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Station-keeping of a high-altitude balloon with electric propulsion and wireless power transmission: A concept study

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ABSTRACT

A stable, ultra long-duration high-altitude balloon (HAB) platform which can maintain stationary position would represent a new paradigm for telecommunications and high-altitude observation and transmission services, with greatly reduced cost and complexity compared to existing technologies including satellites, telecom towers, and unmanned aerial vehicles (UAVs). This contribution proposes a lightweight superpressure balloon platform for deployment to an altitude of 25 km. Electrohydrodynamic (EHD) thrusters are presented to maintain position by overcoming stratospheric winds. Critical to maintaining position is a continual supply of electrical power to operate the on-board propulsion system. One viable solution is to deliver power wirelessly to a high-altitude craft from a ground-based transmitter. Microwave energy, not heavily attenuated by the atmosphere, can be provided remotely from a ground-based generator (magnetron, klystron, etc.) and steered electrically with an antenna array (phased array) at a designated frequency (such as 2.45 or 5.8 GHz). A rectifying antenna ("rectenna") on the bottom of the balloon converts waves into direct current for on-board use. Preliminary mission architecture, energy requirements, and safety concerns for a proposed system are presented along with recommended future work.

1. Introduction

A geostationary balloon platform located at high altitude could offer economically and strategically advantageous methods of data collection and transmission, as compared to orbiting space satellites, telecommunication towers and unmanned aerial vehicles (UAVs) such as drones. Such a novel platform could provide high-demand services such as high-capacity wireless broadband Internet distribution to remote and under-serviced regions [1] while also enhancing line-of-site propagation transmission [2]. Other potential applications include search-and-rescue operations, disaster relief, national defense, border patrol, intelligence, surveillance, and reconnaissance gathering and relaying, emergency communication restoration, remote sensing, surveying and mapping, forest-fire and other disaster detection, environmental monitoring, climate and science research, astronomy, meteorology, and education. The proposed system would provide an easily deployable, long duration, sustainable solution to many high altitude services valuable to strategic, scientific, and commercial endeavors.

Stratospheric balloons have over a century of practical experience for high-altitude activities. Superpressure balloons in particular have a long and successful history dating back many decades [3,4], and have experienced significant advancement in the past two decades, with demonstrated flights at a fixed altitude lasting several months [5–8]. The advantage of such balloons over other potential high altitude craft or stationary transmission towers lies in its versatility. The balloon platform offers more power, longer flight times (months instead of days or hours), stable position, minimal ground footprint (no long runways) compared to unmanned aerial vehicles (UAVs). The balloon is also easily movable to a new position, a significant advantage over telecommunications towers. Compared to a geosynchronous Earth-orbit (GEO) satellite, despite a comparatively reduced coverage area, the stationary balloon offers many advantages: substantially reduced cost, complexity, and risk; greater scanning resolution and lower power burden for transmission from closer proximity to the Earth; cost-effective redundancy, resiliency, and uninterrupted service (multiple balloons working collaboratively in a region); rapid deployment (days, compared to years for rockets); relative ease of manufacture; and ease of modification and/or replacement for various applications by quickly lowering and re-raising a balloon [9].

However, the critical limitation of current balloon based systems is the inability in maintaining a continuous position (latitude

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and longitude). Endeavors such as Project Loon [10,11] (Google) risk added costs and impediments with balloons that cross over many national borders and through sovereign airspace as they traverse the globe. Conversely, a stationary balloon avoids these problems altogether by remaining within one jurisdiction.

A proposed station-keeping solution to enable balloon flight control for such projects is a craft which can rise or sink to a desired altitude, thereby harnessing stratospheric winds to move the craft [12]. However, such winds are generally West to East, so that while a craft can make some minor adjustments to course, they ultimately cannot remain within a tightly confined region for any meaningful period of time to facilitate long-term, geostationary operation [13]. Additionally, the winds may not be available at the desired time in the preferred direction (or accessible fast enough) to cover a targeted area for shorter duration flights, leaving the craft to float adrift or in the wrong direction [14]. The continual filling and emptying of the balloon vessel can cause detrimental strain on the sheath, leading to leaks and eventual drainage of buoyant gas, for added cost and environmental impact, potentially weakening it to the point of destruction.

A more stable and reliable approach to maintaining position would be to ensure a continual supply of electrical power to operate an on-board propulsion system. To provide the energy needed for constant station-keeping both day and night, solar power is one possible option. Modern organic photovoltaics show promise as both lightweight and flexible solar energy harvesters [1,15]. However, such materials are vulnerable to degradation from the extreme cold of high altitude and UV radiation from the sun [16–20], as well as the fluctuating temperatures and harsh weather conditions on the journeys up and down through the atmosphere. Such factors may limit their long-term effectiveness, or require ongoing costly and resource-consuming maintenance. Further, a substantial amount of additional solar energy must be harvested and stored during each day to ensure continual operation of thrusters at night. Proposals for geostationary balloons using solar power have admitted that year-long operation is not feasible [13].

While technology in lightweight, rechargeable batteries is making significant advancements [21], carrying a large complement of batteries would add substantial mass burden, thus increasing the size of the balloon and subsequently the cost, all the while occupying payload space that could otherwise be reserved for client services. The risk also remains of degradation due to extreme environmental conditions, and forcing repeated landings to service or replace the batteries. Frequent landings and re-fillings would weaken the balloon sheath, as above, diminishing life expectancy and increasing service costs.

One viable solution that limits these considerations is to deliver power wirelessly to the high-altitude craft from a ground-based transmitter. We propose that it is possible to provide sufficient energy by transmitting a constant, steady supply of microwave power, wirelessly from the ground, to a receiver in the form of a rectifying antenna ("rectenna") on the bottom of the craft. This will satisfy all propulsive power needs as well as provide any and all power required by the client payload, alleviate repeated landings, facilitate longer-term missions, and eliminate the reliance on high-altitude winds. Precedence exists for sending power wirelessly from the ground into the air, including remote-powered helicopters [22] and UAVs [23,24].

A propulsion system on a stratospheric balloon must be extremely lightweight, of high thrust–mass ratio, high thrust–power ratio, and with minimal or no fuel consumption to avoid repeated landings. Additionally, such a system needs to work efficiently with thin atmospheres and cold temperatures. These requirements make traditional propulsion systems, such as propellers and various engine technologies impractical and unsustainable [13]. Although cold gas propulsion systems [25] have been proposed for high altitude station-keeping purposes, the burden of a supply of propellant also makes them undesirable.

Electrohydrodynamic (EHD) thrusters, popularly referred to among hobbyists and enthusiasts as ioncraft or lifters, address all of these concerns. These devices are aptly suited to operate in the low-density environment of high altitudes as their thrust tends to increase with a decrease in the ambient pressure, and higher efficiency is expected in higher Knudsen number regimes [26,27]. Such devices also offer superior thrust-to-weight ratio in the lab compared to jet engines [28], and have no mechanical moving parts, ideal for these low-temperature environments.

In this paper, the feasibility of a novel geostationary high-altitude platform is presented, combining existing and well-proven technologies including a superpressure balloon for buoyancy, electrohydrodynamic thrusters for lateral station-keeping, and microwave energy transmitted wirelessly from ground, into a single application that could provide significant advantages and a paradigm-shifting approach to air-born services. Technical components discussed include the necessary power generator, transmitter, receiver, to support the thruster system, sensors, controls, safety components, and ground support infrastructure. Altitude optimization, safety considerations, and recommendations for future work will also be discussed.

2. Primary components

A proposed geostationary high-altitude platform consisting of a superpressure balloon, EDH thrusters, rectifying antenna (rectenna), sensors, and payload is displayed and summarized in Fig. 1. To physically support the large complement of thrusters, the craft also carries a scaffolding superstructure, visualized in Fig. 1 as thin rods descending from the balloon at a slight angle. The thrusters are represented in greater detail in Fig. 2. Not shown is the ground-based power transmission system. Each of the necessary components is described in detail in the following sections.

2.1. Superpressure balloon

A superpressure balloon is a sealed, plastic cell that floats at a constant density altitude, despite ambient temperature fluctuations between day and night [3]. Internal pressure of the lighter-than-air gas is kept at a greater value (super) than ambient pressure at all times to ensure buoyancy, without significant change in volume. Embedded ropes ensure that the balloon volume is roughly constant at the target altitude [3]. For long-duration flights at stratospheric altitudes, superpressure balloons are superior to alternative such as the zero-pressure balloon which function by jettisoning cooled lift gas at night to maintain altitude, and are therefore limited by their requirement of carrying exhaustable ballast [4]. Helium is generally preferred over hydrogen to prevent combustion.

Design of the superpressure balloon depends on various criteria including atmospheric drag, operational efficiency, cost, material strength, and ease of manufacture. Balloon skin is typically made of very thin, lightweight, durable material such as Mylar or 1.5 mil co-extruded LLDPE film [3]. A sphere shape is preferred for superpressure applications compared to the cylinder, tetrahedron, or onion, as the sphere retains the highest values of internal pressure for a given maximum safe stress on the material [3]. Research in the past two decades has shown that the elastica or pumpkin shape can also be a viable alternative shape, from material strength and durability perspectives [7].

However, drag is a critical consideration when selecting optimal shape for long duration flights. While a sphere is high in drag compared to elliptic shapes such as the dirigible or blimp, the sphere offers the advantage of *consistency* in drag, in all three axes.