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Near-Space Station-Keeping Performance of a Large High-Altitude Notional Airship

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A key technical challenge for high-altitude, or near-space concepts is autonomous station keeping, or the ability to remain fixed over a geolocation in the presence of winds. Although at 65,000 ft altitude and above, one is above weather (i.e., storms, rain), winds still exist. And to station keep in the presence of these winds requires propulsive power. This paper focuses on the analysis of the station-keeping performance of a notional solar-powered airship operating at an altitude around 65,000. The vehicle has a lifting-gas volume of 6.1×10^6 ft^3, and is solar electric powered with the entire upper surface covered by solar cells. Electric motors and propellers provide propulsion, additional on-board power is required for the payload and auxiliary equipment, and batteries are used for power storage. In this paper, the aerodynamic drag of the vehicle is estimated, the wind environment is characterized, and the solar power available is determined for several geolocations and time of year. This power available is then compared to the power required for station keeping in the presence of winds. It is shown that due to diurnal solar variations and season winds a large airship may be unable to meet station-keeping performance requirements in certain months of the year due to power limitations.

Nomenclature

$C_{D\text{front}}$	=	drag coefficient referenced to maximum projected frontal area
$C_{D\text{wet}}$	=	drag coefficient referenced to wetted surface area
F	=	probability distribution function
L/D	=	airship length-to-diameter ratio
P	=	probability density function
Re	=	Reynolds number
U	=	wind velocity
$\bar{U}$	=	mean wind velocity
$U_{50\%}$	=	50th percentile (mean) wind velocity
$U_{95\%}$	=	95th percentile wind velocity
$U_{99\%}$	=	99th percentile wind velocity
W_{OEW}	=	airship operating empty weight (lifting gas not included)
Γ	=	gamma function
η	=	power efficiency (power out/power in)
σ_U	=	standard deviation of the wind velocity

Introduction

THERE is growing worldwide interest in using autonomous atmospheric flight vehicles as platforms operating for extended periods of time at very high altitudes (between 65,000 and 300,000 ft) to accomplish military and commercial missions heretofore accomplished using spacecraft [1]. Such missions include persistent ground surveillance and/or communications, for example. In the Department of Defense community, and increasingly in the commercial world, using such vehicles in this manner is referred to as a "near-space" solution to a mission requirement, as apposed to a "space-based" solution. And the platforms are referred to as "near-space vehicles."

Currently, few vehicles operate in this altitude range, and when they do, it is for a relatively brief time. But interest in near-space solutions is increasing, both in the military and commercially, because such solutions are potentially less expensive and more flexible than space-based solutions. Plus, near-space solutions offer the possibility of continuous coverage (persistence) over the ground target area; the near-space vehicle can remain fixed over a target, but a spacecraft can only pass over that location once each orbit. Some missions call for the near-space platform to remain aloft for up to one year.

Interest in near-space solutions has also increased because they are more feasible than in the past, due to technological advances in light-weight materials and in solar-power technology. Many near-space vehicular concepts would use some form of solar-electric power for propulsion: electric motors and propellers, for example. Near-space vehicle concepts may be heavier than air (unmanned air vehicles, or UAVs), lighter than air (airships), or hybrid designs that both generate aerodynamic lift and possess buoyancy. But no near-space vehicle has delivered the capability of remaining aloft for a year.

A key technical challenge remaining is autonomous station keeping, or the ability to remain fixed over a geolocation in the presence of winds. Although at 65,000 ft altitude and above, one is above weather (i.e., storms, rain), winds still exist. And to station keep in the presence of these winds requires propulsive power. This paper focuses on the analysis of the station-keeping performance of a notional solar-powered airship operating at an altitude around 65,000 ft.

A proprietary integrated platform analysis approach was developed for this type of analysis, and the methodology is depicted schematically in Fig. 1. Given the vehicle geometry and type of propulsion, the methodology includes a vehicle aerodynamic assessment, a statistical characterization of the relevant solar and wind environment, a characterization of the power system, an assessment of the vehicle dynamics, and an assessment of the station-keeping performance. Highlights of all aspects of the methodology and results from the analysis will be presented.

Notional Airship

The vehicle investigated is a notional airship with characteristics described in Fig. 2. Though notional, this vehicle has many

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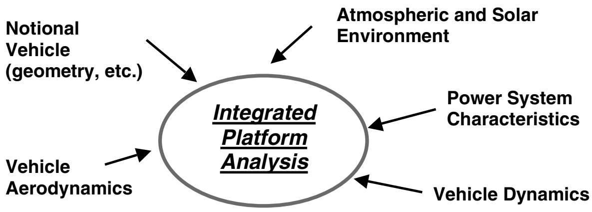

Fig. 1 Integrated platform analysis methodology.

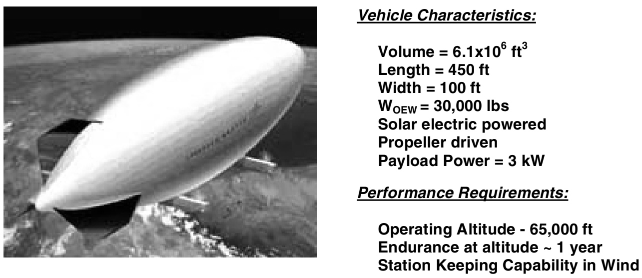

Fig. 2 Notional airship considered.

characteristics similar to vehicles currently being considered for near-space applications. To carry some of the larger payloads (e.g., surveillance and/or communication equipment and associated electronics) to 65,000 ft requires a large airship, with a lifting-gas volume of over 6×10^6 ft^3. W_{OEW}, (gas envelope) volume, and L/D were all selected based on empirical airship-design data. The vehicle would be entirely solar electric powered, with the whole upper surface covered by solar cells. Electric motors and propellers would provide propulsion. Additional on-board power will be required for the payload and auxiliary equipment, and batteries would be used for power storage. No additional power generation capability is assumed.

Drag Characteristics

The drag of the vehicle was determined empirically and experimentally validated. Based on data presented by Hoerner [2], shown in Fig. 3, the drag coefficient (referenced on the maximum projected cross-sectional area) was determined to be approximately 0.012. To be noted is that at 65,000 ft altitude, and a nominal 40 kn. flight velocity, the flight Reynolds number Re is approximately 2×10^7. Consider the solid line in Fig. 3, with the $*$ data point corresponding to the airship Los Angeles. Extrapolating this line down to a Reynolds number of 2×10^7 yields a drag coefficient $C_{D\mathrm{wet}} = 0.0044$. This coefficient is associated with a reference area corresponding to the total surface area of the vehicle ("wetted area"). If the reference area is instead taken to be the maximum projected frontal area of the vehicle, the drag coefficient becomes $C_{D\mathrm{front}} = 0.120$ (assuming the shape is an ellipsoid of revolution).

This drag coefficient was validated via a brief wind-tunnel test using a wind-tunnel model that was similar to, but not an exact replica of, the notional vehicle. The wind-tunnel model, shown in the tunnel in Fig. 4, had a L/D ratio of 3.9, compared to the L/D of 4.5 for the notional vehicle. The experiment required the use of a

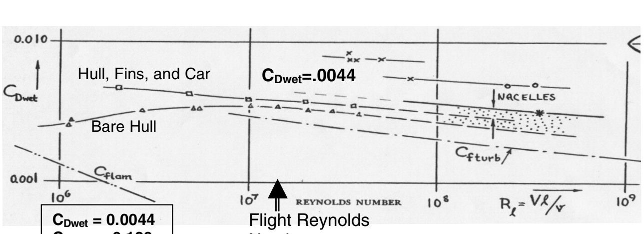

Fig. 3 Airship drag data [2].

Fig. 4 Wind-tunnel model mounted in tunnel test section.

turbulence screen, since the tunnel Reynolds number (1.3×10^5) was considerable lower than that of the full-scale vehicle (2×10^7). Also, a streamlined fairing around the model mount was found to be necessary to reduce the interference due to the mounting apparatus.

Data were obtained for tunnel velocities varying from 10 to 55 kn, and the drag coefficient, measured with the turbulence screen and mount fairing, was constant over this range of velocities. Without the screen, the drag coefficient decreased with increasing velocity. With no turbulence screen and fairing, the drag coefficient at 40 kn was 0.49. Adding the screen reduced the measured drag coefficient to 0.23, and with both screen and the mount fairing the measured drag coefficient was 0.095. Based on these results, it was concluded that the empirically determined drag of $C_{D\mathrm{front}} = 0.120$ was a reasonable estimate.

Wind Environment

The wind environment was characterized statistically, using data from the National Weather Service (see [3], for example). The United States National Weather Service, in cooperation with the National Oceanic and Atmospheric Administration (NOAA) and the National Center for Atmospheric Research (NCAR), has been archiving weather data for over 50 years. For the purpose of this study the most interesting observations are the upper-air soundings that exceed 60,000 ft above ground level (AGL). Interestingly enough, only within the last five to ten years are there observations above this level, and these data are sparse.

This study thus focused on those observations available above 60,000 ft, for two sites of interest, which were Akron, OH and White Sands, NM. These two sites were selected because of their different latitudes and weather patterns, and because they are locations where airship testing is expected to occur. An example scatter diagram of wind velocity as a function of altitude over Akron, OH for the year of 2004 is shown in Fig. 5. Although the wind velocities posses a "knee" around 70,000 ft, it is clear that wind speed as high as 100 kn. exist at this altitude.

Based on such observational data, the wind statistics for each month may be extracted. Past modeling efforts have indicated that a Weibull or Rayleigh distribution is a realistic distribution for natural winds over longer periods of times, monthly or yearly. The tails of the distributions tend to be finite and shortened toward the zero and elongated at the high end. So a reasonable assumption is that a Weibull model is a good approximate distribution for the daily, monthly, or yearly wind data for the upper-air observations. This assumption was qualitatively validated in the study.

The Weibull probability density function is

$$P(U) = \left(\frac{k}{c}\right)\left(\frac{U}{c}\right)^{k-1} \exp\left[-\left(\frac{U}{c}\right)^{k}\right]$$

and the cumulative distribution function is

$$F(U) = 1 - \exp\left[-\left(\frac{U}{c}\right)^{k}\right]$$

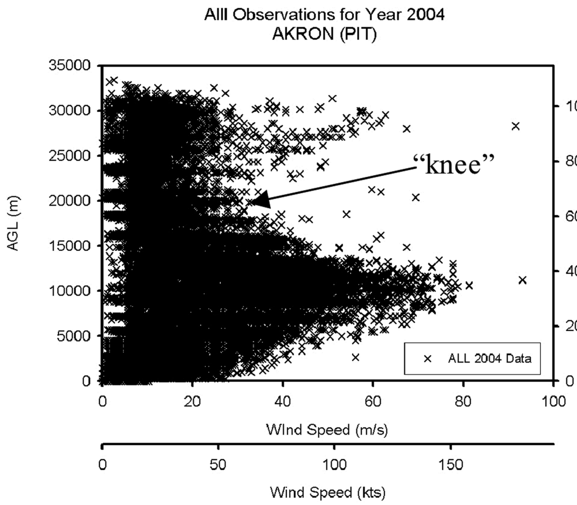

Fig. 5 Wind velocities over Akron, OH in 2004.

with

$$k = \left(\frac{\sigma_U}{\bar{U}}\right)^{-1.086} \qquad c = \frac{\bar{U}}{\Gamma[1 + (1/k)]}$$

Thus, the parameters needed (k and c) to describe the distributions are based on standard statistics obtained directly from the data.

With the Wiebull distribution and the cumulative distribution function determined, the 50th, 95th, or 99th percentile winds can be estimated for any given month or year. Examples of these statistics are summarized in Table 1. Because of both a higher mean and the shape of the probability distributions, Akron tended to have significantly higher 99% winds than White Sands (not shown). For example, the estimated 99% wind in December in Akron is 85.6 kn, while the highest 99% wind in White Sands is estimated at 54.5 kn in February. Also note the significant monthly variation in the winds, with significantly higher winds in the winter than in the summer months. These monthly variations in distributions will play major roles in determining the power required for station keeping.

Power Available

To determine the on-board power available, the effects of time of day (diurnal effects), latitude, vehicle geometry, and annual season must be considered. In addition, an energy-management strategy must be assumed. The energy-management strategy determines, among other things, whether all power goes through the batteries or is somehow split.

The diurnal effect is the daily distribution of solar insolation available. To begin the analysis, the sun's path was assumed to proceed directly overhead, and the day was assumed to be 12 h long. (For now the effects of latitude and time of year are not included.) The result for this purely geometric problem is shown in Fig. 6, in which the fraction of the peak insolation (sun straight up) is plotted as a function of time of day. For reference, ignoring atmospheric effects at this high altitude, the solar energy incident on a surface normal to the sun's rays (the solar constant) is 1350 W/m^2, which could be used to approximate the peak solar insolation shown in this figure. The 24-h average solar energy available is also shown. The available solar energy for the north–south orientation is slightly higher than that for east–west, because the broadside of the vehicle is exposed to the sun immediately after sunrise.

To determine the sensitivity of the above results to vehicle geometry, both a purely cylindrical shape and an ellipsoid were considered. In both cases, the entire upper surface of the vehicle was assumed covered with solar cells. The major differences for an ellipsoid arise due to an eclipsing effect at low sun angles and for an east–west orientation some solar-cell area is illuminated at sunrise. Because the difference in solar insolation for these shapes was on the order of 1%, it was concluded that shape issues would not be a significant factor.

Available solar insolation also depends on geolocation (latitude) and time of year. The monthly average solar energy (in W/m^2) impinging on the solar cells of the notional vehicle is shown for two different geolocations (latitudes) throughout the year in Fig. 7. The seasonal trend and effect of latitude (difference between Akron, OH and White Sands, NM) is revealed in this figure. (The data also include the effects of diurnal solar variation and vehicle geometry.)

Power Required for Station Keeping

The assessment of the station-keeping performance focuses on the power required versus the power available for the airship. Here the power available is taken to be available motor shaft power generated by the solar-power system and electric motors, and (shaft) power required is the propulsive power necessary for station keeping in the presence of winds. The former must consider the efficiencies of the solar cells, batteries, and motor, whereas the latter must consider propeller efficiency. Finally, the power available and required clearly depends on the results presented in previous sections: the airship drag, winds, and solar insolation.

Using the previous results on drag and wind, the monthly average propulsive power required to remain stationary at 65,000 ft in the

Table 1 50th, 95th, and 99th percentile winds over Akron, OH at 65,000 ft in 2004

Month	Observations	$U_{50\%}$, kn	$U_{95\%}$, kn	$U_{99\%}$, kn
January	118	26.1	41.8	48.6
February	133	26.0	47.0	56.4
March	179	19.7	36.9	44.7
April	163	12.7	21.5	25.3
May	162	9.7	20.0	25.5
June	170	9.5	18.0	21.5
July	155	12.6	19.0	21.5
August	172	9.8	18.0	21.5
September	155	9.2	18.5	23.3
October	168	13.0	22.0	26.0
November	173	22.1	38.0	45.0
December	132	34.4	68.5	85.6

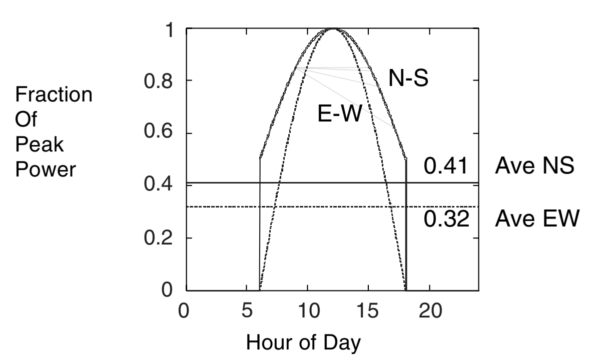

Fig. 6 Diurnal variation in solar insolation.

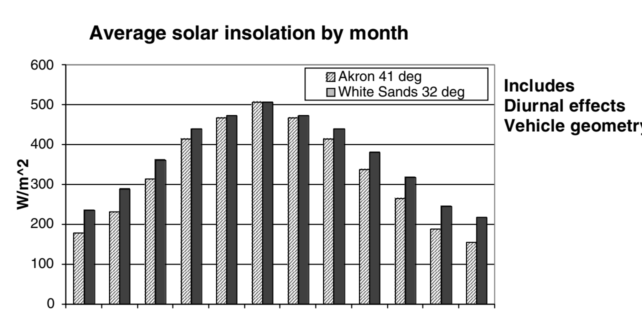

Fig. 7 Monthly average solar insolation available.

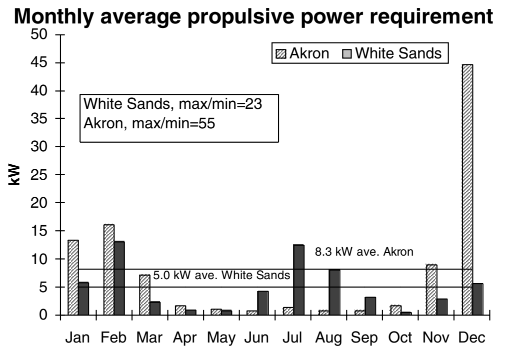

Fig. 8 Monthly average propulsive power requirement.

presence of winds is presented in Fig. 8. Also shown in this figure is the average power required over the year at these two geolocations.

Note the large variations in power requirements between geolocations and seasons. The average power required for the year is only 8.3 kW for Akron and 5.0 kW for White Sands, but the ratio of max/min power required for Akron is 55, compared to about half that (23) for White Sands. And peak power required over Akron is more than twice that over White Sands. Furthermore, the peak power requirements occur in the winter months, although White Sands also has rather high power required in the summer months. The differences are due to the seasonal differences in winds between these two geolocations.

The high Akron winds in December were verified by reviewing the wind data over an eight-year period. The distributions for December not only have the highest mean, but also have the widest distribution, or the largest deviation about the mean. Recalling that the propulsive power required is proportional to the cube of wind velocity, a small increase in wind speed leads to a large increase in propulsive power required.

Pulling everything together, we now compare the average monthly (shaft) power available with the average monthly (shaft) power required. These results will now include the effects of solar-cell, battery, motor, and propeller efficiencies. The results, however, do not include payload and auxiliary power required. The payload, as noted in Fig. 1, requires 3 kW of continuous power, while the auxiliary power requirement is estimated to be 0.5 kW, continuous. Finally, these results do not include the additional power required to maintain position (or maneuvering) when experiencing turbulence, which is discussed in detail in [4]. Hence in this regard the analysis below is conservative.

The range of values considered for the component efficiencies is summarized in Table 2 and is consistent with the data in [5]. Specific efficiencies selected for the baseline analysis are also shown in the table, and except for the propeller, fixed efficiencies were used for each simulation case evaluated. Propeller efficiency varied with flight (or wind) velocity.

Several things are notable from Fig. 9. First, there would be insufficient average airship power available over Akron in December (assuming 2004 wind data), and the power deficit is large. Second, the power available peaks in the summer months, whereas the power required peaks in the winter months (especially over Akron). Hence, although on the *average over the year* there is sufficient power available, there is insufficient average *monthly* power in December (over Akron). This shows the problems associated with working only with averages over an extended period of time. Averages can be misleading, as shown further on.

Table 2 Power-system component efficiencies

Component	Efficiency range	Baseline efficiency
Propellers	70–85%	Velocity dependent
Motors	70–90%	80%
Batteries	60–80%	60%
Solar cells	5–9%	6%

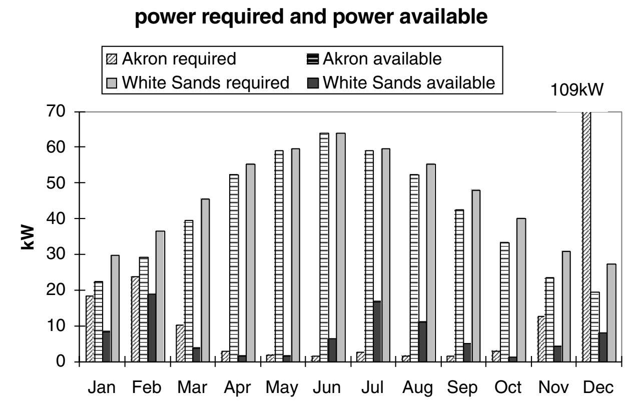

Fig. 9 Monthly average (shaft) power required vs available (2004 wind data).

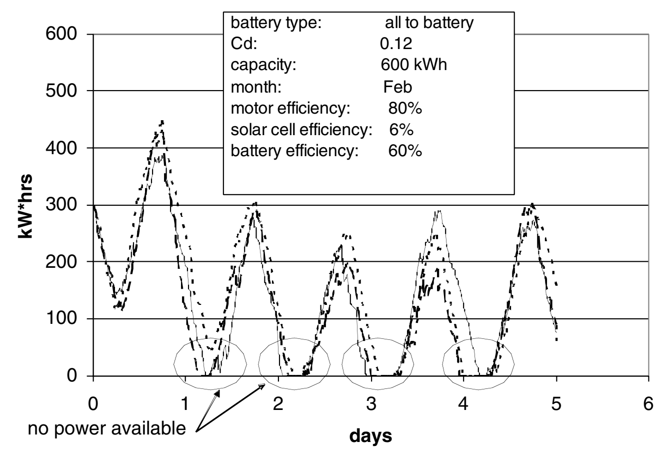

Fig. 10 Monte Carlo simulation of battery power (February 2004, Akron).

To investigate these distributional effects in more detail, consider the results for the month of February over Akron. The results in Fig. 9 above indicate sufficient *average* power is available. But a Monte Carlo simulation of the (shaft) power available during several typical days in February over Akron, shown in Fig. 10, reveals something else. The relevant parameters used in the simulation are listed in the box in the figure, and all solar-generated power passes through the batteries before distribution to the motors. Details of the charging process are not included, but battery efficiency (power out/power in) is included.

These simulation results show that although there was sufficient average monthly power available in February, the battery-power available actually goes to zero for several hours during the early morning. During this time, the batteries have been completely drained, and because this occurs during hours with no sunlight, they cannot be recharged. Hence, there is insufficient power available over Akron during February as well as during December. And from the simulations one can see that the major daily variation in power available is due to the diurnal (day/night) effect on the solar power.

Summary and Conclusions

An integrated platform analysis technique is necessary to appropriately assess the station-keeping performance capability of near-space vehicles. The technique must use a statistical approach, rather than rely merely on averages, and must include an aerodynamics assessment, winds modeling, and a power-available/power-required analysis.

Application of such an analysis technique to a notion airship was completed, and the results showed that average excess vehicle power available over power required is a necessary, but not sufficient, condition to assure near-space platform station-keeping ability: the power-requirement *distribution* (available through simulation, for example), must be evaluated.

It was also shown that for the notional airship investigated there can be a very large variation in month-to-month power requirements and a significant variation in month-to-month power available. In addition, these two variations can be *out of phase*: high power available in summer months, and high power required in the winter.

Consequently, a large airship may be unable to meet station-keeping performance requirements in certain months of the year, due to power limitations. Major design implications include the importance of power-system component efficiencies. The overall system efficiency depends on the product of all component efficiencies, hence small increases in component efficiencies may have high payoff, in terms of overall efficiency.

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