ANALYTICAL STUDY OF THE CRUISE PERFORMANCE OF A CLASS OF REMOTELY PILOTED, MICROWAVE-POWERED, HIGH-ALTITUDE AIRPLANE PLATFORMS

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SUMMARY
The performance of a class of remotely piloted, microwave-powered, high-altitude airplane platforms was studied. Each cycle of the flight profile consists of climb while the vehicle is tracked and powered by a microwave beam, followed by gliding flight back to a minimum altitude. Parameter variations were used to define the effects of changes in the characteristics of the airplane aerodynamics, the power-transmission systems, the propulsion system, and winds.

Results show that wind effects limit the reduction of wing loading and increase of lift coefficient, two effective ways to obtain longer range and endurance for each flight cycle. Calculated climb performance showed strong sensitivity to some power and propulsion parameters. A simplified method of computing gliding endurance was developed.

INTRODUCTION
Remotely piloted vehicles operating at high altitude have been proposed to perform communication or observation tasks for various regions of the Earth's surface (refs. 1 and 2). A remote power supply, such as solar radiation or a microwave beam from a ground station, could give endurance limited only by systems reliability. Applications for such high-altitude aircraft platforms include mapping, resource monitoring, relaying communications, and conducting other tasks currently performed by satellites or manned aircraft.

Long-endurance aerial platforms offer advantages over alternate systems. Endurance of a manned aircraft is limited by fuel storage and human fatigue. Furthermore, the payload and equipment must include provisions for the pilot and his environmental control system. These factors adversely affect cost and complexity. A geosynchronous satellite has long endurance; however, it also has high cost, poor resolution for observation tasks, and constraints for communications tasks because of the extreme range. A satellite operating in a low orbit passes only infrequently and briefly over a given region. Compared to a platform in the upper atmosphere, a low-orbit satellite requires observation systems to have resolutions at least six times as great for equivalent quality of results.

Several types of high-altitude aircraft platforms have been proposed. Lighter-than-air concepts have been considered (ref. 3). Some of the difficulties of operating these vehicles at altitudes of 18 km (60,000 ft) and above...
relate to the atmospheric environment. The airships would have to generate lift at air densities less than one-tenth that of sea level (ref. 4), and, according to reference 5, have the capability to fly against winds of up to approximately 50 m/s (100 kt). Airplane configurations using solar power have been discussed in references 6, 7, and 8. The study of reference 8 concludes that improved battery technology and extremely low wing loadings (down to 15 Pa (0.3 lb/ft²)) would be required. Even so, a solar-powered configuration would be constrained to operate at low latitudes to obtain enough daylight hours and at locations and altitudes with modest wind velocities.

Studies of the design and operation of microwave-powered high-altitude airplane platforms (HAAP) have been reported in references 3 and 9 to 11. The HAAP configurations of all these reports were propeller-powered airplanes operating in the low-wind region near 20 kilometers (66,000 ft) altitude. Rectennae in the wing lower surface receive microwave energy and convert it to direct-current power for electric motors. These studies indicated that the designs were feasible based on the assumption of some extrapolation of existing microwave technology (such as that described in ref. 12).

This study provides predictions of cruise performance for the class of HAAP configurations that use a "linear" mode of flight. (These are described in the feasibility study of reference 10 and the design sensitivity study of reference 10.) In that mode, the flight profile consists of powered climb near a microwave ground station, followed by gliding flight that either returns the vehicle to the same microwave ground station or carries it to another station. Launch and recovery are not addressed in this study. Emphasis is placed on vehicle design and not power transmission.

Analyses of the results of this parametric study define trends that apply to HAAP vehicles within a wide range of sizes and weights. Performance is characterized as a function of altitude at the end of climb, excess energy stored in batteries, range, and endurance for each cycle of the flight profile. Parametric studies are conducted for variations in the aerodynamic characteristics, power-transmission system, propulsion system, flight profile, and winds. A minimum altitude of 18 kilometers (59,000 ft.) was selected for all cases as a probable constraint due to wind.

Operating characteristics of a microwave-powered airplane are sufficiently unconventional to require the development of a new computer program for performance prediction. The program used in this study is documented in Appendix A.

SYMBOLS

Positive senses of some angles, axes and forces are presented in figure 1.

A wings aspect ratio

A_p propeller disk area, m²

a constant defined in equation (11)
b wing span, m; also, constant defined in equation (11)

C_D drag coefficient, D/qs

C_D,o profile-drag coefficient

C_L lift coefficient, L/qs

C_p propeller-power coefficient, P_p/\rho n^3 D_p^5

D drag, N

D_p propeller diameter, m

E_s stored energy, J

E_t total energy received, J

e Oswald efficiency factor; also, base of natural logarithms

g acceleration of gravity, 9.80 m/sec^2 at sea level

h altitude above sea level, km

h_i altitude at initiation of glide, km

h_s altitude at beam intercept point, km

J propeller advance ratio, V/nD_p

k_a acceleration correction factor (see eq. (4))

k_r microwave-beam intensity factor (see eq. (12))

k_w wind-profile scale factor

L lift, N

n propeller rotational speed, revolutions/second

P maximum power available in beam, W

P_p power absorbed by the propellers, W

P_r power available at rectenna, W

q dynamic pressure, 1/2 \rho V^2, N/m^2

R reference value of radial distance from microwave ground station, km

r actual radial distance from microwave ground station, km

S wing area, m^2
T propeller thrust, N
T_d degraded propeller thrust, N
t elapsed time, s
V true airspeed, m/s
V_e equivalent airspeed, V\sqrt{\rho/\rho_o}, m/s
V_g ground speed, m/s
V_{tip} propeller tip speed, m/s
V_w local horizontal wind speed, m/s
W vehicle gross weight, N
x horizontal range, km
x_s horizontal distance between ground station and beam intercept point, km
z dummy variable of integration, km (see eq. (B3))
\gamma flight path angle, deg
\Delta increment of parameter
\eta propeller efficiency factor
\theta microwave-beam/evaluation angle, deg
\mu angle between wind vector and required ground-track vector
\rho air density, kg/m^3
\rho_o sea-level air density, 1.255 kg/m^3

Subscripts

c end of climb
g end of glide
max maximum
t total for one climb and glide cycle

A dot over a symbol denotes differentiation with respect to time. A bar over a symbol denotes an average value.
CONCEPT DESCRIPTION

The remotely piloted, microwave-powered HAAP of this study is based on the concept described in reference 9. Drawings of representative vehicles are shown in figure 2. A baseline configuration and microwave system are described in table I.

The linear mode of flight, used in this study (and those of references 9, 10, and 11) has a two-part cycle. The climb segment begins when a microwave beam begins to track the vehicle and transmit power to it. That power is used to climb and to store energy in batteries for use by the payload, guidance, and control systems. After power transmission terminates, the vehicle begins a long glide that either carries it to another ground station or back to the same station.

The transmission of microwave energy is modeled largely with the assumptions of reference 9. The multi-element retrodirective array or equivalent antenna (ref. 11) transmits a linearly polarized beam that is focused on the rectenna built into the HAAP. The two-dimensional tracking capability of the transmitter constrains the vehicle to fly in a predefined vertical plane over the ground station. The sum of all range-related phenomenon is assumed to attenuate beam intensity as an inverse function of range.

The conceptual design of the vehicle for this study is similar to a powered version of a high-performance sailplane. The payload fraction of 0.3 contains allocations for the observation or communications payload, batteries, and the guidance and control systems. The baseline configuration calls for high aerodynamic efficiency to be achieved with high-aspect-ratio wings and extensive amounts of natural laminar flow. The wing-mounted rectenna uses linear polarization unless otherwise noted. Rectenna-received power below a minimum level for motor starting, or above the power capacity of the motor, is stored in batteries. Power in the range required for propulsion is used by high-efficiency electric motors to drive variable-pitch, constant-speed propellers. During both flight segments, the vehicle remains trimmed at one lift coefficient. Although the propellers stop and fold streamwise when not in use to reduce drag, there is still a small increment in drag during gliding flight.

A more detailed study of HAAP should consider criteria for stability, control, aeroelasticity, reliability, and other factors. The design illustrated in figure 2(b) reflects some concern for reliability by minimizing the number of essential systems. Propulsion is provided by a single propeller. Aerodynamic control is achieved through control surfaces at the end of the tail booms; differential inputs of the horizontal surfaces produce wing twist. This design was examined briefly in an unpublished study which indicated that the two vehicles of figure 2 can have the same performance, control power, and weight. The generalized approach of this study is not constrained by choice of configuration.
ANALYSIS

The evaluation of vehicle performance for a microwave-powered airplane requires mathematical modeling of vehicle motion, atmospheric effects (including wind), power transmission, and propulsion-system characteristics. The development of the equations used in the microwave-HAAP performance program of Appendix A is given in the following sections.

Flight Mechanics

Equations for force balance along the body axes can be developed with the conventions shown in figure 1(a). The associated assumptions are that: thrust and drag act along the same axis; airspeed is adjusted by changing flight-path angle to obtain the required lift; configuration lift coefficient remains constant; and excess thrust is used to climb. The resulting equations are:

\[ L - W \cos \gamma = 0 \]  \hspace{1cm} (1)

\[ T - D - W \sin \gamma - W \frac{\dot{V}}{g} = 0 \] \hspace{1cm} (2)

These equations can be modified to obtain the forms used in the performance program of Appendix A. First, thrust can be described in terms of propeller efficiency as:

\[ T = \eta \frac{P_P}{V} \] \hspace{1cm} (3)

The term for the inertial acceleration force can be written as follows:

\[ \frac{W}{g} \dot{V} = \frac{W}{g} \frac{dV}{dh} = \frac{W}{g} \frac{dV}{dt} \frac{1}{g} \sin \gamma \]

For sufficiently small increments of altitude, an acceleration correction factor \( k_a \) can be defined as:

\[ k_a = \frac{V}{g} \frac{dV}{dh} = \frac{V}{g} \frac{\Delta V}{\Delta h} \] \hspace{1cm} (4)

Thus, equation (2) can be rewritten as:

\[ \eta \frac{P_P}{V} - D - (1 + k_a) W \sin \gamma = 0 \] \hspace{1cm} (5)

An expression for true airspeed, obtained from equation (1) may be written as:

\[ V = \sqrt{\frac{W}{S} \frac{2 \cos \gamma}{\rho C_L}} \] \hspace{1cm} (6)

Except for the term \( \cos \gamma \), equivalent airspeed is simply the equilibrium airspeed for a given configuration at sea level.
The equations for the vehicle trajectory above a flat earth are based on the conventions shown in parts (b) and (c) of figure 1:

\[ V \cos \gamma \sin \phi - V_w \sin \mu = 0 \] (8)

\[ \frac{\dot{x}}{V} - V \cos \gamma \cos \phi + V_w \cos \mu = 0 \] (9)

\[ \dot{h} - V \sin \gamma = 0 \] (10)

The use of these equations assumes that the airplane heading is automatically adjusted to compensate for the effects of wind. During climb, the resulting flight path must lie in the unique vertical plane swept out by the path of the microwave beam.

Several parameters are functions of altitude. Air density is modeled on the geometric standard atmosphere of reference 4. The ratio of local density to sea-level density is calculated as

\[ \frac{\rho}{\rho_0} = e^{-ah} - bh^2 \] (11)

where the exponential coefficients hold constant over a typical altitude increment of two kilometers. As in reference 10, it is assumed that \( L/D \) increases with altitude for the operating range of cruise altitudes because of the greater extent of laminar flow. The value of \( L/D \) is decremented (as a function of propeller size) for glide because of the drag of the folded propeller.

### Power Transmission

The available power at the vehicle rectenna is assumed to be proportional to both range and the angular orientation of the rectenna surface with respect to the beam. Although the beam is considered to be focused, the effects of focusing precision and other factors are represented by a reciprocal relationship with range:

\[ P_r \propto (R/r)^{kr} \] (12)

where \( R \) is a reference radial range from the ground station, \( r \) is the true radial range, and \( k_r \) has a nominal value of 1.0. The power available is assumed to be proportional to the projected area of the rectenna that can be observed from the microwave ground station (eq. 122, vol. 2 of ref. 13). This can be approximated as

\[ P_r \propto S \sin (\Theta + \gamma) \] (13)

If both transmitter and rectenna use linear polarization, the power transfer can be conservatively approximated as a function of the phase angle between the two units (ref. 14 and eq. 25, vol. 1 of ref. 13):
If the rectenna or antenna have circular polarization, then the transmission efficiency drops by a factor of one half but remains unaffected by relative ground angle between the antenna and rectenna axes.

All of these power-transmission relationships (expressions 12, 13, and 14) can be combined into one equation. It is convenient to describe power available for storage or propulsion in terms of power per unit weight as:

\[
\frac{P_r}{W} = \frac{P}{S} \left( \frac{S}{W} \right) \left( \frac{R}{r} \right)^{k_r} \sin (\theta + \gamma) \cos^2 \phi
\]  

where \( P/S \) is the maximum transmitted power per unit wing area available at the reference range \( R \), \( W/S \) is wing loading, and both antenna and rectenna have linear polarization. As used in Appendix A, the equation, in addition, assumes an efficiency factor of 74 percent between the power reaching the rectenna surface and the power delivered to either the propeller shaft or the batteries.

### Propulsion

Values of propulsive efficiency (eq. (3)) are determined from the tabulated values of reference 15 and are given as functions of advance ratio \( J \) and propeller-power coefficient \( C_p \). These latter quantities can be determined as functions of both calculated and input parameters of the program of Appendix A:

\[
J = \frac{\pi V}{V_{\text{tip}}}
\]

\[
C_p = \frac{\pi^4}{8} \left( \frac{P_p}{A_p} \right) \left( \frac{1}{V_{\text{tip}}} \right)^3
\]

\[
\frac{P_p}{A_p} = \frac{P_p}{W} \left( \frac{W}{S} \right) \frac{S}{A_p}
\]

where \( P_p/W \) is the power available to the propulsion system. It can be shown that net thrust for any number of propellers can be determined with this method if: \( A_p \) is total propeller-disk area; \( P_p \) is total power absorbed by the propellers; and all propellers have the same value of both tip speed and power loading (\( P_p/A_p \)).

The program of Appendix A imposes both an upper and lower limit on the power-to-weight ratio of equation (18). As shown in the sketch below all energy not used for propulsion is stored.
The model of the wind aloft is based on one set of wind data. This data is the 99 percent profile of reference 5 in figure 3 which describes a wind profile that is exceeded only one percent of the time at five sites in the United States. Figure 3 shows that the profile shifts substantially when the probability of including all winds is decreased from 99 to 95 percent. The second 99 percent profile of figure 3 is based on data from a world-wide set of sites (ref. 16) and indicates that the reference wind profile is reasonable but generally conservative. In the computer program of Appendix A, the magnitude of the wind at a given altitude is the product of the associated value from the reference profile and an amplitude factor $k_w$. In the program, the direction of the wind vector at any altitude is assumed to remain constant at the same azimuth throughout an entire climb-glide cycle.

DISCUSSION OF RESULTS

The results of calculations of HAAP system performance are presented to show the effect of variations in aerodynamic, power-system, and other parameters. Although not all of the combinations of values represent reasonable systems, the more extreme sets help to define trends. In most cases, the results are compared with the performance of the baseline HAAP system described in Table I. (This baseline system is similar to, but not identical with, that of reference 9.)

The variety of potential uses for a HAAP system has led to the use of several measures of performance to define results for most sections of this study. Requirements for a nominal ground-track pattern and the availability of sites for ground stations could produce emphasis on long endurance (total time per flight cycle) and zero-wind range. The need for high resolution in
observation tasks and wide-area coverage in communications tasks may produce some differences in the specifications for maximum altitude capability. Wide variations may also occur in the level of stored energy required to operate each payload as well as guidance and control systems. Therefore, the results presented for each parametric variation usually include range, endurance, final climb altitude, and stored energy.

**Typical Flights**

One cycle of flight is presented in figures 4 and 5 for each of three HAAP configurations with differing wing loadings. The essentially linear flight profile for gliding flight in figure 4 is a direct function of \( \frac{L}{D} \). As shown in figure 5, the climb segment is affected by numerous parameters. The low wing-loading case of \( \frac{W}{S} = 50 \text{ Pa} \) (1.0 lbf/ft\(^2\)) has a fairly simple calculated history. During climb, the flight path is fairly linear, the rate of climb nearly constant, and the propeller provides thrust all of the time. The highest wing-loading case of \( \frac{W}{S} = 250 \text{ Pa} \) (5.2 lbf/ft\(^2\)) has an "s-shaped" climb profile (fig. 4) and climb history (fig. 5). Initially, the relatively smaller wing for \( \frac{W}{S} = 250 \text{ Pa} \) does not receive enough power to start the motors. The airplane continues to store the received energy and to lose altitude as it glides nearer to the ground station (fig. 5(b)). When it is close enough to receive adequate power, the airplane uses all available power to climb. Near the end of the nominal climb period, the power received again drops below the minimum level. The airplane then glides and stores the received energy again. This latter glide segment illustrates the reasons that \( h_c \) can be less than the maximum altitude achieved in climb.

Figure 5 indicates that there are strong relationships between performance, power available, and the flight path (defined with respect to the ground station). Consequently, the flight profile could be changed to maximize stored energy or some other parameter. All subsequent sets of results, however, are obtained for the simple, nominal type of flight at constant lift coefficient.

**Equivalent Airspeed**

The design value of \( V_e \) is important for a HAAP vehicle. As shown in equation (7) and figure 6, \( V_e \) is a function of both \( C_L \) and \( \frac{W}{S} \). Maximizing \( L/D \) to improve range leads to the selection of the highest value of \( C_L \) that allows some margin of safety against stall. Requirements for adequate rectenna area and for long endurance (i.e., slow descent rate) can produce design emphasis on low values of \( \frac{W}{S} \). Figure 6 shows that these design trends lead to low values of \( V_e \).

The effect of winds produce constraints on the minimum acceptable level of \( V_e \). Figure 7 presents a wind profile that is exceeded only one-percent of the time at five sites (ref. 5). As indicated in a subsequent discussion on wind effects, this profile can provide a reasonable design criteria for HAAP vehicles that must avoid being blown away from a given site. The data suggests that \( V_e \) above 16.6 m/s (32.2 knots) is required if flight profiles extend to
as low as 18 kilometers in altitude. Application of this criteria to the data of figure 6 limits $C_L$ as a function of $W/S$.

### Airplane Aerodynamic Characteristics

The effect of $W/S$ and $L/D$ on HAAP performance are evaluated in figure 8. The parameter $W/S$ also affects the power and propulsion system, since the rectenna is assumed to cover all the wing area $S$. Thus, decreasing $W/S$ increases available power per unit weight. Large propulsion systems can then operate the propeller continuously at full power during climb. As shown in figure 5, this effect can result in a sustained high rate of climb. Figure 8 shows that reductions in $W/S$ produce substantial improvements in attainable altitude and, below about $W/S = 100$ Pa, large increases in stored energy. Variations in $L/D$ have relatively less effect on altitude and energy performance than variations in $W/S$. Range and endurance are both increased by reduced $W/S$ or by increased $L/D$. (In the case of the baseline HAAP, Reynolds number effects change $L/D$ as a function of altitude; however, the performance in that case can be shown to vary less than one percent from the performance for $L/D = 45$ and $W/S = 100$ Pa ($2.1 \text{ lbf/ft}^2$).)

The effect of $L/D$ can also be considered in light of the independent effects of $C_L$ and $C_D$ (fig. 9). The value of $C_D$ is assumed to be calculated as

$$C_D = C_{D,0} + C_L^2 / A_e$$

The set of $C_{D,0}$ values used provides reasonable agreement between the maximum values of calculated $L/D$ and those obtained from references 17 and 18. The effect of induced drag reduces the level of $L/D$ that results from simply increasing $C_L$ (fig. 9(a)). Both $C_L$ and $C_{D,0}$ appear to have significant effects on range and endurance. All of the trends for changes aerodynamic are in agreement with those determined in reference 11.

### Gliding Flight

A simplified analysis of gliding-flight endurance can be accomplished with an approximate solution to the expression of reference 8 for glide time between specified altitudes. Appendix B presents the development of an expression for a glide-time parameter $t_{gV_e}(D/L)$ which is independent of configuration.

An approximation for air density as a function of altitude allows the glide-endurance equation to assume integrable form. Figures 10 and 11 provide a means of comparing that the appropriate function with the values given in reference 4. Figure 11 shows that the two density models are in good agreement between 18 and 23 kilometers (59,000 and 75,000 ft), which is the altitude range of interest.

The glide-time parameter can be used to determine the relative endurance achieved by gliding between different sets of initial and final altitudes. Figure 12 presents the glide-time parameter as a function of initial altitude.
and altitude decrements. The computed results show that a given decrement of altitude yields a larger glide time at lower altitudes. This occurs because the vehicle travels more slowly through the denser atmosphere at lower altitudes.

Results of gliding-endurance calculations are compared in figures 13 and 14 for the computer program of Appendix A and the closed-form solution of Appendix B. The computer program has the advantage of accounting for acceleration effects and of using a more detailed model of density variation with altitude. The figures show that agreement between the methods is best at low values of \( W/S \), \( L/D \), and \( h_c \). If the acceleration correction factor is removed from the computer program, the computer yields glide times which are virtually identical to those given by the closed-form method of Appendix B.

Power Transmission System

Climb performance is strongly affected by numerous interrelated parameters that characterize the power transmission system. As shown in equation (15) these include \( P/S \), \( R \), and \( k_r \). Parametric variations are considered here even though further development of microwave technology may lead to revisions of equation (15). The review of the present results is simplified by presenting only climb performance since gliding flight has already been treated.

The character of beam-range effects is controlled by the exponent \( k_r \) in equation (15). As shown in figure 15, focused power is independent of range at \( k_r = 1 \). For any value of \( k_r > 0 \), the equation requires that received power increases indefinitely as \( r/R \) approaches 0. In the present study, the values of \( r/R \) range from about 0.4 to 1.0, and the effect of \( k_r \) does not reach physically implausible proportions for \( k_r = 1 \). In an real system the transmitter would have a finite value of beam intensity at zero range; beyond a given range some value of \( k_r \) would model the beam attenuation. Thus, increases in only \( k_r \) imply a disproportionately large increase in actual transmitter power. Due to the large value of \( R \), \( r/R \leq 1 \) during climb; since the effect of \( k_r \) is amplification at those regions, power intensity is always equal to or greater than the reference value \( P/S \).

Climb performance is presented as a function of \( k_r \) in figure 16 and several climb histories are presented in figure 17. Increasing \( k_r \) appears to allow the value of final climb altitude to increase asymptotically to a maximum and stored energy to increase exponentially. Since \( r/R \leq 1 \), increasing \( k_r \) simply increases available power at the vehicle. The calculated results appear to be opposite to the effects that would be anticipated from an increasing decay of beam intensity with distance; however, the short ranges and the implied large increase in transmitted power overcome the effects of decay rate.

Climb performance is also sensitive to reference range \( R \) and the power density at that range \( P/S \). Increasing \( P/S \) leads to large increases in stored energy (fig. 18) and allows the vehicle to climb higher. However, as in the case of \( (P_p/W)_{max} = 4 \) W/N in figure 18, motor size can limit altitude, no matter how much power is received. Similar trends are shown for increasing \( R \) in figure 19. Increases in \( R \) or \( P/S \) are also associated with large increases in transmitted power.
The initial range and altitude for beam intercept also affects climb performance. Figure 20 shows that beam interceptions at longer range permit higher altitudes to be attained. However, the trajectories of these higher flying vehicles can reduce the amount of stored energy per flight cycle due to the attenuation of received power with range. This attenuation and the decrease of density with altitude combine to determine vehicle ceiling. As shown in figure 21, both the rate of climb and the energy storage for the baseline configuration can be estimated to be negligible at an altitude of about 29 km (95,000 ft.).

Propulsion System

The effects of variations in overall propulsion-system efficiency are shown in figure 22. The computer program of Appendix A determines $\eta$ as a function of $J$ and $C_p$ from a conventional propeller-performance table (ref. 15). This tabulated data does not reflect any effects of high-altitude, low Reynolds number phenomena on propeller aerodynamics. This omission, and other simplifications, may lead to optimistic predictions of propeller performance. The result of operating with degraded thrust $T_d$ is a nearly linear decrease in attainable altitude (fig. 23). This indicates that even a small degradation in propulsion-system efficiency translates into noticeable performance decreases.

The effect of relative motor size is shown in figure 23. The parameter $(P_p/W)_{\text{max}}$ reflects not only the maximum power that the propulsion system can absorb, it also indicates the ratio of motor size to total vehicle weight. The largest value of $(P_p/W)_{\text{max}}$ considered here is twice that of the baseline configuration. The computed results show that increasing the relative size of the motor generally leads to decreases in stored energy and to increases in attainable altitude until a maximum performance level is achieved. Beyond that point, increasing $(P_p/W)_{\text{max}}$ is detrimental to performance. This variation indicates that the optimization of propulsion parameters is a function of wing loading (and rectenna size).

A review of the calculated flight histories leading to the results of figure 23 reveals that the variation in performance is related to both trajectory characteristics and limits on the minimum power required. The vehicle with the larger motor may have to glide closer to the ground station before receiving enough power to overcome starting loads and other constraints. The more powerful vehicle climbs faster and generally flies a higher trajectory as it passes over the ground station. The more powerful vehicle then reaches the minimum $(P_p/W)$ condition and begins its glide phase sooner. Detailed design of a HAAP will apparently be sensitive to constraints on minimum and maximum motor power.

The effect of two propeller parameters on climb performance is shown in figure 23 and 24. The baseline value of tip speed (172 m/s) appears to be a good selection (fig. 24), although performance appears to be fairly insensitive to small variations in that parameter until the tip speed encounters compressibility effects. The area ratio $S/A_p$ is a somewhat artificial parameter that is a convenient element in equation (18). That measure of relative propeller size is also set at a good value in the baseline configuration ($S/A_p = 2.65$).
Winds Aloft

Although winds aloft can greatly influence the success of any given mission, wind effects on HAAP design are difficult to quantify. The statistical nature of basic wind data (refs. 5, 16, and 19) must be properly evaluated to avoid developing excessively stringent design criteria. Wind profiles that are exceeded only one percent of the time probably provide adequate design guidelines. The winds that exceed those limits tend to be associated with large storms occurring at lower altitudes. These more detectible, lower-altitude phenomena may provide enough warning to make appropriate changes in the flight program, such as maintaining as much altitude as possible. In addition, the relationships of wind direction at different altitudes are not considered in most sources of data. Nonuniformity of wind direction at different altitudes may make HAAP operations easier than predicted for uniform wind direction.

Operational limits imposed by winds tend to affect HAAP operations at lower altitudes. Figure 7 shows that for $V_e \geq 10$ m/s (19 kt), the selection of a design value of $V_e$ for lower altitudes will ensure an adequate margin of true airspeed $V$ at higher altitudes. Thus, operations need not be restricted to the nominal low-wind region of about 20 kilometers (66,000 ft).

HAAP operations with actual real-time wind profiles will be more complex than for the flight trajectories considered in this study. Profiles for mean wind values from reference 19 show consistent trends with altitude of different seasons in figure 26(a); however, the associated data of figure 26(b) show there is a considerable variation possible between the mean and instantaneous values. Below 18 kilometers altitude, the mean winds blow predominately from west to east, although the instantaneous value appears to vary considerably (fig. 26(b)). Data from references 16 and 19 clearly indicate that winds at 18 kilometers and above are typically much stronger in winter. Despite the evidence of complexity, this study models winds on the basis of the profile shown in figure 7 and on the assumption of uniform wind direction. The wind-profile scale factor $k_w$ affects only the magnitude of the nominal profile (ref. 5); $k_w$ does not directly reflect the probability level of encountering that profile.

Studies were conducted of the effect of wind-profile magnitude and wind direction relative to required ground track. The first cases to be considered are those for the baseline HAAP configuration with a headwind or tailwind over the nominal ground track (fig. 27). Increases in wind-profile magnitude for a headwind ($\mu = 0^\circ$) reduce groundspeed and increase the amount of time spent in passing over the ground station. The additional energy available through the extended climb period produces substantial increases in attainable altitude; however, the headwinds affect the glide for a longer period of time and can substantially reduce total range. The reverse relationships appear true for tailwinds. The data for $\mu = 0^\circ$ terminates at $k_w = 0.97$ because headwinds at 18 kilometers, the initial altitude, can become no stronger without blowing the vehicles away from the ground station.

As shown in figure 1(c), adjustments to vehicle heading can cause the vector summation of wind and airspeed velocities to produce the desired ground track.
for the HAAP (for sufficiently low wind speeds). However, if the vehicle rectenna is not exactly aligned with the transmitting antenna, the use of linear polarization will result in a reduction in power-transmission efficiency (eq. (14)). The effect of parametric variations in wind conditions is shown in figure 28. As in figure 27, the absence of calculated results for a given condition indicates that the baseline HAAP configuration could not fly in those winds. Typical performance near to limiting conditions is shown in figure 28(a) for $\mu = 45^\circ$ and $k_w = 0.74$. As winds approach limiting conditions, the vehicle spends a large part of its climb time in slowly making headway at the lowest altitudes (near 18 kilometers); power storage increases significantly, but final altitude decreases. Figure 28 shows that as amplitude of the wind profile increases, only tailwinds permit flight. In all cases, the unsuccessful attempts at flight were terminated by winds at 18 kilometers blowing the vehicle away from the ground station.

Flight with more severe wind profiles would be possible for all wind directions if the baseline configuration or flight plan were modified. Previously discussed results show that increasing the design value of equivalent airspeed could allow the vehicle to operate in the presence of stronger winds. Another solution would be to increase the value of minimum altitude. As shown in figure 7, the nominal wind profile for this study is more severe at the lower altitudes. Figure 26 shows that such data is representative. An alternate solution would be to accept the cost and complexity of circular polarization, at least for the transmitter. The relative benefits of the last two methods are suggested in figure 29. If stored energy is not a limiting factor, the restriction of the flight profile to higher altitudes appears to offer a simple, viable solution.

Although turbulence and wind shear affect the development on HAAP design criteria, these effects are not considered herein. Some limited data on these phenomena at high altitude are available in references 20 and 21.

CONCLUDING REMARKS

A parametric study of performance has been conducted for remotely-piloted, microwave-powered, high-altitude airplane platforms. The nominal flight plan consists of climb and glide cycles: while receiving power, the vehicle climbs and stores excess energy; it then glides back down to a minimum altitude above a microwave ground station.

Calculated results identified several basic trends. Low values of wing loading and high values of lift coefficient were shown to result in long range, long endurance, and low equivalent airspeed. Wind effects constrain the lower limits of both equivalent airspeed and operating altitude. Calculations also showed that power-transmission and propulsion-system characteristics could strongly affect climb performance. An approximate, closed-form solution was developed to predict gliding endurance.
A computer program has been developed to calculate the performance of a HAAP vehicle. This appendix contains a listing of the program, a sample input file and the corresponding sample set of output listing. The results presented in the output listing can be interpreted with the description of variable names given in Tables II and III.

The program calculations and logic are based on the HAAP operating procedures as described in the main report. The program calculates the flight trajectory and system performance at specified intervals of time. These intervals are 10 seconds for climb and 20 seconds for glide unless the end of climb or glide is approached; at that point, the intervals are adjusted to be one-tenth their previous value. The only configuration change allowed during a given flight is the folding or unfolding of the propellers.

The program yields results for parametric studies. The first set of output information describes initial conditions in terms of the characteristics of the airplane aerodynamics, propeller and power-system variables, wind and trajectory parameters. The listings presented in columns provide histories of performance and flight mechanics. For each run, the input parameter being varied is listed in the first column on the left. Each set of parametric variations may be conducted for performance at a single point (with respect to the ground station), during climb or glide only, or throughout an entire climb and glide cycle.

The sample case included in this appendix illustrates the effect of wind magnitude. Performance is calculated for the baseline configuration HAAP with winds at right angles to the nominal ground ($\mu = 90^\circ$). The required inputs are: $N_1 = 3$, $N_2 = 10$, $A_M = 90^\circ$, $S_1 = 0$, $S_F = 1.0$, and $S_S = 0.2$. Results indicate that a full strength wind profile does not allow the vehicle to initiate climb at 18 kilometers.
PROGRAM YAAP (INPUT, OUTPUT, TAPE6, INPUT, TAPE6, OUTPUT)

DIMENSION A(5), BDN(17), BD(17), Z(8,20)

A - ALPHANUMERIC LABEL, BDN - NAMES OF ELEMENTS OF BASELINE DATA ARRAY
BD - BASELINE DATA ARRAY, Z - FINAL OUTPUT ARRAY

COMMON /PAAH/ WOS, CL, 3L00, HLD0, TS, SOAP, POS, RR, POWL, WK, AMU,
1     XS, HS, POWK, TDOT, HI, RKR, AK, ETA, GAMMA, POW, P0WP, P0WS, PSID,
2   P, RLOD, ROC, THETA, VE, VG, VT, P0CP, PJ, N4, N5, X, H

EQUIVALENCE (BD(1), WOS)

NAMELIST/DD/ WOS, CL, 3L00, HLD0, TS, SOAP, POS, RR, POWL, WK, AMU,
1     XS, HS, SI, SF, SS, N1, N2, N3, N4, TDOT, POWR, HI, RKR

DATA WOS, CL, 3L00, HLD0, TS, SOAP, POS, RR, POWL, WK, AMU,
1     XS, HS, SI, SF, SS, N1, N2, N3, N4, TDOT, POWR, HI, RKR/
2 144.0, 9.36, 0.415, 172.0, 2.653, 1.150, 0.862, 0.0, 0.0, 0.0,
3  40.0, 18.0, 0.0, 0.0, 0.0, 2.50, 1.0, 0.0, 25.0, 25.0, 1.0

DATA BDN/7H W/S, 6H CL, 8H L/D-B, 8H L/D-H, 6H TS,
1     8H S/A-P, 7H P/S, 6H RR, 8H P/W-L, 6H WK,
2     6H MU, 5H XS, 5H HS, 9H P/W M-M, 7H TDOT,
3     5H HI, 6H PKR/

13.HS 14.P0WR 15.TDOT 16.HI 17.RKR

PARAMETER VARIATION CODE SI - INITIAL VALUE
SF - FINAL VALUE
SS - STEP INCREMENT (POSITIVE OR NEGATIVE)

CONTROL CODE N1 -(SINGLE POINT, CLIMB, TOTAL FLIGHT, GLIDE ONLY)
N2 -(ELEMENT IN ARRAY BD TO BE VARIED)
N3 -(NUMBER OF CALCULATION POINTS PER LISTED LINE)
N4 -(RECTENNA POLARIZATION - LINEAR OR CIRCULAR)
N5 -(CDDF=1 WHEN VG< 0)

100 FORMAT (1H1, 5X, 5A10// 5X, 14HAIRCRAFT AER,, 7X, 9HPROPELLER, 11X,
1 5HP0WER, 14X, 5HWINDS, 9X, 11HSTART POINT, 4X, 12HVARIABLE SET,
GO TO 3
2 X = 0.0
H = HS
IF (N1.EQ.1.OR.N1.EQ.4) GO TO 3
WRITE (6,200) BD(N2)
DO 300 I=1,M
WRITE (6,202) Z(I,1),Z(2,1),Z(3,1),Z(4,1),Z(5,1),Z(6,1),Z(7,1),Z(8,1)
300 CONTINUE
3 READ (5,101) A
IF (EOF(5)) 199,4
4 READ (5,30) 80
WRITE (6,100) A, NOS, TS, POS, N, X, S, N1, N2, CL, SOAP, RR, AMU, HS, SF
2 N = 0
C N2 - PARAMETER FOR VARIATION, CHOSEN FROM ARRAY BD
85 7 WRITE (6,111) BD(N2)
   C INITIALIZE PARAMETER --- NEW STARTING POINT IS NEW X OR Y
   N5= 0
   BD(N2)= SI
   GO TO 17
90  C
13  Z (2, N)= X
    Z (3, N)= H
    Z (4, N)= TT
    Z (5, N)= EDWS
    Z (6, N)= EDWT
    IF (N1.EQ.3) GO TO 40
95  C
14  INCREMENT PARAMETER
100  C CONTINUE
105     N5= 0
    IF (N1.NQ.3) Z(7, N)= X
    IF (N1.EQ.3) Z(8, N)= TG
    IF (N1.EQ.4) WRITE (6,201) TG
110  C
16  BD(N2)= 3D(N2) +SS
    DELTA= SF -BD(N2)
    IF (SS.GT.0...AND.DELTA.GE.0.) GO TO 17
    IF (SS.LT.0...AND.DELTA.LE.0.) GO TO 17
115  C
17  N= N+1
    Z(I, N)= BD(N2)
    GO TO (20, 30, 30, 39) ,N1
120  C
125  C CALCULATE VALUES AT ONE POINT
20  T= 0.
    X= C.
    H= HS
    EDWS= 0.
    EDWT= 0.
    GAMMA= 0.
    CALL RCLIMB
    WRITE (6,113) BD(N2), X, H, ROC, POWP, POWS, GAMMA, THETA, R, VG, VT,
    1        VE, T, AK, ETA, PCP, PJ, PSID
125  WRITE (6,114) GO TO 14
C CALCULATE TOTAL CLIMB PHASE

30 NK= 0
POW1= 0.0
POWS1= 0.
GAMMA= 0.
THETA= 0.0
T= 0.

135 EDWS= 0.
EDWT= 0.
RR95= RR* .95
TT= 0.
X= 0.0
H= 45.
TDEL= 10.
WRITE (6,114)

C N3 - PRINTOUT INCREMENT FOR COMPLETE CLIMB

145 IF (NK.EQ.N3) NK= 0
GAMMA= GAMMA/57.2957
31 IF (N5.GE.1) GO TO 14
32 CALL RCLIMF
IF (R*GT.RR95,AND.THETA.LT.90.) TDEL= 1.
150 IF (T.EQ.0.) GO TO 35
NK= NK+1

C X AND H GIVEN IN KM

155 X= X +VG*TDEL/1000.
H= H +ROC*TDEL/1000.

C SPECIFIC-ENERGY INCREMENTS FROM AVERAGED POWER FOR TIME INCREMENT
C STORED SPECIFIC ENERGY (E/W-S) AND TOTAL UTILIZED SPECIFIC
C ENERG Y (E/W-T) ARF GIVEN IN KJ/N

160 EDWS= EDWS +POWS+POWS1)*TDEL/2000.
POWS1= POWS
EDWT= EDWT +(POW+POW1)*TDEL/2000.
POW1= POW
IF (R.GT.RR.AND.THETA.LT.90) GO TO 35
165 IF (X.LT.0.) GO TO 35
IF (NK.EQ.N4) GO TO 35
T= T+TDEL
GO TO 31
C WRITE DATA FOR ONE INCREMENT OF CLIMB OR FINAL CLIMB POINT
   170 CONTINUE
   WRITE (6,113) BD(N2), X, H, ROC, POWP, PDWS, GAMMA, THETA, R, VG, VT,
                VE, T, AK, ETA, PCP, PJ, PSID
   TT= T/3600.
   T= T+TDEL
   IF (X.LT.0.) GO TO 13
   IF (X.GT.RR. AND. THETA.LT.90) GO TO 13
   GO TO 31

C CALCULATE Glide PHASE
   180
   39 T= 20.
   TDEL= 20.
   X= 0.
   H= HI
   40 NG = 0
   HS101= 1.01* HS
   T= T -TDEL
   PDF= 2.653/SOAP
   41 GAMMA= GAMMA/57.2957
   PDF IS PROP DRAG FACTOR-PROPORTIONAL TO RATIO OF DISK AREA TO WING AREA
   TDEL = 20.
   GAMMA= 0.0

   190 C BEGIN CALCULATION FOR NEW GAMMA AT NEW ALTITUDE
   42 RL0D= BLOD +HL0D*H
   IF (NG.EQ.N3) NG= 0
   C DECREMENT L/D DUE TO DRAG OF FOLDED PROPELLER
   IF (N1.LT.4) RL0D= RL0D -1.5*PDF
   43 KK= KK +1
   IF (KK.EQ.10) GO TO 50
   KK= 0
   C ITERATE FOR GAMMA
   VE= 1.27775*SQRT (WDS*COS(GAMMA)/CL)
   CALL ALTF (AMU, VE, WK, H, PSI, VT, VG, N5)
   VY= -VT*COS(GAMMA) /RL0D
   CALL ACCEL(VY, H, VG, AMU, VE, WK, GAMMA, AK)
   ROC= VY/(1. +AK)

C CALCULATE RESULTING CLIMB ANGLE
GAMMAC = ASIN(ROC/VT)
DELG = ABS(GAMMAC - GAMMA)
IF (DELG.LT.0.002) GO TO 50
C
JUST CLIMB ANGLE AND REPEAT
GAMMA = GAMMAC
GO TO 43
50 NG = NG + 1
C
X AND H GIVEN IN KM
54 X = X + VG*TDEL/1000.
H = H + ROC*TDEL/1000.
T = T + TDEL
IF (H.LT.HS101) TDEL = 2.
IF (NG.EQ.N3) GO TO 55
225 IF (H.GT.HS) GO TO 42
55 GAMMA = GAMMA*5.2957
C
WRITE DATA FOR ONE INCREMENT OF GLIDE OR FINAL POINT
WRITE (6,115) BD(N2),X,H,ROC,GAMMA,VG,VT,VE,T,AK
IF (H.GT.HS) GO TO 41
230 TG = T/3600.
Z(7,N) = X
Z(8,N) = TG
GO TO 14
C
199 STOP
END
SUBROUTINE DENSITY (CH, SIGMA)

CURVE FIT TO 62 ATMOS. FOR CALCULATION OF DENSITY RATIO

INPUT: ALTITUDE IN KM; OUTPUT: DIMENSIONLESS DENSITY RATIO (SIGMA)

DIMENSION DC1(15), DC2(15)

SIGMA = E **(CC1*H + CC2*H**2) WHERE H IS IN KM

DATA (DC1(I), I=1,15) / .0956554, .0948554, .0955529, .0950089, .0942258, 
1 .0942258, .0770834, .0879373, .0962236, .1027082, 
2 .1045655, .1107329, .1160101, .1204581, .1243220/

DATA (DC2(J), J=1,15) / .117337, .117337, .124898, .133965, .143754, 
1 .143754, .307572, .230044, .178253, .142229, 
2 .132942, .104908, .082920, .065512, .052013/

ICH = 1 + IFIX(CH/2.)

CC1 = DC1(ICH)
CC2 = DC2(ICH)

IF (CH.LE.11. OR. CH.GE.12.) GO TO 20

CC1 = .0679418
CC2 = .387085

SIGMA = EXP(-CC1*CH - CC2*CH*CH/100.)
RETURN
END
SUBROUTINE ALTF(AMU, VE, WK, H, PSI, VT, VG, N5)
CALCULATE TRUE AIRSPEED, WINDSPEED, AND GROUNDSPEED - SI UNITS

INPUTS: WIND AZIMUTH, EQUIVALENT AIRSPEED, WIND SCALE FACTOR, AND
ALTITUDE; OUTPUT: GROUND-TRACK OFFSET ANGLE, TRUE AIRSPEED, AND
GROUND SPEED. (ALL SPEEDS IN M/S; ALL ANGLES IN DEGREES.)

FOR WK = 1,+, RESULTING WIND PROFILE IS FOR 99% INCLUSIVE
PROFILE FJP 5 LAUNCH SITES FROM NASA TM 78118.

300 FORMAT (4X, 24H WIND SPEED TOO LARGE AT ,F4.1, 4H KM.)

CALL DENSITY (H, SIGMA)
VT = VE*(SIGMA)**(-.5)

IF (H.GE.14.) GO TO 50
VW = WK*8.3.
GO TO 62

50 IF (H.GE.15.) GO TO 51
VW = WK* (8. -18.*(H -14.))
GO TO 62

51 IF (H.GE.20.) GO TO 52
VW = WK* (7.6 -5.8*(H -15.))
GO TO 62

52 IF (H.GE.23.) GO TO 53
VW = WK*41.
GO TO 62

53 VW = WK* (41. +4.7778*(H -23.))

62 SPSI = VW*SIND(AMU)/VT
IF (SPSI.GE.1.) GO TO 64
PSI = ASIN(SPSI)
VG = VT*COS(PSI) -VW*COSD(AMU)
GO TO 65

64 WRITE (6,300) H
N5 = 1

65 CONTINUE
RETURN
END
SUBROUTINE PRPICAL (PCP, PJ, ETA)
DIMENSION PT(15, 41)

INPUT: PROPPELLER POWER COEFFICIENT AND ADVANCE RATIO
OUTPUT: PROPPELLER EFFICIENCY FACTOR
DATA SOURCE: HAM. STD. CHARTS FOR Cl-I= 0.3, AF= 80°, AND THREE BLADES

EACH DATA STATEMENT GIVES VALUES OF ETA AS CP, RANGES FROM .0 TO .35

DATA (PT(1, 1), I=1, 15) / .0, .74, .66, .57, .48, .42, .37, .33, .30, .28, .24, .22, .20, .18, .16, .14 / .40
1.19, .17, .16, .14 /
DATA (PT(1, 2), I=1, 15) / .0, .78, .71, .61, .54, .47, .41, .36, .32, .28, .24, .20, .17, .14, .10 / .45
1.22, .19, .17, .16 /
DATA (PT(1, 3), I=1, 15) / .0, .80, .76, .66, .56, .45, .41, .35, .31, .27, .24, .20, .17, .14, .10 / .50
1.24, .22, .19, .18 /
DATA (PT(1, 4), I=1, 15) / .0, .83, .80, .71, .62, .56, .49, .45, .39, .35, .30, .27, .24, .20, .17, .14, .10 / .55
1.27, .24, .22, .19 /
DATA (PT(1, 5), I=1, 15) / .0, .84, .82, .75, .67, .60, .54, .48, .43, .38, .35, .30, .27, .24, .20, .17, .14, .10 / .60
1.29, .26, .24, .22 /
DATA (PT(1, 6), I=1, 15) / .0, .83, .81, .73, .65, .57, .52, .46, .41, .37, .34, .30, .27, .24, .20, .17, .14, .10 / .65
1.32, .28, .25, .24 /
DATA (PT(1, 7), I=1, 15) / .0, .87, .86, .80, .73, .67, .61, .55, .50, .44, .40, .37, .34, .30, .27, .24, .20, .17, .14, .10 / .70
1.35, .31, .29, .25 /
DATA (PT(1, 8), I=1, 15) / .0, .88, .87, .82, .76, .70, .64, .59, .53, .47, .43, .38, .35, .30, .27, .24, .20, .17, .14, .10 / .75
1.38, .34, .30, .29 /
DATA (PT(1, 9), I=1, 15) / .0, .88, .88, .84, .78, .73, .67, .62, .57, .52, .46, .41, .37, .34, .30, .27, .24, .20, .17, .14, .10 / .80
1.40, .37, .34, .29 /
DATA (PT(1, 10), I=1, 15) / .0, .88, .89, .86, .81, .75, .70, .65, .60, .55, .49, .44, .39, .35, .30, .27, .24, .20, .17, .14, .10 / .85
1.44, .39, .36, .33 /
DATA (PT(1, 11), I=1, 15) / .0, .88, .90, .87, .82, .78, .72, .68, .63, .58, .52, .47, .42, .39, .34, .30, .27, .24, .20, .17, .14, .10 / .90
1.47, .42, .39, .34 /
DATA (PT(1, 12), I=1, 15) / .0, .87, .90, .88, .84, .80, .75, .70, .65, .61, .56, .51, .46, .41, .38, .35, .30, .27, .24, .20, .17, .14, .10 / .95
1.5, .45, .41, .38 /
DATA (PT(1, 13), I=1, 15) / .0, .87, .91, .89, .85, .81, .77, .72, .68, .63, .60, .55, .50, .45, .40, .36, .32, .28, .24, .20, .17, .14, .10 / 1.00
1.54, .49, .45, .40 /
DATA (PT(1, 14), I=1, 15) / .0, .86, .91, .89, .85, .81, .77, .72, .68, .63, .60, .55, .50, .45, .40, .36, .32, .28, .24, .20, .17, .14, .10 / 1.05
1.56, .51, .47, .44 /
DATA (PT(1, 15), I=1, 15) / .0, .85, .91, .90, .88, .84, .80, .76, .72, .68, .64, .60, .55, .50, .45, .40, .36, .32, .28, .24, .20, .17, .14, .10 / 1.10
1.64, .60, .55, .50, .47, .44 /
DATA (PT(1, 16), I=1, 15) / .0, .84, .91, .91, .89, .85, .81, .78, .74, .70, .66, .62, .58, .54, .50, .46, .42, .38, .34, .30, .26, .22, .18 / 1.15
1.62, .67, .57, .54, .49 /
<table>
<thead>
<tr>
<th></th>
<th>DATA (PT(1, 17), I=1, 15)</th>
<th></th>
<th>0.69, 0.65, 0.60, 0.55, 0.53/</th>
<th>1.20</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>DATA (PT(1, 18), I=1, 15)</td>
<td></td>
<td>0.67, 0.63, 0.58, 0.55/</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>DATA (PT(1, 19), I=1, 15)</td>
<td></td>
<td>0.62, 0.52, 0.40, 0.30/</td>
<td>1.25</td>
</tr>
<tr>
<td></td>
<td>DATA (PT(1, 20), I=1, 15)</td>
<td></td>
<td>0.60, 0.50, 0.40, 0.30/</td>
<td>1.30</td>
</tr>
<tr>
<td>50</td>
<td>DATA (PT(1, 21), I=1, 15)</td>
<td></td>
<td>0.57, 0.50, 0.40, 0.30/</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>DATA (PT(1, 22), I=1, 15)</td>
<td></td>
<td>0.52, 0.40, 0.30, 0.20/</td>
<td>1.40</td>
</tr>
<tr>
<td></td>
<td>DATA (PT(1, 23), I=1, 15)</td>
<td></td>
<td>0.50, 0.40, 0.30, 0.20/</td>
<td>1.45</td>
</tr>
<tr>
<td></td>
<td>DATA (PT(1, 24), I=1, 15)</td>
<td></td>
<td>0.48, 0.40, 0.30, 0.20/</td>
<td>1.50</td>
</tr>
<tr>
<td>60</td>
<td>DATA (PT(1, 25), I=1, 15)</td>
<td></td>
<td>0.45, 0.40, 0.30, 0.20/</td>
<td>1.55</td>
</tr>
<tr>
<td></td>
<td>DATA (PT(1, 26), I=1, 15)</td>
<td></td>
<td>0.45, 0.40, 0.30, 0.20/</td>
<td>1.60</td>
</tr>
<tr>
<td></td>
<td>DATA (PT(1, 27), I=1, 15)</td>
<td></td>
<td>0.45, 0.40, 0.30, 0.20/</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td>DATA (PT(1, 28), I=1, 15)</td>
<td></td>
<td>0.45, 0.40, 0.30, 0.20/</td>
<td>1.70</td>
</tr>
<tr>
<td>70</td>
<td>DATA (PT(1, 29), I=1, 15)</td>
<td></td>
<td>0.45, 0.40, 0.30, 0.20/</td>
<td>1.75</td>
</tr>
<tr>
<td></td>
<td>DATA (PT(1, 30), I=1, 15)</td>
<td></td>
<td>0.45, 0.40, 0.30, 0.20/</td>
<td>1.80</td>
</tr>
<tr>
<td></td>
<td>DATA (PT(1, 31), I=1, 15)</td>
<td></td>
<td>0.45, 0.40, 0.30, 0.20/</td>
<td>1.85</td>
</tr>
<tr>
<td></td>
<td>DATA (PT(1, 32), I=1, 15)</td>
<td></td>
<td>0.45, 0.40, 0.30, 0.20/</td>
<td>1.90</td>
</tr>
<tr>
<td>80</td>
<td>DATA (PT(1, 33), I=1, 15)</td>
<td></td>
<td>0.45, 0.40, 0.30, 0.20/</td>
<td>1.95</td>
</tr>
<tr>
<td></td>
<td>DATA (PT(1, 34), I=1, 15)</td>
<td></td>
<td>0.45, 0.40, 0.30, 0.20/</td>
<td>2.00</td>
</tr>
<tr>
<td></td>
<td>DATA (PT(1, 35), I=1, 15)</td>
<td></td>
<td>0.45, 0.40, 0.30, 0.20/</td>
<td>2.05</td>
</tr>
<tr>
<td></td>
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DATA (PT(I,38),I=1,15)/.0,.7,.85,.89,.913,.92,.92,.918,.913,.907/ 2.25
1 .895,.835,.87,.855,.84/ 2.25
DATA (PT(I,39),I=1,15)/.0,.7,.84,.88,.911,.92,.92,.918,.915,.908/ 2.30
1 .9,.89,.875,.86,.845/ 2.30
DATA (PT(I,40),I=1,15)/.0,.7,.83,.88,.91,.918,.92,.918,.915,.91/ 2.35
1 .902,.89,.88,.865,.85/ 2.35
DATA (PT(I,41),I=1,15)/.0,.7,.82,.87,.907,.916,.918,.918,.916/ 2.40
1 .912,.905,.895,.885,.87,.86/ 2.40

INTERPOLATION OF ETA FROM HAM.-STD TABLES FOR AF=80,B=3,CLI=3

RCP = 40.*PCP +1.
ICP = IFIX(RCP)
DCP = RCP - FLOAT(ICP)
RJ = 20.*PJ -7.
IJ = IFIX(RJ)
DIJ = RJ - FLOAT(IJ)

POINTS A & B AT GIVEN JP VALUE; POINT A AT LOWER J VALUE THAN POINT B

PTA = (1.-DCP)*PT(ICP,IJ) + PT(ICP+1,IJ)*DCP
PTB = (1.-DCP)*PT(ICP+1,IJ+1) + PT(ICP+1,IJ+1)*DCP

ETA = PTA + (PTB-PTA)*DIJ

RETURN
END
SUBROUTINE ACCEL (VY, H, VG, AMU, VE, WK, GAMMA, AK, N5)

C INPUT: VERTICAL VELOCITY IN M/S, ALTITUDE IN KM, GROUND SPEED
C IN M/S, WIND AZIMUTH IN DEG, EQUIVALENT AIRSPEED IN M/S, WIND SCALE
C FACTOR, AND FLIGHT PATH ANGLE IN DEG; OUTPUT: ACCELERATION CORRECTION
C FACTOR

IF (VY .LT. 0) GO TO 84
Y1 = H + 1
GO TO 85

IF (N5 .EQ. 1) GO TO 87
V1 = SQRT (VG1**2 + (VT1*SIN(GAMMA))**2)
V2 = SQRT (VG2**2 + (VT2*SIN(GAMMA))**2)
DELV = V1 - V2
AK = DELV*VAV/1900.
CONTINUE
RETURN
END
SUBROUTINE RCLI

COMMON /PAAH/ WOS, CL, BLOD, HLOD, TS, SOAP, POS, RR, POWL, WK, AMU,
1 X5, HS, POWR, TDOT, AI, RKR, AK, ETA, GAMMA, POW, POWP, POWS, PSID,
2 R, RLOD, ROC, THETA, VE, VG, VT, PCP, PJ, N4, N5, X, H

DATA C1/9.9397/
C1 EQUALS (PI**4 )/(R*(S.L. DENSITY))

BASIC PARAMETERS
XR = X - X5
R = SQRT (XR*XR + H*H)
THETA = ATAN2 (H, XR)
RLOD = BLOD + HLOD*H
Kodef = 1
KK = 0.0
VE = 1.27775*SQRT (WOS*COS (GAMMA)/CL)

NOTE: VE IS CORRECTED FOR FLIGHT PATH ANGLE, GAMMA
CALL ALTF (AMU, VE, WK, H, PSI, VT, VG, N5)

IF (N5.EQ.1) GO TO 90
CALL DENSITY (H, SIGMA)

CALCULATION OF POWER - RECEIVED, AVAILABLE AND STORED
740 FACTOR IS 1000 W/<W X .74 EFFICIENCY FACTOR

ANGLE = 3.1415926 - THETA + GAMMA
POW = ((PR/R)**RKR) * 740.0*(POS/WOS)*SIN (ANGLE)

IF (N4.EQ.1) POW = POW* (COS (PSI))**2
KK = KK+1
IF (KK.GT.10) GO TO 90
POWRL = POW/POWL
IF (POWRL.GT.POWR) GO TO 75

KEEP PROP FOLDED AND STORE ALL INCOMING ENERGY

ETA = 0.0
POWP = 0.0
PJ = 0.0
PCP = 0.0

DECREMENT L/D TO ACCOUNT FOR DRAG OF FOLDED PROPELLERS
RLOD = RLOD - 1.5
KJDE = -1
POWS = PW
GO TO 83

DPOW = POW - POWL
IF (DPW) 76,76,77
C ALL POWER TO PROP

45 76 POWP= POW
POWS= 0,0
GO TO 78
C POWER TO PROP AND REMAINDER TO STORAGE

50 77 POWP= PWL
POWS= DPW
78 IF (KODE) 79,79,82
79 RLOD= RLOD +1.5
C

C CALCULATION OF NONDIMENSIONAL CHARACTERISTICS OF PROPELLER

55 82 PJ= 3.14159*VT/TS
POAP= POWP*WS* SOAP
PCP= C1*POAP/(SIGMA*TS**3)
CALL PROPCAL (PCP,PJ,ETA)
C

C CALCULATION OF RATE OF CLIMB - THRUST AND DRAG COMPONENTS
C TDOT IS RATIO OF ACTUAL, DEGRADED THRUST TO THRUST FROM TABLE LOOK-UP
ETA= ETA*TDOT

63 VYT= ETA*POWP
VYD= VT*COS(GAMMA)/RLOD
VY= VYT-VYD
CALL ACCEL (VY,H,VG,AMU,VE,WK,GAMMA,AK)
IF (N5.GE.5) GO TO 90
ROC= VY/(1.+AK)
C

C CALCULATE RESULTING CLIMB ANGLE
GAMMAC= ASIN(ROC/VT)
DELG= ABS(GAMMAC-GAMMA)
IF (DELG.LT..O0[) GO TO 90
C

AJUST CLIMB ANGLE AND REPEAT
GAMMA= GAMMAC
GO TO 60
C

C CALCULATION FOR GAMMA (FLIGHT PATH ANGLE) HAS CONVERGED

90 THETA= THETA*57.2957
GAMMA= GAMMA*57.2957
PSI0= PSI*57.2957
RETURN
END
## Sample Case: Variation of Wind-Profile Magnitude

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<tr>
<th>Aircraft Aero.</th>
<th>Propeller</th>
<th>Power</th>
<th>Winds</th>
<th>Start Point</th>
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<tr>
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<td>XS = 40.00 KM</td>
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| Min P/W = 0.25 X Max P/W |

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31
APPENDIX B

GLIDE-TIME PARAMETER

An expression for the time required to glide between two altitudes is given as equation 29 of reference 8. The development of that equation assumes that the aerodynamic characteristics ($C_L$ and $C_D$) remain constant and that acceleration effects (eq. (4)) are negligible. That endurance equation for gliding flight is written as:

$$ t_g = \frac{L}{D} \sqrt{\frac{C_L}{W/S}} \frac{h_2}{(\cos \gamma)^{3/2}} \int_{h_1}^{h_2} \frac{D}{h} \, dh $$

(B1)

where $h_1$ and $h_2$ are the final and initial altitudes, respectively. Equation (B1) can be simplified in two ways. First, since $\gamma$ is a small angle, the cosine term can be approximated as 1.0. Second, if the range of altitudes lies between about 16 and 26 kilometers, equation (11) can be used to approximate density variation by choosing $a = 0.105$ and $b = 0.0013$ throughout that altitude range.

Substituting equation (11) into equation (B1) yields an integrable expression:

$$ t_g = \frac{L}{D} \sqrt{\frac{C_L \rho_0}{2 W/S}} e^{(a^2/8b)} \int_{h_1}^{h_2} e^{-\frac{(b/2)(h + (a/2b))^2}{2}} \, dh $$

(B2)

$$ = \frac{L}{D} \frac{1}{V_e} e^{(a^2/8b)} \sqrt{\frac{2}{b}} \int_{z_1}^{z_2} e^{-z^2} \, dz $$

$$ = \frac{L}{D} \frac{1}{V_e} e^{(a^2/8b)} \sqrt{\frac{\pi}{2b}} (\text{erf}(z_2) - \text{erf}(z_1)) $$

(B3)

where $z = \sqrt{b/2} (h + (a/2b))$

Equation (B3) may be rearranged to produce an expression independent of vehicle aerodynamic characteristics. After substituting the values of $a$ and $b$, the equation becomes:

$$ t_g V_e \frac{D}{L} = 27.873 (\text{erf}(z_2) - \text{erf}(z_1)) $$

(B4)
where \( z = 1.0296 + 0.025495h \)

where \( h \) is expressed in kilometers, \( V_e \) in meters per second, and \( t_g \) in hours. As in equation (B1), \( h_1 \) is the final altitude because of the negative rate of climb.

Glide time can be determined for a specific vehicle where \( L/D \) and \( V_e \) are given. For the class of vehicles considered in this study, the values of \( L/(DV_e) \) lie approximately between 10 and 0.1. The largest value yields the longest glide time and is produced by low W/S and high L/D.
REFERENCES


TABLE I.- DESCRIPTION OF BASELINE CONFIGURATION OF HIGH-ALTITUDE AIRPLANE PLATFORM

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<td>Lift coefficient, $C_L$</td>
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<td>Lift-to-drag ratio</td>
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<td>Activity factor</td>
<td>80.</td>
</tr>
<tr>
<td>Design lift coefficient</td>
<td>0.3</td>
</tr>
<tr>
<td>Ratio of wing area to propeller-disk area, $S/A_p$</td>
<td>2.653</td>
</tr>
<tr>
<td>Tip speed, $V_{tip}$</td>
<td>172 m/s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Motors(s):</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum specific power (available), $(P/W)_{max}$</td>
<td>8.62 W/N</td>
</tr>
<tr>
<td>Minimum specific power (required), $(P/W)_{min}$</td>
<td>2.16 W/N</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Power transmission:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Power intensity at reference range, $P/S$</td>
<td>1.10 kW/m²</td>
</tr>
<tr>
<td>Reference range, $R$</td>
<td>50 km</td>
</tr>
<tr>
<td>Range-power attenuation factor</td>
<td>$R/r$</td>
</tr>
<tr>
<td>Transmission initiation point</td>
<td></td>
</tr>
<tr>
<td>Altitude, $h_s$</td>
<td>18 km</td>
</tr>
<tr>
<td>Horizontal range, $x_s$</td>
<td>40 km</td>
</tr>
<tr>
<td>Transmission-termination slant range</td>
<td>50 km</td>
</tr>
</tbody>
</table>
TABLE II.- INPUT PARAMETERS FOR PERFORMANCE PROGRAM OF APPENDIX A

<table>
<thead>
<tr>
<th>Array number</th>
<th>Program name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WOS</td>
<td>W/S</td>
</tr>
<tr>
<td>2</td>
<td>C&lt;sub&gt;L&lt;/sub&gt;</td>
<td>C&lt;sub&gt;L&lt;/sub&gt;</td>
</tr>
<tr>
<td>3</td>
<td>BLOD</td>
<td>L/D component independent of altitude of altitude</td>
</tr>
<tr>
<td>4</td>
<td>HLOD</td>
<td>coefficient of altitude-dependent term in L/D equation, km&lt;sup&gt;-1&lt;/sup&gt;</td>
</tr>
<tr>
<td>5</td>
<td>TS</td>
<td>V&lt;sub&gt;tip&lt;/sub&gt;</td>
</tr>
<tr>
<td>6</td>
<td>SOAP</td>
<td>S/A&lt;sub&gt;p&lt;/sub&gt;</td>
</tr>
<tr>
<td>7</td>
<td>POS</td>
<td>P/S</td>
</tr>
<tr>
<td>8</td>
<td>RR</td>
<td>R</td>
</tr>
<tr>
<td>9</td>
<td>POWL</td>
<td>maximum P/W used by propulsion system</td>
</tr>
<tr>
<td>10</td>
<td>WK</td>
<td>k&lt;sub&gt;W&lt;/sub&gt;</td>
</tr>
<tr>
<td>11</td>
<td>AMU</td>
<td>μ</td>
</tr>
<tr>
<td>12</td>
<td>XS</td>
<td>x&lt;sub&gt;S&lt;/sub&gt;</td>
</tr>
<tr>
<td>13</td>
<td>HS</td>
<td>h&lt;sub&gt;S&lt;/sub&gt;</td>
</tr>
<tr>
<td>14</td>
<td>POWR</td>
<td>ratio of minimum P/W to maximum P/W for propulsion system</td>
</tr>
<tr>
<td>15</td>
<td>TDOT</td>
<td>T&lt;sub&gt;d&lt;/sub&gt;/T</td>
</tr>
<tr>
<td>16</td>
<td>HI</td>
<td>h&lt;sub&gt;i&lt;/sub&gt;</td>
</tr>
<tr>
<td>17</td>
<td>RKR</td>
<td>k&lt;sub&gt;r&lt;/sub&gt;</td>
</tr>
<tr>
<td>N1</td>
<td></td>
<td>code for flight mode calculation (1- single, 2- climb, 3- climb plus glide, or, 4- glide only)</td>
</tr>
<tr>
<td>N2</td>
<td></td>
<td>element in input array to be varied</td>
</tr>
<tr>
<td>N3</td>
<td></td>
<td>number of calculation points per listed line</td>
</tr>
<tr>
<td>N4</td>
<td></td>
<td>transmitter polarization code (1- linear; 2- circular)</td>
</tr>
<tr>
<td>SF</td>
<td></td>
<td>final value of variation set</td>
</tr>
<tr>
<td>SI</td>
<td></td>
<td>initial value of variation set</td>
</tr>
<tr>
<td>SS</td>
<td></td>
<td>step size of variation set</td>
</tr>
</tbody>
</table>
TABLE III.- OUTPUT PARAMETERS FOR PERFORMANCE PROGRAM OF APPENDIX A

<table>
<thead>
<tr>
<th>Output listing name*</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>x</td>
</tr>
<tr>
<td>H</td>
<td>h</td>
</tr>
<tr>
<td>R/C</td>
<td>h</td>
</tr>
<tr>
<td>P/W-P</td>
<td>P/W available for propulsion</td>
</tr>
<tr>
<td>P/W-S</td>
<td>P/W available for storage</td>
</tr>
<tr>
<td>GAMMA</td>
<td>γ</td>
</tr>
<tr>
<td>THETA</td>
<td>θ</td>
</tr>
<tr>
<td>R</td>
<td>r</td>
</tr>
<tr>
<td>VG</td>
<td>Vg</td>
</tr>
<tr>
<td>VT</td>
<td>V</td>
</tr>
<tr>
<td>VE</td>
<td>Vₑ \sqrt{\cos γ}</td>
</tr>
<tr>
<td>T</td>
<td>t</td>
</tr>
<tr>
<td>AK</td>
<td>ka</td>
</tr>
<tr>
<td>ETA</td>
<td>n</td>
</tr>
<tr>
<td>CP</td>
<td>C_p</td>
</tr>
<tr>
<td>J</td>
<td>J</td>
</tr>
<tr>
<td>PSI</td>
<td>φ</td>
</tr>
<tr>
<td>XC</td>
<td>x_c</td>
</tr>
<tr>
<td>HC</td>
<td>h_c</td>
</tr>
<tr>
<td>TC</td>
<td>t_c</td>
</tr>
<tr>
<td>E/W-S</td>
<td>E_s/W</td>
</tr>
<tr>
<td>E/W-T</td>
<td>E_t/W</td>
</tr>
<tr>
<td>XT</td>
<td>x_t</td>
</tr>
<tr>
<td>TT</td>
<td>t_t</td>
</tr>
</tbody>
</table>

* given in listing sequence
(a) Forces in longitudinal plane.

(b) Flight path profile

Figure 1. - Conventions used to define senses of displacements, forces, angles and velocities.
Ground track for perfect alignment of transmitting antenna with rectenna

(c) Velocities in lateral plane.

Figure 1. - Concluded
(a) configuration of reference 9

(b) alternate configuration

Figure 2. - Conceptual HAAP designs.
--- 99% profile (reference 5)
--- 95% profile (reference 5)
--- 99% profile (reference 19)

Figure 3. - Wind profile data.
Figure 4. - Flight profiles.
Figure 5. - History of flight parameters for representative variations in baseline configurations.

(a) Trajectory.
(b) Power and range parameters.

Figure 5. - Continued.
(c) Propeller parameters.

Figure 5. - Concluded.
Figure 6. - Variation of equivalent airspeed with wing loading and lift coefficient.
V<sub>e</sub>

- 10 m/s (19 kt)
- 15 m/s (29 kt)
- 20 m/s (39 kt)

**Figure 7.** - Comparison of limiting wind profile and vehicle airspeed.

(a) True airspeed profile.
(b) Equivalent airspeed profile.

Figure 7. - Concluded.
Figure 8. - Effect of wing loading and lift-to-drag ratio on the performance of the baseline configuration.
Figure 8. - Concluded.
Figure 9. - Effect of airplane lift and drag coefficients on performance.
Figure 9. - Concluded.
Figure 10. - Comparison of two models of air density variation with altitude.
Figure 11. - Ratio of approximate density (Appendix B) to density from reference 4.
Figure 12. - Variation of glide-time parameter with initial altitude and altitude decrement.
Figure 13. - Variation of time to glide from 25 to 18 km with wing loading and lift-to-drag ratio; $CL = 0.9$. 
Figure 14. - Variation of glide time with altitude and wing loading; glide termination at 18 km; L/D = 40; CL = 0.9.
Figure 15. - Relative variation in microwave-beam intensity with range.
Figure 16. - Variation of baseline configuration performance with microwave-beam intensity factor $k_r$ of equation 15.
Figure 17. - Climb performance for three values of $k_r$; baseline configuration; $x_s = 40$ km.
Figure 18. - Effect of beam intensity and motor size on climb performance.
Figure 19. - Effect of variation in reference range and motor size.
Figure 20. - Effect of initiating climb at different altitudes and horizontal ranges.
Figure 21. - Effect of variation in initial altitude on climb performance; $x_c = 40$ km.
Figure 22. - Effect of propulsion degradation factor on climb performance.
Figure 23. - Effect of motor size and wing loading on climb performance.
Figure 24. - Effect of propeller tip speed and wing loading on climb performance.
Figure 25. - Effect of propeller size and wing loading on climb performance. $V_{\text{tip}} = 172$ m/s.
(a) Mean velocities

Figure 26. - Wind profile data (ref. 19).
(b) Mean and standard deviation profiles for April.

Figure 26. - Concluded.
Figure 27. - Effect of headwinds and tailwinds on the performance of the baseline configuration.
Figure 28. - Effect of wind direction and profile amplitude on the performance of the baseline configuration.

(a) Variation of wind-profile magnitude
(b) Variation of wind direction.

Figure 28. - Concluded.
Figure 29. - Climb performance for $\mu = 90^0$ and $P/S = 1.1 \text{ kW/N}^2$. 
ANALYTICAL STUDY OF THE CRUISE PERFORMANCE OF A CLASS OF REMOTELY PILOTED, MICROWAVE-POWERED, HIGH-ALTITUDE AIRPLANE PLATFORMS

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National Aeronautics and Space Administration
Washington, DC 20546

The performance of a class of remotely-piloted, microwave-powered, high-altitude airplane platforms was studied. Each cycle of the flight profile consists of climb while the vehicle is tracked and powered by a microwave beam, followed by gliding flight back to a minimum altitude. Parameter variations were used to define the effects of changes in the characteristics of the airplane aerodynamics, the power-transmission systems, the propulsion system, and winds.

Results show that wind effects limit the reduction of wing loading and increase of lift coefficient, two effective ways to obtain longer range and endurance for each flight cycle. Calculated climb performance showed strong sensitivity to some power and propulsion parameters. A simplified method of computing gliding endurance was developed.