspeed increases, the vehicle continues to alternate its bank angle to fly a "figure 8" ground track (fig. 7). This pattern shrinks to a point when windspeed increases to equal airspeed.

The ratio of windspeed to airspeed determines which constant-altitude pattern should be flown. As shown in figure 7, a smaller pattern is achieved with the "figure-8" flight path if the windspeed-airspeed 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 windspeeds (ref. 2).

Boost-Glide Flight

A boost-glide flight profile simplified transmitter operations while significantly constraining the boost portion of flight. Although the beam can track only within a narrow vertical corridor, the beam can sweep efficiently over a ±45-degree deviation from the local vertical. As indicated in figure 8, a representative microwave HAAP can be tracked for about 20 nautical miles and glide well beyond that point. Less conservative estimates of the effects of tracking accuracy yield significantly greater range.

Figure 9 illustrates several basic characteristic of boost-glide performance for zero-wind conditions. Maximum achieveable 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 performance at low values of wing loading.

Wind profiles also affect the performance for boost-glide systems. Analytical results are presented in figure 10 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 feet of altitude and 10 nautical miles range from the transmitter.) The reference wind profile is the same one shown in figure 2. Increasing misalignment between the ground track and the wind (assuming wind azimuth invariant with altitude) generally reduces the time in the beam and, consequently, the attainable altitude. Increasing the misalignment leads to small increases in range due to the simple effect of changing from a headwind to a tailwind. In the case of the maximum wind-profile amplitude, the cases involving a headwind are infeasible due to inadequate vehicle airspeed.

The analytical methods for performance analysis of boost-glide systems are documented in reference 13. There is no simple design algorithm for this mode of flight: an iterative design process is currently required. Existing study results indicate that changes in operating altitude should be an efficient way to minimize wind effects (ref. 13).

Design Guidelines

The establishment of a design process for a microwave-powered HAAP is strongly affected by mission-payload requirements. An initial guess at requirements for vehicle size and configuration can be obtained with the simplified sizing method presented in this paper. The iterative use of performance analysis for continuously powered or boost-glide flight can further define vehicle characteristics essential to deal with wind effects. A rough approximation of system costs can be developed from references 3, 5, and 6.

CONCLUDING REMARKS

Both performance-analysis and simplified sizing methods have been considered for remotely piloted, high-altitude airplanes powered by microwave energy. The special characteristics of both the power-transmission system and vehicle produce a unique set of sizing and performance relationships. Adequate definition of mission and payload requirements should allow the development of basic design features of the required vehicle and system.

REFERENCES

1. Kuhner, M. B.; and McDowell, J. R.: User Definition and Mission Requirements for Unmanned Airborne Platforms. Battelle Columbus Laboratories, NASA CR-156861, 1979.

2. Sinko, J. W.: Circling Flight in Wind for HAPP Aircraft. SRI International, Technical Note SED-716, August 1978.

3. Fordyce, Samuel W.; and Brown, William C.: Applications of Free-Space Microwave-Power Transmission. Astronautics and Aeronautics, vol. 17, no. 9, September 1979, pp. 54-61.

4. Brown, William C.: A Profile of Power Transmission by Microwaves. Astronautics and Aeronautics, vol. 17, no. 5, May 1979, pp. 50-55.

5. Brown, William C.: Design Definition of a Microwave Power Reception and Conversion System for Use on a High Altitude Powered Platform. NASA CR-156866, 1981.

6. Brown, William C.: Design Study for a Ground Microwave Power Transmission System for Use With a High Altitude Powered Platform. NASA CR-168344, 1983.

7. Petrone, Frances, Jr.; and Wessel, Paul R.: HASPA Design and Flight Test Objectives. AIAA Paper Number 75-924, July 1975.

8. Graves, Ernald B.: The Feasibility of a High-Altitude Aircraft Platform With Considerations of Technological and Societal Constraints. NASA TM 84508, 1982.

9. Phillips, William H.: Some Design Considerations for Solar-Powered Aircraft. NASA TP-1675, 1980.

10. Youngblood, J. W.; and Talay, T. A.: Solar-Powered Airplane Design for Long-Endurance, High-Altitude Flight. AIAA Paper Number 82-8011, May 1982.

11. Heyson, Harry H.: Initial Feasibility Study of a Microwave Powered Sailplane as a High-Altitude Observation Platform. NASA TM 78809, 1978.

12. Turriziani, R. Victor: Sensitivity Study for a Remotely Piloted Microwave-Powered Sailplane Used as a High-Altitude Observation Platform. Kentron International, Incorporated, NASA CR-159089, 1979.

13. Morris, Charles E. K., Jr.: Parametric Study of Microwave-Powered High-Altitude Airplane Platforms Designed for Linear Flight. NASA TP 1918, 1981.

14. Brown, William C.: Experiments Involving a Microwave Beam to Power and Position a Helicopter. IEEE Tranaction on Aerospace and Electronic System, vol. AES-5, no. 5, September 1969, pp. 692-702.

15. Anon: Solar Power Satellite Microwave Power Transmission and Reception. NASA CP 2141, 1980.

16. Dickinson, R. M.; and Brown, W. C.: Radiated Microwave Power Transmission System Efficiency Measurements. JPL TM 33-727, May 1975.

17. Hansen, R. C., ed.: Microwave Scanning Antennae. Volume 1 -Apertures, 1964; Volume II - Array Theory and Practice, 1966. Academic Press.

18. Lindsay, I. R.: Microwave Radiation: Biloogical Effects and Exposure Standards. A Paper Presented at the International Symposium on Solar Power Satellites, Toulouse, France, 1980.

19. Conigliaro, P. E.: An Experimental Investigation of the Low Reynolds Number Performance of the Lissaman 7769 Airfoil. AIAA Paper Number 83-0647, 1983.

20. Liebeck, R. H.: Design of Subsonic Airfoils for High Lift. Journal of Aircraft, vol. 15, no. 9, September 1978, pp. 547-561.

21. MacCready, P. B.; Lissaman, P. B. S.; Morgan, W. R.; and Burke, J. D.: Sun Powered Aircraft Design. Journal of Aircraft, vol. 20, no. 6, June 1983, pp. 487-493.

22. Maslowski, Edward A.: Electronically Commutated dc Motors for Electric Vehicles. NASA TM 81654, 1981.

23. Waco, David E.: Variation of Turbulence With Altitude to 70,000 Feet. Journal of Aircraft, vol. 13, no. 12, December 1976, pp. 981-986.

24. Kaufman, John W., ed.: Terrestrical Environment (Climatic) Criteria Guidelines for Use in Aerospace Vehicle Development. NASA TM 78118, 1977.

25. Coates, Andrew: Jane's World Sailplanes and Motor Gliders. Flying Books, Ziff-Davis Publishing Company, Great Britain, 1978.

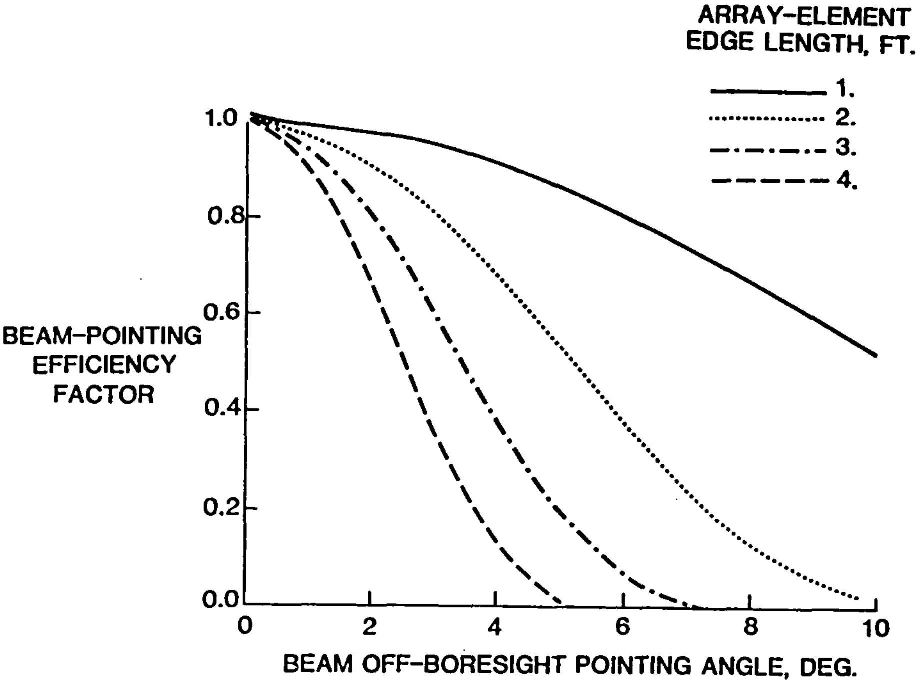

Figure 1. - Attenuation of power of microwave beam deflected from array-transmitter boresight (normal to array face).

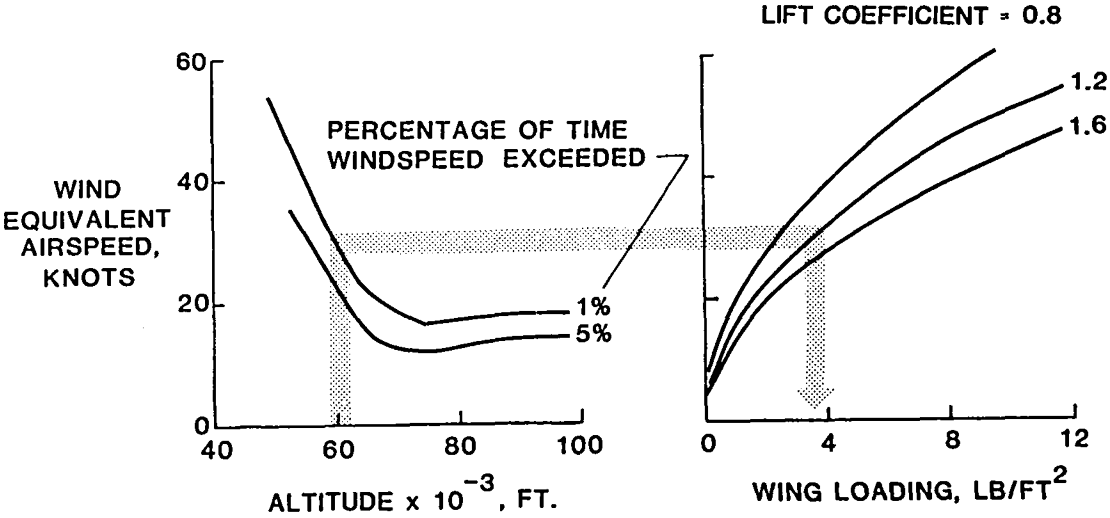

Figure 2. - Effect of statistically expected winds (ref. 24) on vehicle design.

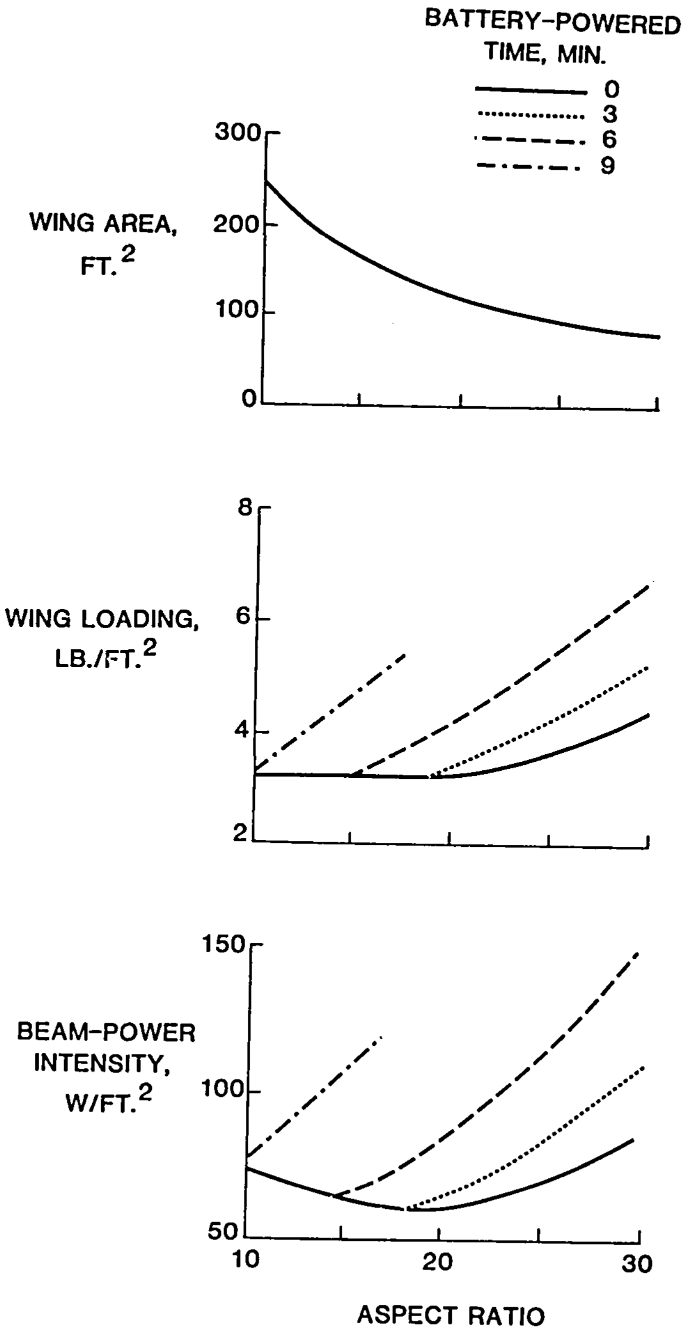

Figure 3. - Effect of wing design and energy-storage requirements on system characteristics; continuous-power for constant-span, representative HAAP.

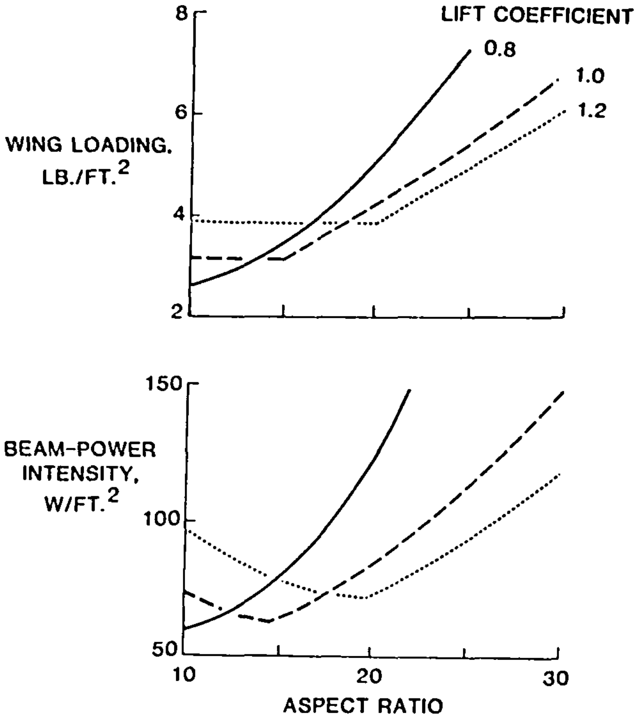

Figure 4. - Effect of varying aspect ratio and lift coefficient on system characteristics for continuous-power, constant-span, representative HAAP.

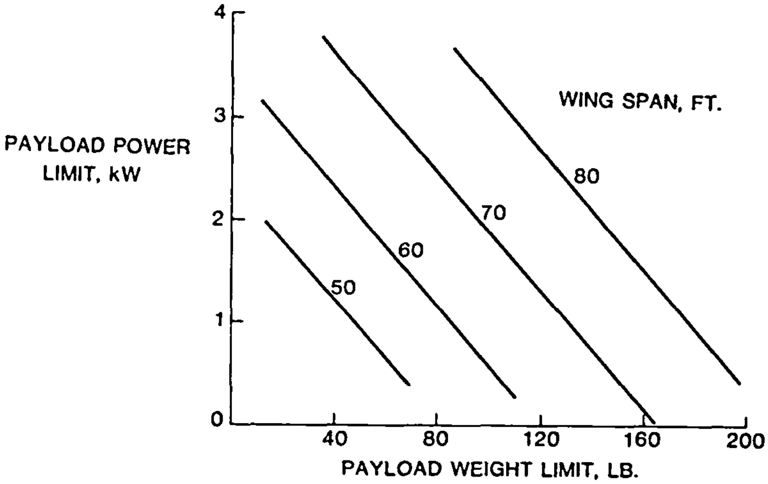

Figure 5. - Payload limitations for continuous-power baseline configuration.

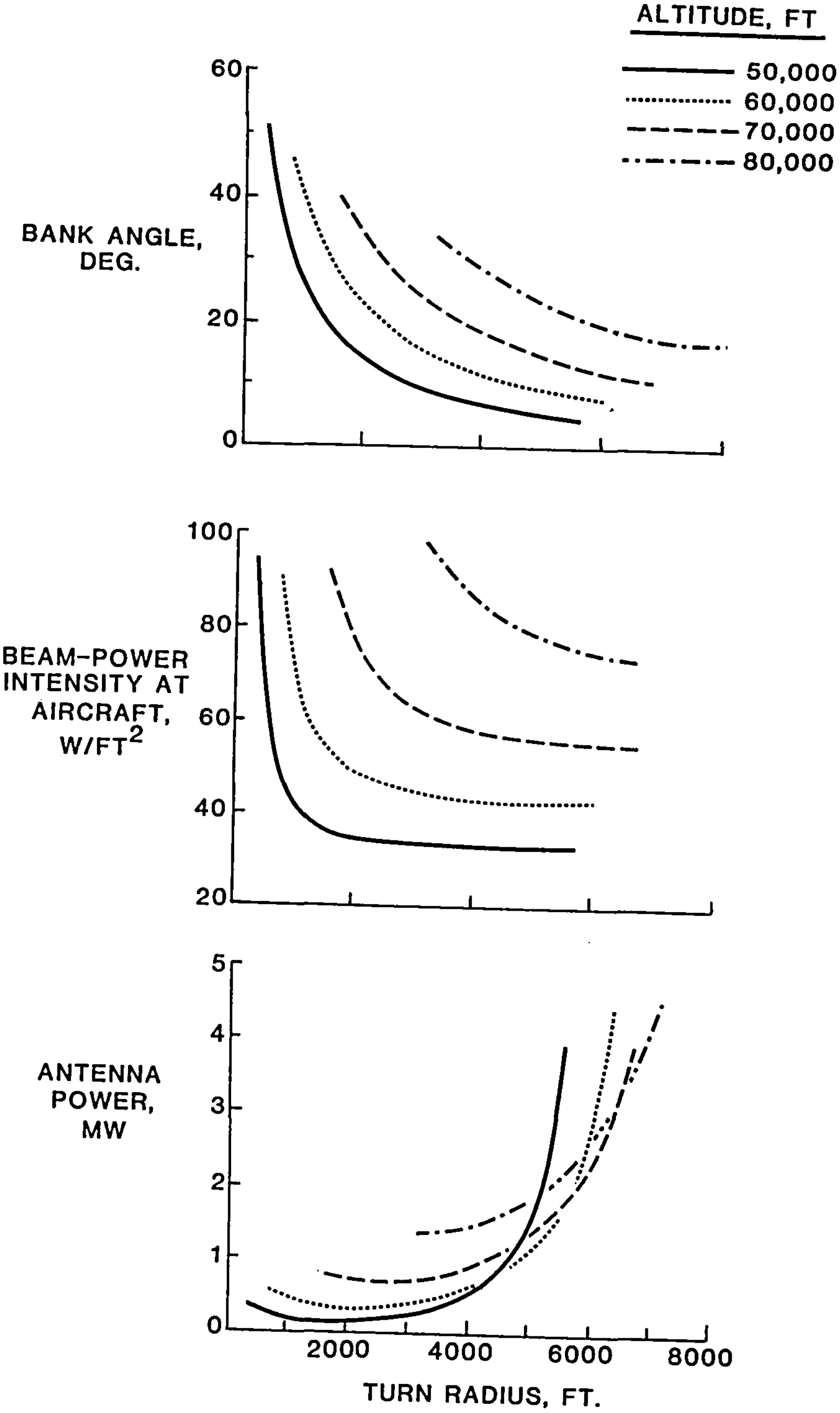

Figure 6. - Effect of variation in turn radius on HAAP system with continuous-power transmission; one representative configuration with 100-lb., 400-W payload and zero windspeed.

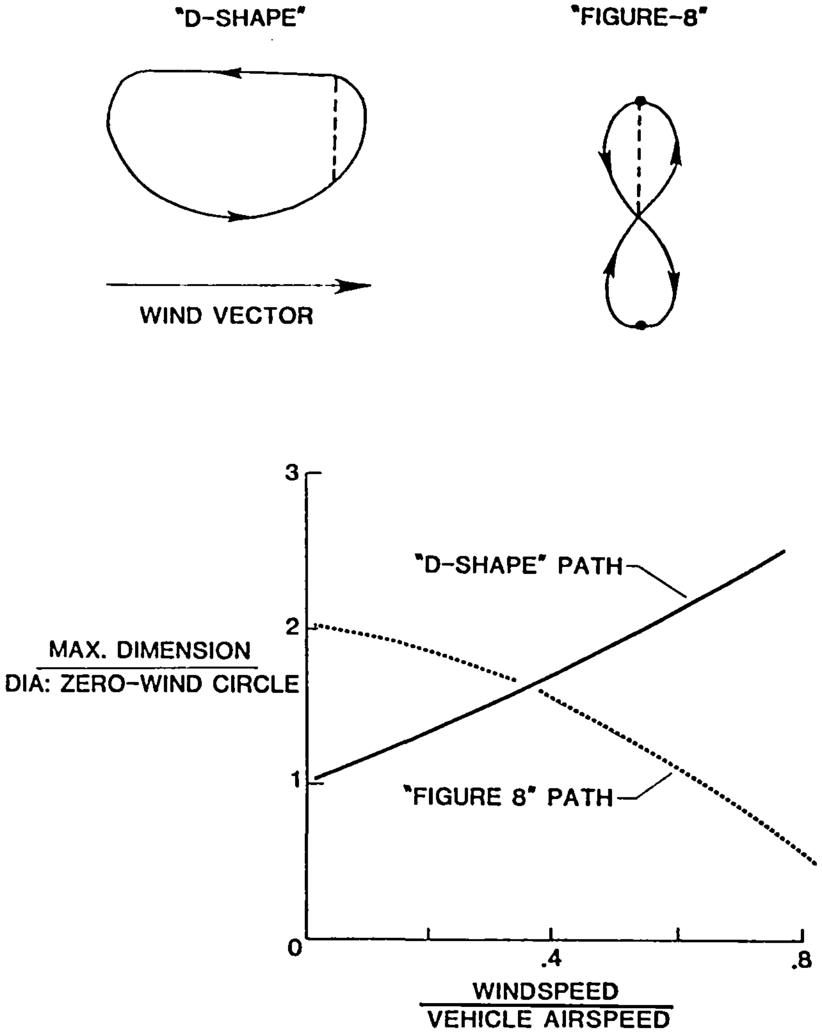

Figure 7. - Effect of windspeed on size of flight-path shapes for continuous-power, constant-altitude HAAP.

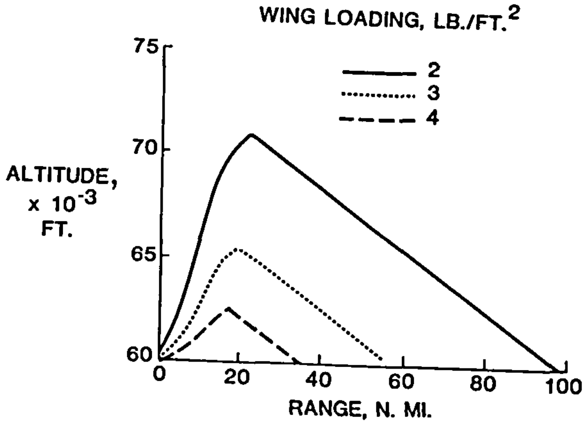

Figure 8. - Flight profiles of representative, boost-glide, microwave-powered HAAP.

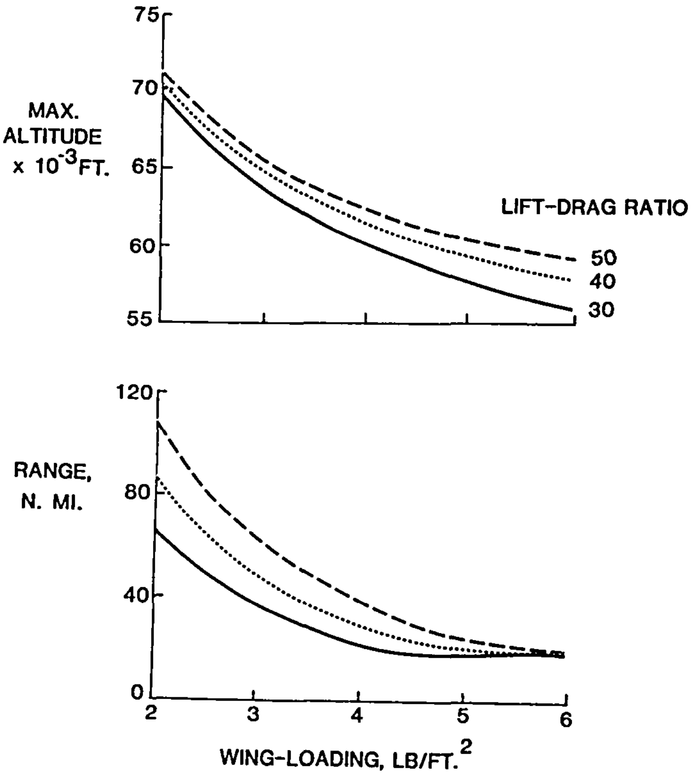

Figure 9. - Effect of wing loading and lift-drag ratio on performance of representative, boost-glide, microwave-powered HAAP.

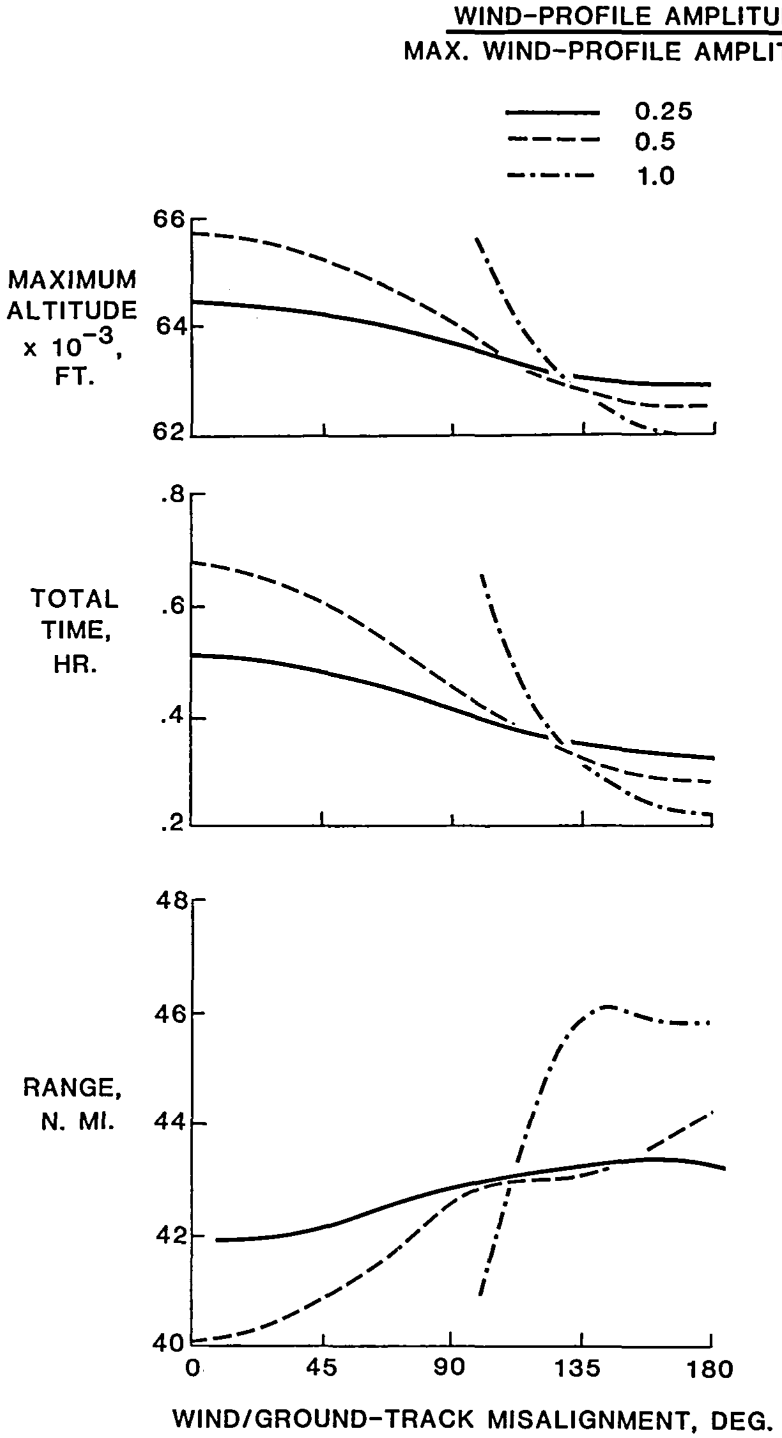

Figure 10. - Performance of representative, boost-glide, microwave-powered HAAP as affected by wind magnitude and misalignment with required ground track. (0 degree misalignment corresponds to a headwind.)

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16. Abstract

Several types of systems have been considered in a design study of unmanned, microwave-powered, long-endurance, high-altitude airplanes. The study includes vehicles that use power from a continuously transmitted beam and other aircraft that receive intermittent power during cycles of boost-glide flight. Simple design algorithms are presented. Examples of sizing and performance analyses are used to suggest design-procedure guidelines.

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