PERFORMANCE ESTIMATES FOR A FUEL-FREE STATIONARY PLATFORM IN THE STRATOSPHERE

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ABSTRACT

High-altitude pseudo-satellites (HAPS) may be kept aloft indefinitely with station-keeping provided by plasma air thrusters (PAT) using wireless power transfer (WPT) from a terrestrial phased array antenna (PAA). One example is the patented "Sitallite" superpressure balloon with a rectifying antenna (rectenna) covering its underside, with thrusters around the periphery. Such a stationary platform can provide continuous observation and communications capabilities covering vast areas for a fraction of the cost required for an orbiting satellite. This work builds upon the design and safety study published elsewhere to provide performance estimates for a long-duration, persistent HAPS powered by electronically-steerable microwave beams. Newly-derived efficiency equations are used to provide accurate estimates of free-space WPT transfer efficiency based on the dimensions of the ground-based PAA and the rectenna. Calculations of air drag for a spheroidal bouyant shape are used to derive PAT power requirements, and these, together with power conversion circuitry, are used to size the overall system. Accurate estimates of cost are derived. These performance estimates can be used to help make economic and logistic decisions, as a fuel-free HAPS with PAT and powered by WPT can be lofted in less time, and with lower risk, than an orbital satellite of comparable capabilities.

INTRODUCTION

A High-Altitude Pseudo-Satellite (HAPS) is an attractive alternative to orbital satellites for applications involving observation and communication. Satellite orbits for these purposes involve tradeoffs between a geostationary earth orbit (GEO) that remains fixed in the sky relative to a spot on the ground, versus a low- or medium- earth orbit (LEO or MEO) which has relatively long periods of occlusion behind the limb of the earth. GEO orbits are very restrictive, occuring only at a fixed altitude of 35,786 km, and only available directly above the earth's equator. While a GEO satellite can view approximately one-third of the earth's surface with constant duration, the distance is large, incuring time lag and challenges to optics. Furthermore, a GEO orbit is more costly to reach than a LEO or MEO orbit, and those orbital "slots" at GEO are highly contested, making permitting a challenge. While launch costs are dropping rapidly for LEO orbits, the persistence of such satellites over a given spot on the earth is generally less than 9 minutes out of each 90 minute cycle.

By contrast, a propellor or jet-driven HAPS can remain fixed above a spot or region on the ground for many hours before refueling. The stratosphere is an ideal altitude for fuel-free HAPS, being higher than aircraft, and lower than most meteorites. Weather balloons and superpressure balloons routinely ascend to heights of around 25 km. Solar-powered, HAPS can theoretically remain aloft for long durations, but require heavy battery packs to survive the night, thus limiting the payload mass. HAPS designs include: Aerovironment Hawk30, Boeing Odysseus, Lockheed HAA, Thales Stratobus, Facebook Aquila, Airbus Zephry, and Google Solara50.

An attractive alternative is the fuel-free HAPS which uses Wireless Power Transfer (WPT) to provide thrust energy to plasma air thrusters (PAT), providing long-duration operation with no resupply for months, and possibly for years. The US patent 10,404,353 to van Wynsberghe [1] explains the design of an untethered aerostat going by the trade name "Sitallite". One such HAPS has a viewing area of up to 1 M sq. km. This system was first studied and published in [2] to demonstrate technical feasibility. This paper extends that work to determine performance estimates for a fuel-free, long-duration stationary platform in the stratosphere using WPT.

METHODS

System design of a HAPS must consider the thrust required to hold station against stratospheric winds. From this can be derived the performance of the PAT, and therefore the demands on the WPT and power conversion system.

A. Drag Force

For an untethered superpressure balloon in the stratosphere, the air density (ρ) can be found from this equation, where the subscript b is a reference altitude/height (h), g_0 is the gravitational constant, M is the molecular weight of air, R is the gas constant, and T is temperature [3].

$$(1) \qquad \rho = \rho_b \exp\left(\frac{-g_0 \cdot M \cdot (h - h_b)}{R \cdot T_b}\right)$$

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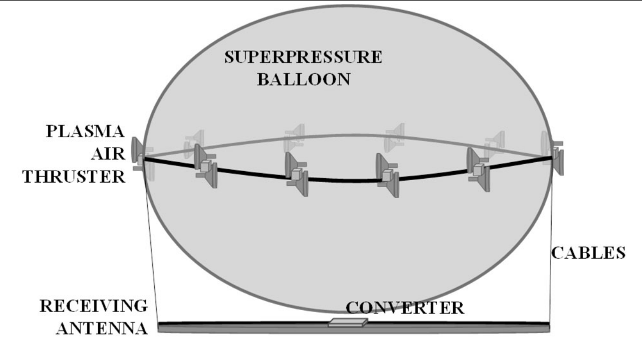

Figure 1. Side view schematic of the Sitallite HAPS.

The drag force is given by equation (2) in which the velocity V is the wind speed, A is the cross-sectional area perpendicular to the wind direction, and C_D is the coefficient of drag.

$$(2) \qquad F_D = \frac{1}{2}\rho V^2 C_D A$$

The drag coefficient depends on the Reynolds number, given in equation (3), where μ is the dynamic viscosity, having a value at 25 km of 1.45E-5 N-s/m^2 [4].

$$(3) \qquad R_e = \frac{\rho V \sqrt{A}}{\mu}$$

For wind speeds V at expected stratospheric levels up to 30 mps, the value of Re becomes sufficiently large to trigger the "drag crisis" wherein the boundary layer disengages from the surface, and the drag coefficient drops from approximately 0.5 to about 0.1 [5]. For an 80 m diameter superpressure balloon this begins to occur at 28 m/s, so it is possible that there may be sudden changes in drag force at extreme stratospheric wind speeds, possibly inducing rapid fluctuations. Therefore the thrust mechanism must have a fast response rate, and be sized for the drag force F_D.

B. Plasma Air Thrusters

Several concepts for plasma air thrusters may be considered, but an attractive solution for a HAPS using RF WPT is the ponderomotive force. This method induces thrust in the same direction for both positively-charged ions and negatively-charged electrons. Thus, no neutralizer is required in the exhaust stream, and this method avoids generation of a large exterior electric field which could interfere with WPT or communications. The ponderomotive force equation for a particle is shown in equation (4), where m is mass, ω is the plasma frequency, q is the electronic charge, and E is the internal electric field [6].

$$(4) \qquad F_{PM} = \frac{-q^2}{4m\omega^2}\nabla E^2$$

A patent on F_{PM} indicates ionization of at least 50%, up to 90% of the air inside the device cavity [7]. The thrust efficiency including RF ionization and ponderomotive thrust is taken as 0.13 N/kW [8].

C. Wireless power transfer

Figure 2 shows the computed value of HPBW versus the number of elements across the diagonal of a PAA having elements spaced at d=0.8λ on a triangular grid. A Dolph-Chebychev power profile designed to minimize sidelobe levels is applied from center to edge. Peak directivity (D) for each design is shown in orange/black, with values read along the right ordinate axis. The AWR Design Environment by Cadence was used for these calculations, in which each antenna element has a gain of 14.4 dB.

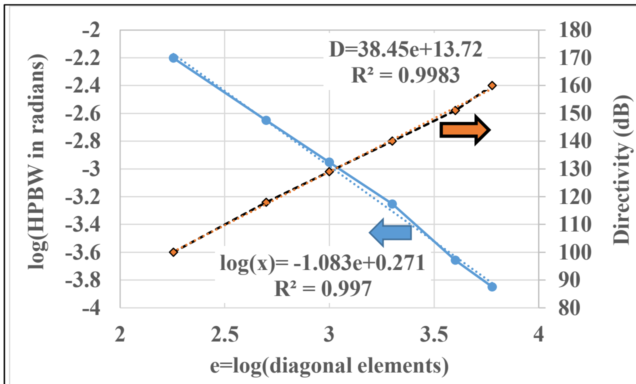

Figure 2. Half-Power Beam Width (parameter x, blue) and Directivity (D, orange/black), as a function of the number of PAA elements along one side, having a triangular grid.

D. Power Conversion

A ponderomotive thruster requires high voltage electric fields at RF frequencies, such as 77,000 V/m over 35 mm, or approximately 2700 V. As explored in [2], the DC rectified power at each antenna element can be combined in either series or in parallel depending on whether high voltage or high current is more valuable. In this case, high voltage is desired, so a series connection of elements is preferred. The alignment between power beam and receive antenna will rarely be static, so that a plurality of series regions are to be partitioned across the receive antenna. As the HAPS is buffeted by stratospheric zephyrs, the voltage of each individual region will fluctuate. To prevent drop-out and to ensure steady power when full thrust is needed, the power conversion circuitry shall include converters to maintain sufficient ionization voltage.

DC to DC solid state converters used to maintain the output voltage from regions of nominally 270 rectifying antenna (rectenna) elements will be required. This mass counts against the parasitic payload carried by the HAPS. State of the art figures of merit for a DC-DC converter are 1.2 to 3.8 kW/kg with efficiency of 87 to 97% [9, 10].

E. Transmit Antenna Beam Steering

The ground-based transmitting PAA is presumed to lay flat, with a broadside beam directed at the zenith, where the Sitallite HAPS is holding station. The composite beam is steered electronically by including phase shifters with each antenna element. In each dimension, the beam direction from zenith θ is determined by the phase shift Φ of the RF power signal between adjacent elements according to equation (5).

$$(5) \quad \theta = \arcsin\left(\frac{\lambda}{2\pi d}\Phi\right)$$

Most phase shift components have a 2π (360°) range, and a resolution of 6 or 8 digital bits. This is too coarse for the small-angle movements expected of a station-keeping HAPS. A mechanical solution is the phase trimmer, which provides small, analog adjustments through a manually-operated twist knob. A more suitable solution can be found in a coplanar waveguide with varactor diodes implemented in GaN semiconductor technology. This method provides fast electronic control of arbitrarily small phase values up to 20 GHz, with low insertion loss [11].

Feedback for WPT beam steering to orbital rectennae frequently cite a retrodirective pilot beam through which detectors in the transmit antenna use local phase conjugation to adjust the phase within subarrays of the PAA [12]. Within earth's atmosphere, it is convenient to instead use a GPS locator on the HAPS. This data can be radioed in real time to the transmit antenna control circuitry, which then adjusts the phase at elements across the array to steer the power beam. As a back-up method, a telescope can be used to optically track the HAPS and direct the beam elevation (θ) and azimuth (ϕ) angles.

RESULTS

The delivery of power across free space has traditionally been calculated using equations by Friis and Gaobau, both of which were derived for singleton antenna elements of various "apparent size". As described in [13] both of these significantly overestimate the transfer efficiency relative to published experimental values. Despite the apparent inaccuracy of using these equations to describe the performance of PAAs having very high directivity, they remain in widespread use. For this reason, we present their results in Fig. 3 for the case study of a Sitallite at 25 km altitude. The Friis and Gaobau equations relate to the size of the antenna, without regard to the spacing between elements found in a PAA, so the axes of the Fig. 3 contour plot are the square root of the area for comparison with Fig. 2. This data was calculated using the WPT GUI Tool being developed by Bergsrud and Zellner of the NSWC Crane naval base (Indiana), which uses the Gaobau equation for power and W.C. Brown's data for RF-to-DC efficiency. It can be seen that, while power transfer fraction scales with both transmit antenna (TxA) and receive antenna (RxA) sizes, the TxA size is more significant. This is a good result because size and thereby mass is less critical for the ground-based TxA relative to the lofted RxA on the HAPS.

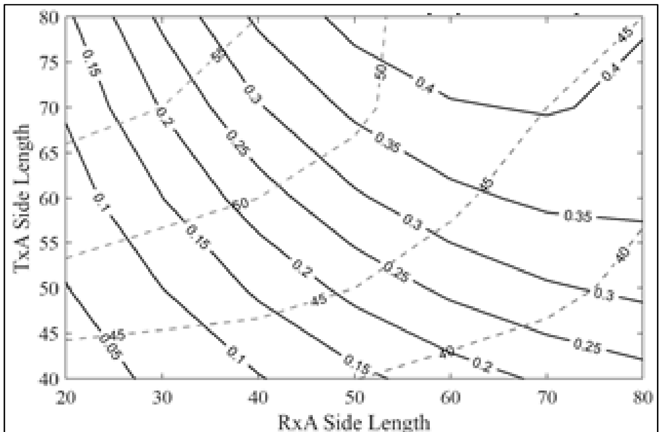

Figure 3. Fraction of free-space power received at 25 km (solid blue) and transfer efficiency (green dashed) by Goubau's equation as function of antennae dimensions.

An alternate calculation for power transfer fraction can be derived from geometrical considerations for a transmit PAA having very high peak directivity D_{max} and small half-power beam width (HPBW), and a receiving antenna (RxA) having a diameter r_R. A factor of ¾ is used as the average power out to HPBW, then a factor which becomes unity when either the directivity is very high, or the angle subtended by the RxA is very small. Finally, a term which represents the ratio of the RxA area to that HPBW, which becomes unity when the receiver is larger than the beam.

$$(6) \quad \frac{P_R}{P_T} = \begin{cases} \frac{3}{4}\cdot\left(1-\frac{h}{r_R * D_{max}}\right)\cdot\left(\frac{r_R}{h * HPBW}\right) & r_R < h\cdot HPBW \\ \frac{3}{4}\cdot\left(1-\frac{h}{r_R * D_{max}}\right) & r_R \gtrsim h\cdot HPBW \end{cases}$$

This alternate equation does not depend on the TxA dimensions or element spacing explicitly, however, the calculation of peak directivity and HPBW must be provided by a software design tool which includes these important factors. Figure 4 shows the dependence of overall power transfer as a function of RxA diameter assuming 0.8λ element spacing, 2.45 GHz. The received power at the RxA needed to maintain maximum thrust at the shoulder of the drag crisis speed is computed with the following assumptions (1) a 50% ionization of air in the PAT, (2) 80% rectification efficiency, (3) 90% conversion efficiency to the high voltages needed for ionization (total 0.32 RxA), and (4) the power through the TxA to free space is 80% efficient. Fig. 4 shows that the transmit power is insensitive to RxA dimension, and is slightly less than 13,000 kW for all cases. This is the maximum ground power needed for the Sitallite to maintain station during peak stratospheric wind conditions, based on equations (2) and (3). An onboard anemometer can be used to relay instant wind speeds (along with the GPS coordinates for phase control mentioned above) to a power modulator at the TxA.

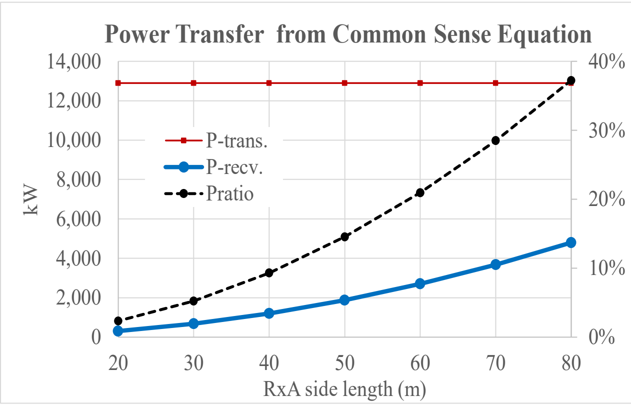

Figure 4. Transmitter power (red) and Sitallite power (blue) as function of RxA side length, with power transfer efficiency on right ordinate axis (dashed line).

A grid-tie baseload wholesale power consumer can expect to pay between 6 and 38 USD per MWh (statista.com), depending on country. As a case study, we consider a surveillance system installed near the Arctic Circle and drawing from the power grid in a Canadian province such as Alberta or Ontario, anticipating increases a few years from this publication at 30 USD/MWh, so that monthly operating costs for the Sitallite are 352,000 USD, or 4.2 M/year. Satellite launches to LEO range from 13 M (Lo scenario) to 400 M (Hi scenario) USD. A comparison metric is the cost per square kilometer (to the horizon) per unit time. Table 1 shows the altitude, the area of visibility, and the fraction availiability of said area (diameter divided by orbital speed). The rightmost column is the cost per visible area normalized to the available time for viewing said area. Personnel costs are not included.

Table 1. Specific cost per area normalized to unit time

Scenario	Altitude (km)	Area (Mkm^2)	Availability (fraction)	Metric USD/km^2
Sitallite	25	1.00	1.0	4.2
Lo LEO	200	8.14	0.076	21.1
Hi LEO	2000	92.7	0.184	23.4

A second scenario explores an off-grid installation such as Antarctica where no grid exists, and the operations must power by diesel generators. Figure 5 shows the size tradespace of the TxA for an 80 m RxA at 25 km altitude. This analysis includes the cost of TxA antenna elements, such as power amplifiers, phase shifters, antenna elements, circuit boards, power cables, connectors, RF oscillator, and ground screws for mounting, plus structural members to support the PAA above the snow. The cost of diesel fuel uses high estimates based on the spot price in remote regions of the Canadian province of Nunavut. The total cost for a remote installation is the topmost line, with the minimum cost shown with a red dot ($25M), this being at a 35 m TxA PAA side length.

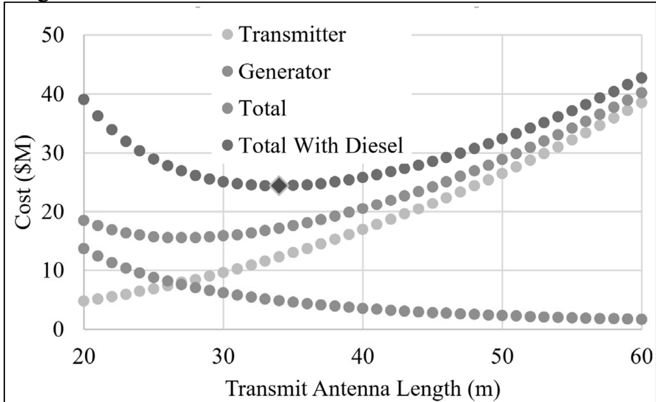

Figure 5. Relative cost curves for PAA transmitter antenna as a function of side length, with the cost of fuel and diesel generators, identifying an optimal design point (red dot).

In order to receive power wirelessly aboard the craft, the rectifying antenna (rectenna) must be designed such that each panel can effectively manage the power load it receives. Panels closer to the center of the beam will be subject to greater energy density than panels toward the periphery.

The rectifying circuits for each panel were designed based on the work of W.C. Brown, whose circuit design employs a single parallel diode across the leads of the antenna element. A parallel capacitor is also included to minimize harmonics, and, with a resistive load, the output is DC power. This simple rectifying antenna element circuit is called a “rectenna”. For the current study, only those diodes which could be sourced at industrial quantities were considered. Several commercially-available diodes were are available, and were compared on the basis of five variables: forward on voltage (V_f); reverse breakdown voltage (V_{BR}); on-resistance (R_S); junction capacitance (C_{JO}); and, maximum frequency (f_{max}). A spiderweb chart of this analysis is shown in Fig. 6. Using the Brown rectenna configuration with a shunt diode across the antenna leads [14], the efficiency of the rectenna is optimized at higher power densities by the difference between V_f and V_{BR}, and the quality of the output DC depends on the capacitance [15]. The Schottky diode YSD110 appears to offer a good balance in performance.

Discussion

Stratospheric temperatures average -40 ºC, at which semiconductor activity can be impaired. Thermal management may require a parasitic load to warm components, however, the waste heat from power converters may be advantageously captured and insulated to maintain the warmth of the electronics converter box shown at the center of the RxA in fig. 1. Furthermore, the backplane for the RxA can be made lossy near the Schottky diodes so that the microwave beam itself provides some amount of self-warming.

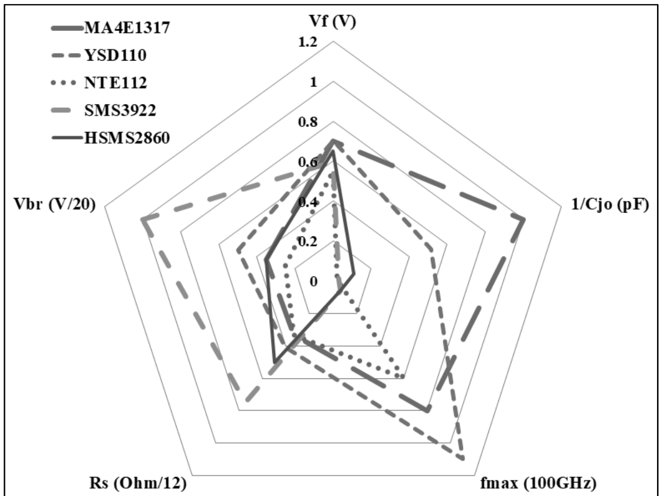

Figure 6. Schottky diode comparison for rectenna circuit using normalized metrics.

WPT from ground stations presents significant opportunities for all-electric aircraft or flying cars for indefinite flight, remote power to satellites, orbital telescopes, and other space assets. Space debris detection and removal can be effected by clever use of the HAPS platform described herein. All of this is available without the risk, complexity, and time delay associated with orbital launch.

When space operations are ready at scale, the methods presented here can be used to transmit solar-harvested power from orbit down to earth (Space-Based Solar Power). This form of baseload ("always on") energy can be used to power metropolitan statistical districts without harmful emissions to land, air, or water. Nighttime diversion loads can include the charging of electric vehicles, or the electrolysis of water to produce hydrogen for fuel cell vehicles. These technologies offer carbon-free energy for fixed and mobile applications, which run on renewable resources using sunlight and water.

Conclusions

The unique, patented HAPS platform known as a Sitallite, for its ability to "sit" in a geostationary location, uses WPT and RF-to-DC rectification to provide long-duration, persistent surveillance and data links. The grid-tied reference case has at least a five-to-one cost advantage relative to an orbiting satellite, and provides continuous visibility over 1M sq. km. By using RF-driven plasma air thrusters based on the ponderomotive force, there is no fuel consumption during ascent, descent, and while holding station above the transmit antenna. With beamed power there is no need for the mass and volume of fuel storage, and minimal need for heavy on-board energy storage. Annual costs are bounded by 4.2M USD, asumming worst-case stratospheric winds, requiring 13 MW of electric power to hold station. This technology can be fielded more quickly and with lower risk than alternate means for regional observation and communication.

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