A Method for Establishing a Station-Keeping, Stratospheric Platform for Astronomical Research

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Abstract During certain times of the year at middle and low latitudes, winds in the upper stratosphere move in nearly the opposite direction than the wind in the lower stratosphere. Here we present a method for maintaining a high-altitude balloon platform in near station-keeping mode that utilizes this stratospheric wind shear. The proposed method places a balloon-borne science platform high in the stratosphere connected by a lightweight, high-strength tether to a “tug” vehicle located in the lower or middle stratosphere. Using aerodynamic control surfaces, wind-induced aerodynamic forces on the tug can be manipulated to counter the wind drag acting on the higher altitude science vehicle, thus controlling the upper vehicle’s geographic location. We describe the general framework of this station-keeping method, some important properties required for the upper stratospheric science payload and lower tug platforms, and compare this station-keeping approach with the capabilities of a high altitude airship and conventional tethered aerostat approaches. We conclude by discussing the advantages of such a platform for a variety of missions with emphasis on astrophysical research.

1 Introduction

It has long been realized that a high-altitude observing platform located in the stratosphere and thus above a significant fraction of the Earth’s atmosphere could offer image quality competitive with space-based platforms. This was the motivation behind the series of Stratoscope I and II balloon flights that ran in the late 1950s, 1960s, and early 1970s flying 0.3 to 0.9 m telescopes to an altitude of 24 km (80 kft) and obtaining 0.2 arcseconds resolution images of the Sun, planets, and selected stars and galaxies [5,37,47]. Stratoscope images along with recent atmospheric turbulence...
studies [3,19,21,46] have shown that near diffraction-limited image quality can be achieved at altitudes at or above 20 km (65 kft) where the telescope is above \( \approx 95\% \) or more of the atmosphere.

Since the end of the Stratoscope missions, few high-altitude balloon flights have carried optical and near-infrared astronomical telescopes and detectors. NASA's highly successful multi-million cubic foot, high-altitude balloons flown at altitudes of 30 to 40 km (100 – 130 kft) have largely been limited to the Arctic and Antarctic summers and have typically involved heliophysics, x-ray, gamma-ray, particle astrophysics, and IR/sub-mm programs that are unaffected by daylight observing conditions. Only a few high altitude balloon flights, like the recent heliophysics SUNRISE telescope [41], have been conducted outside of the polar regions.

However, such high altitude, daylight balloon missions are generally not suitable for a broad spectrum of general astronomical observing programs requiring dark sky observing conditions. The few nighttime high-altitude astronomical balloon flights that have occurred have been limited to relatively short duration times of a week or less [9,30,45].

2 Airships

Despite an ever increasing number of space missions, there has been renewed interest in recent years for exploring the use of high-altitude balloon flights for nighttime astronomical research. This has resulted in a number of papers discussing possible lighter-than-air (LTA) vehicles and telescope arrangements for optical and infrared observations from non-polar locations [6,15,20,36,43,44]. A self-propelled, high-altitude, long endurance (HALE) stratospheric airship capable of keeping station over a desired geographic location would be a highly attractive platform for a variety of astronomical and other science missions [14].

A solar-powered airship operating at altitudes near 20 km, where the stratospheric winds are lightest could, in principle, remain aloft for days, weeks, or even months thus serving as a general purpose astronomical observatory for night observations covering a broad set of targets having a wide range of declinations. Besides avoiding so-called “no-fly zones” over some countries that restrict free-floating balloon flights over their territory, a station-keeping airship could provide simple and continuous line-of-sight telemetry allowing for high-bandwidth data communication to a single ground station.

In basic terms, a stratospheric airship differs from a conventional airship or blimp in terms of cruising altitude, balloon fabric, and propulsion. Blimps have thick and robust gas envelopes, are flown at relatively low altitudes (< 3000 m), at low speeds (< 15 m/s), and are powered by conventional piston engines. Their advantage over airplanes is their ability to stay aloft and hover for long durations without refueling and to do so at a relatively low cost of energy consumption (see the recent historical review of airships by Liao and Pasternak [25]).

The possibility of relatively low construction and operations costs have made airships attractive for a host of potential uses. For example, the US Department of Defense (DoD) has funded several high-altitude airship designs and test programs
over the last decade with the goal of developing a reliable low cost stratospheric, long duration platform which could provide wide area surveillance and communications capabilities with good air defense. Recent DoD projects include Southwest Research Institute’s (SwRI) Sounder and HiSentinel vehicles [38,40] and Lockheed-Martin’s High Altitude Airship (HAA) and High Altitude Endurance-Demonstrator (HALE-D) airships.

Unfortunately, despite considerable effort and expense, no self-propelled airship built by any manufacturer has flown at stratospheric altitudes for more than one day. The current record for a high altitude airship flight duration may still be the High Platform II vehicle built by Raven Industries and flown in the late 1960s at 20.4 km (67 kft) for a few hours [39].

A 2007 NASA study of a variety of LTA and heavier-than-air (HTA) unmanned HALE vehicles found LTA vehicle concepts attractive in terms of performance but were viewed as carrying a high technical risk [28]. This assessment was arrived at, in part, due to the fact that the design and construction of a high-altitude airship poses several major obstacles including large envelope size, extremely lightweight and fragile balloon fabric for lifting gas containment, energy storage and power systems, launch and recovery operations, diurnal thermal management, and high-altitude propulsion motors and propellers [6].

A more recent 2012 assessment of US military airship efforts (GAO Report 13-81) also gave an unfavorable outlook for the future development and deployment of high altitude airships. In reviewing various recent HALE airship efforts, the report noted that many have been either terminated or have suffered “significant technical challenges, such as overweight components, and difficulties with integration of software development, which, in turn, have driven up costs and delayed schedules.”

Despite such setbacks, strong interest in the development of a high-altitude, long endurance airship persists. Several commercial telecommunication companies continue to pursue HALE airship development because such platforms could provide communication and data services to consumers in rural or remote areas [8,11,31,33,42] and would combine some of the best features of satellite and fixed wireless services such as short transmission delay times, low propagation loss, and relatively large service areas [17]. Airship programs such as the recently completed European HAPCOS project (http://www.hapcos.org), the Japanese Stratospheric Airship Platform Study [13], the Google Internet balloon project (“Project Loon”), and Thales Alenia Space Consortium’s “StratosBus” are among some of the more recent efforts to use balloons for telecommunications purposes.

One of the most difficult problems in airship design is propulsion power. While stratospheric wind speeds are lowest (5 – 15 m/s) at altitudes around 20 km (65 kft), wind can vary significantly both daily and throughout the year, exceeding 25 m/s at times and even higher in gusts. At these speeds, wind force on a conventional natural shape balloon is considerable, driving airship designers toward aerodynamic balloon shapes with low form drag values and propulsion systems involving large solar arrays or hydrogen fuel cells.
The form or shape drag force $F_{\text{form}}$ acting on a vehicle moving through a fluid of density $\rho$ at speed $v$ is

$$F_{\text{form}} = \frac{1}{2} \rho v^2 A_f C_D,$$

where $A_f$ is the drag area (equal to the projected frontal area) of the vehicle and $C_D$ is the coefficient of form drag corresponding to the particular shape of the vehicle. Similarly, the frictional drag force $F_{\text{friction}}$ is

$$F_{\text{friction}} = \frac{1}{2} \rho v^2 A_w C_{SF},$$

where the area $A_w$ is the “wetted surface” and the coefficient $C_{SF}$ is the skin frictional drag coefficient (which depends on the viscosity of the fluid).

To illustrate the wind induced drag forces on an airship, we will consider the HiSentinel50 airship built by SwRI. This vehicle was cylindrical in shape with length $L = 54$ m and diameter $D = 12$ m. Its frontal area was $A_f = 115$ m$^2$, its wetted area was $A_w = 2500$ m$^2$ with drag coefficients estimated at $C_D = 0.022$ and $C_{SF} = 0.0026$. At an altitude of 65 kft the air density is $\rho = 0.091$ kg/m$^3$ meaning that for a wind speed of 10 m/s, its total drag force is

$$F_{\text{drag}} = F_{\text{form}} + F_{\text{friction}} = 12 \text{ N} + 30 \text{ N} = 42 \text{ N}.$$

This force is the thrust needed to oppose its wind-induced drag.

The power the airship needs to match this wind force and thereby enable it to keep station is

$$P = F_{\text{drag}} \times v = 42 \text{ N} \times 10 \text{ m/s} = 420 \text{ W}.$$

This amount of power is relatively small and practical for an airship using photovoltaic (PV) panels and lightweight electric motors. But this example represents a fairly favorable scenario in terms of mild stratospheric winds of just 10 m/s at the “sweet spot” altitude around 20 km plus a very low drag airship design. Since drag is proportional to the square of velocity and power is drag times velocity, propulsion power is really proportional to $v^3$. Thus airship power requirements increase rapidly with wind speed.

For instance, using the same airship numbers above but now for a wind speed of 30 m/s, the airship’s total drag force increases to nearly 370 N requiring 11 kW of power to keep station. This is a considerable amount of power to generate in order to maintain the airship floating above its desired position point, apart from any power that might be required by the airship’s payload.

However, even at lower wind speeds, having an airship keep station could be challenging. If the airship’s overall drag forces were twice as large due perhaps to a larger form drag coefficient for the airship or caused by a large and highly non-streamlined mission payload shape, the power required would increase by a factor of two. This would mean some 20 kW of power would then be needed for station-keeping, an amount difficult to generate using PV panels alone on this relatively
modest sized airship. Since steady wind speeds around 30 m/s are not exceptionally rare at 20 km, this means that strict year-round station-keeping for such an airship might simply not be possible.

3 Tethered High-Altitude Airships and Balloons

A radically different approach for establishing a lighter-than-air stratospheric station-keeping platform involves tethering the vehicle to a ground station. This scheme again would keep the platform’s altitude to 20 km or so as to take advantage of the lightest stratospheric winds and hence the lowest drag forces on the airship.

However, no tethered high altitude stratospheric aerostat has been successfully flown for even one full diurnal cycle, although several attempts were made by French atmospheric scientists in the late 1970s [32]. The main obstacles include aviation restrictions, tether strength and weight, the tether winch, and tether wind drag. Storms and wind gusts in the troposphere can generate large transient wind loads on the tether, the winch, and the vehicle itself especially during initial deployment and recovery.

Despite this, a tethered stratospheric aerostat offers some distinct advantages over powered airships. These include no propulsion motors or propellers allowing for higher mass payloads, no large solar panel arrays to power the propulsion motors, and no large batteries for nighttime propulsion. In addition, the advent of technically advanced, high tensile strength materials such as Ultra High Molecular Weight Polyethylene (UHMWPE) such as Spectra and Dyneema), Polybenzobisoxazole (PBO) such as Zylon, and Liquid Crystal Polymers such as Vectran, Kevlar, and Technora has made the concept of a tethered stratospheric aerostat more practical than in the past.

Several papers concerning the feasibility and flight properties of a tethered aerostat at altitudes around 20 km have appeared recently. These include a study of a sea-anchored stratospheric, long duration balloon [2], the construction, launch and operation of tethered stratospheric balloons as alternatives for satellites [4,26], and investigations of the dynamic response for a high altitude tethered balloon aerostat and tether line to winds and their effects on payload pointing stability [1,18].

The chief advantage of the tethered LTA platform scheme is simplicity. In principle, a land or sea deployed tether to a stratospheric balloon from a launch site with favorable tropospheric winds, few aviation hazards or flight restrictions, and seasonal periods of low stratospheric wind speeds, might allow flight durations exceeding a few days. However, weather conditions throughout the tropospheric column (e.g., surface and low altitude winds and gusts, storms and downdrafts) along with tether mass and tether wind loading may severely restrict its applicability and flight duration.

As is done for low altitude aerostats, most high-altitude tethered airship models have the tether attached to a ground-based winch which must be operated so as to limit the tension on the tether below its minimum breaking strength. Despite a number of articles discussing this approach [1,2,4,6,26], the only partially successful series
of flights seems to have been done by atmospheric researchers in the 1970s [32] and, to our knowledge, no high-altitude tethered aerostats have been attempted since.

4 A Tethered Stratospheric Wind Shear Approach

Here we describe an alternative means of establishing a stratospheric station-keeping LTA platform that makes use of a tether. During certain times of the year at mid- and low latitudes, winds in the upper stratosphere move in nearly the opposite direction than the wind in the lower stratosphere. A balloon or airship at high altitude could be tethered to a heavier-than-air glider “tug” at a lower altitude where the wind blows essentially in the opposite direction. By adjusting the aerodynamic configuration of the tug, wind forces acting on it can be made to counteract those acting on the airship.

An example configuration exploiting this naturally occurring wind shear is shown in Figure 1. The airship and its payload float at an altitude around 24 km (80 kft) while the tug flies some 7 km lower at around 17 km (55 kft). The tether connecting them
is shorter and hence lighter than it would need to be if it were to extend to the ground and it does not penetrate the turbulent weather of the troposphere. The tug’s relatively high altitude places it well above the maximum operating ceilings of all commercial aircraft (43 kft) and private or corporate jets (51 kft) thereby greatly reducing aviation restrictions and hazards. Wind at the tug’s altitude is generally stronger and the air denser than higher up meaning the tug can be relatively small and still develop the necessary forces to balance that experienced by the upper airship.

This approach to a station-keeping capability depends upon stratospheric wind shear—that is, the difference in wind speed and direction between the altitude of the airship and that of the tug. Figure 2 shows plots of wind speed and direction as a function of altitude and latitude where altitude is indicated by the associated atmospheric pressure. Although these plots are multi-year averages for each season, they illustrate the basic stratospheric wind shear phenomenon. Each plot is annotated with the example altitudes discussed above and with a range of latitudes for which favorable conditions prevail.

Although the plots of Figure 2 and the results of other stratospheric wind studies [35] indicate the existence of a usable stratospheric wind shear, such multi-year average plots do not reflect the variable day-to-day wind conditions that would actually
govern the behavior of the proposed system. Such day-by-day wind direction differences at altitudes of 16.7 and 24.4 km (55 and 80 kft) are shown in Figure 3. Each of the four plots is for a 60-day interval in the spring of the years 2000, 2005, 2010, and 2013 for the atmosphere above Hilo, Hawaii (latitude +19.8°) and assembled from radiosonde data available from the University of Wyoming’s upper air sounding website (http://weather.uwyo.edu). Typically, two radiosonde flights are made each day and both measurements are plotted when available. The plot for 2013 shows the most recently available data. More details may be found in [35].

Data for a tug altitude of 16.7 km (55 kft) were extracted from the radiosonde database within a relatively small altitude range (± 0.2 km), while the airship’s altitude was allowed to vary by ±1 km so as to reflect the likelihood of altitude variations due to diurnal heating effects. In cases of missing radiosonde data within these altitude ranges, we interpolated between the two closest values. Although the data shown in Figure 3 cover an upper altitude range centered at 24.4 km, nearly 75% of the measurements plotted correspond to values taken at altitudes between 23.5 and 24.3 km.

It is important to note that not all sounding data covering these time intervals are shown in these plots. Besides some missing radiosonde data (typically just a few days
during a month), we do not show wind direction differences that exceed 70°. Large variations in upper air flows can occasionally lead to unfavorable wind conditions for several days each month. This is the reason that during the year 2000 we show wind direction differences for March 16 – May 15 rather than April 1 – May 30. During that year, the wind direction reversal formed over Hawaii about two weeks earlier than typically seen. During the four periods shown, the number of 12-hour periods during which easterly and westerly wind direction were greater than 70° apart were 23 in 2000, 18 in 2005, 15 in 2010, and 20 in 2013. However, on many of these occasions, wind speeds were relatively low at one or both altitudes.

Keeping in mind these limitations, the plots of Figure 3 illustrate that between 16.7 and 24.4 km (55 kft and 80 kft) the stratospheric wind directions are within 45° of being 180° apart for the majority of the days shown. The best of these two-month periods is April and May 2005 when over 85% of the time the upper and lower altitude winds were within 30° of being 180° apart. The worst two month period shown occurred in 2013. Marked differences year to year is not surprising. This is, after all, weather, and weather patterns can change significantly from one year to the next. However, the regular appearance of such opposing wind flows between stratospheric layers only some 7 km apart can be exploited to maintain the geographical location of a high-altitude platform without the need of propulsion power.

Because of seasonal wind variations above a particular geographic location, stratospheric wind shear will not permit year-round station-keeping. Suitable opposing winds are found around 40° latitude in hemispheric summers, but in spring and fall they are found at lower latitudes around 15 to 25° (see Figure 2). This is shown in Figure 4 where we plot wind direction differences at 15.2 km and 24.4 km (50 kft and 80 kft) for the months of June and July in the years 2000 and 2010 over Denver, Colorado (latitude +39.8°). Although there is considerable scatter, the lower to upper stratospheric wind shear is still within 45 degrees of being directly opposite over 75% of the time. These plots also show that the wind shear can be experienced by a tug at lower altitudes, here at 15.2 km (50 kft).

The seasonal shift in latitude of the stratospheric wind shear means that in order to operate year-round the airship and tug will need to move north or south some 20 – 30 degrees in latitude during the course of a year. A shift in latitude of the wind shear may be partially responsible for some of the unfavorable wind shear days seen in the Spring months over Hawaii (see Fig. 3).

5 Payload Platform and Tug Operation

The operation of the proposed station-keeping system depends on balancing the aerodynamic forces on the airship with those acting on the tug. The air density at the tug’s altitude of 17 km is roughly three times that at the airship’s altitude of 24 km. In addition, wind speeds are generally two to four times greater at the lower altitude than at the higher altitude. The tug will therefore experience drag forces some 10 to 50 times higher than the airship even if the two vehicles are of similar size and shape. If the airship is streamlined so as to minimize drag, the tug could be made quite compact
Fig. 4 Plots of summer wind direction differences between stratospheric winds at 15.2 km and 24.4 km above Denver, Colorado for the years 2000 and 2010 based on radiosonde data. A difference of 180° (solid line) indicates directly opposing winds.

and lightweight while still developing the counter force necessary for hold the airship steady in the wind.

Table 1 shows sample wind induced drag force calculations for three airship sizes and shapes. These computations assumed an airship altitude of 23.7 km (78 kft) and a variety of ambient wind speeds. The listed drag force values were calculated assuming only form and surface drag. Case 1 is an airship similar in size to SwRI’s streamlined HiSentinel80 airship, Case 2 is a “super-sized” HiSentinel80, and Case 3 is for a spherical balloon having a displaced volume similar to that of HiSentinel80 in Case 1.

Comparing Cases 1 and 3, it is clear that having a streamlined airship versus a spherical balloon lowers the total wind drag force by about a factor of 20. Also, going from a small to a larger streamlined airship (Cases 1 and 2) the system gains a factor of nearly 10 in potential lift while the total drag force increases by only a factor around 2.5.

The drag values listed in Table 1 must be comparable to the wind drag numbers for the lower altitude tug vehicle which are listed in Table 2 for a range of wind speeds likely to be encountered at the tug’s altitude of around 17 km. As an example, we have adopted a tug design in the form of a conventional glider consisting of a narrow fuselage and thin, high-aspect wings with high lift-to-drag ratios. We have assumed some sort of variable drag device as part of the tug with a form drag force proportional to an adjustable area of the device. The table shows drag force values resulting from both open and closed configurations.

As Table 2 shows, it appears feasible for a tug to generate drag forces covering the complete wind speed range calculated for the two streamlined airship cases in Table 1 (Cases 1 and 2) but not for a spherically shaped airship (Case 3). This again disfavors a spherical airship shape.

Lastly, we show in Table 3 estimated wind loading values for both a ground-tethered high altitude aerostat and our proposed high altitude airship-tug scheme. Here we have assumed a constant wind speed of 20 m/s at all altitudes. Although there
Table 1 Airship Drag Forces at 23.7 km (78 kft), $\rho = 0.048$ kg/m$^3$

**Case 1: HiSentinel80**
- $D = 15$ m, $L = 60$ m; volume: $10600$ m$^3$ balloon: $320$ kg (@ $0.1$ kg/m$^2$); helium: $70$ kg; displaced air: $510$ kg

| Drag Parameters | Wind Speed 5 m/s | Wind Speed 10 m/s | Wind Speed 20 m/s | Wind Speed 30 m/s |
|-----------------|------------------|------------------|------------------|------------------|
| $C_D = 0.03$; $A_f = 177$ m$^2$ | 3 N | 13 N | 51 N | 114 N |
| $C_{SF} = 0.003$; $A_{sw} = 3500$ m$^2$ | 6 N | 25 N | 100 N | 227 N |
| **Total Drag Force** | 9 N | 38 N | 151 N | 341 N |

**Case 2: Super-HiSentinel**
- $D = 25$ m, $L = 100$ m; volume: $49100$ m$^3$ balloon: $885$ kg (@ $0.1$ kg/m$^2$); helium: $325$ kg; displaced air: $2350$ kg

| Drag Parameters | Wind Speed 5 m/s | Wind Speed 10 m/s | Wind Speed 20 m/s | Wind Speed 30 m/s |
|-----------------|------------------|------------------|------------------|------------------|
| $C_D = 0.03$; $A_f = 490$ m$^2$ | 9 N | 35 N | 141 N | 317 N |
| $C_{SF} = 0.003$; $A_{sw} = 9000$ m$^2$ | 16 N | 65 N | 260 N | 583 N |
| **Total Drag Force** | 25 N | 100 N | 401 N | 900 N |

**Case 3: Spherical Balloon**
- $D = 28$ m; volume: $11500$ m$^3$ balloon: $250$ kg (@ $0.1$ kg/m$^2$); helium: $75$ kg; displaced air: $550$ kg

| Drag Parameters | Wind Speed 5 m/s | Wind Speed 10 m/s | Wind Speed 20 m/s | Wind Speed 30 m/s |
|-----------------|------------------|------------------|------------------|------------------|
| $C_D = 0.5$; $A_f = 615$ m$^2$ | 185 N | 740 N | 3000 N | 6700 N |
| $C_{SF} = 0.003$; $A_{sw} = 2460$ m$^2$ | 4 N | 18 N | 70 N | 160 N |
| **Total Drag Force** | 190 N | 760 N | 3100 N | 6900 N |

Table 2 Tug Vehicle Drag Forces

**Tug**
- $D = 0.75$ m, $L = 4$ m fuselage + 4 m drag device, altitude = 16.7 km (55 kft)

| Vehicle Component | Drag Parameters | Wind Speed 10 m/s | Wind Speed 20 m/s | Wind Speed 30 m/s |
|------------------|------------------|------------------|------------------|------------------|
| fuselage + wings | $C_D = 0.12$; $A_f = 1.8$ m$^2$ | 2.0 N | 9.0 N | 20 N |
| $C_{SF} = 0.03$; $A_{sw} = 7.1$ m$^2$ | 2.0 N | 8.0 N | 19 N |
| drag device closed | $C_{SF} = 0.03$; $A_{sw} = 7.1$ m$^2$ | 2.0 N | 8.0 N | 19 N |
| “ opened | $C_D = 1.0$; $A_f = 28$ m$^2$ | 270 N | 1090 N | 2450 N |
| **Total Force Range** | 6 - 275 N | 26 - 1115 N | 60 - 2490 N |
Table 3  Tether Masses and Wind Loads at 20 m/s

| Altitude | Single Tether: Altitude: 0 to 20 km; Total Tether Length: 20 km; CD = 1.0 |
|----------|-------------------------------------------------------------------------|
|          | Dyneema (SK78) | 0 - 5 km | 5 - 10 km | 10 - 15 km | 15 - 20 km | Totals |
|          |               | 0.96 kg/m$^3$ | 0.56 kg/m$^3$ | 0.30 kg/m$^3$ | 0.13 kg/m$^3$ |        |
| 5mm; MBS | 3300 kg       | 480 kg    | 280 kg    | 150 kg    | 760 kg |
| mass: 15 | kg/km         | 75 kg     | 75 kg     | 75 kg     |        |
| 3mm: MBS | 1400 kg       | 90 kg     | 40 kg     | 130 kg    |        |
| mass: 5  | kg/km         | 25 kg     | 25 kg     | 25 kg     |        |
| Totals   |              |           |           |           | 1090 kg |
| Airship: | Altitudes: 17 and 24 km; Total Tether Length: 12 km; CD = 1.0 |
|          | Dyneema (SK78) | 0 - 5 km | 5 - 10 km | 10 - 15 km | 15 - 20 km | Totals |
|          |               | 0.10 kg/m$^3$ | 0.06 kg/m$^3$ |        |        |
| 2mm: MBS | 450 kg        | 16 kg     | 7 kg      | 23 kg     |        |
| mass: 2.4 | kg/km         | 17 kg     | 12 kg     | 29 kg     |        |
| Totals   |              |           |           |           | 52 kg   |

A thinner 2 mm cord was chosen for the airship-tug tether since wind loading conditions are far more benign above the jet stream and most storms at altitudes 17 km (55 kft) and higher.

Comparison of the two high-altitude tethered airship approaches in Table 3 shows that a single tether will experience just under one metric ton of horizontal wind loading plus tension due to 200 kg of tether mass. Although this estimate assumes a constant wind speed of 20 m/s along the entire 20 km length, these wind loads and tether mass could actually be an underestimate. It is unlikely that the tether would be as short as 20 km given wind loading and varying wind directions and speeds from the ground winch up to the altitude of 20 km, and thus a tether length as much as 30 km is probably more realistic. In that case, again dividing the tether into 3 mm and 5 mm thicknesses—but now each 15 km long—an even greater wind loading might exist while the total tether mass increases to around 300 kg.

In real life, the situation might be even less favorable since tropospheric wind speeds often exceed 20 m/s and can even be over 50 m/s in the jet stream. At a wind speed of 40 m/s, just a 1 km long section of a 5 mm thick tether at an altitude around 10 km (30 kft; $\rho = 0.4 \text{ kg/m}^3$) would have a wind load of 150 kg for this short section.

In any case, a minimum break strength (MBS) safety factor for a single tether with the chosen thicknesses is low and much less than the usually desired factor of 5 or more. Thus, such tether weight and wind loading estimates would seem to pose serious operational challenges for maintaining a stratospheric airship with a grounded tether complicating the ground tether approach further.

While, as in the single tether case, a considerably longer tether will be needed in reality than just the 7 km altitude separation of airship and tug, a shorter and thinner tether in an airship-tug scheme offers both a lower tether mass and wind loading. A tether of SK78 Dyneema 12 km long will have a combined mass load and wind load...
well below the tether’s MBS of 450 kg. For example, even a relatively high 30 m/s wind speed over the entire 12 km long 2 mm tether at altitudes between 17 and 24 km will only generate a total wind load of less than 100 kg.

6 Discussion

The airship-tug station-keeping arrangement discussed above uses the naturally occurring seasonal stratospheric wind shear to provide the needed energy to keep the system on station. The payload carrying platform’s altitude around 80 kft is also much higher than that of a self-propelled airship at 65 kft thereby providing wider horizon to horizon coverage of the Earth and better upward viewing image quality. This tether scheme also avoids several problems associated with a ground-based tethered platform; namely, little if any aviation hazard, no winch, no stormy weather to fly through, and a shorter tether meaning less tether weight and wind loading. In addition, the tether is expected to be always under some tension so slack issues that can arise in a ground-based winch tether arrangement are reduced. Wind loading at altitudes above 15 to 17 km (50 to 55 kft) should also be relatively low even in high wind conditions, making a thin and lightweight tether practical.

There are several key components of the concept that will determine its reliability and effectiveness. The higher-altitude LTA platform must be constructed so as to have no appreciable fabric or seam leaks of lifting gas (i.e., hydrogen or helium) thus permitting long float durations of weeks to months. Both it, the tug and the tether should be as lightweight as possible enabling the greatest payload mass in relation to the balloon’s lift capability.

Ideally, the upper LTA platform would also have a streamlined aerodynamic shape so as to lessen wind drag forces as much as possible. It should also have some directional lift capability such as through a rear vertical stabilizer so as to help steer it into or against the prevailing winds and be designed for flexibility in payload mounting configuration. For example, astronomers may want a top-mounted telescope that has unobstructed access to targets near the zenith, while Earth scientists may prefer down pointing instruments.

However, the most critical component of the proposed concept is perhaps the tug vehicle. We conceive the tug as taking the form of a ultra-lightweight glider with intrinsically low drag. It could develop the forces needed to counter drift of the airship in two ways: deployment of a variable drag device such as a parachute or umbrella like device or variable pitch propeller(s), or it could generate appropriate aerodynamic forces with its wings.

Drag is necessarily in the direction of airflow, so it may seem that the high-drag configuration would only work if the winds at the two altitudes exactly oppose. But if the airship were a “dirigible” design, it could develop aerodynamic forces that are not precisely parallel to wind direction. Similarly, the tug could be controlled to fly in a direction that produced the necessary tether force over a wide range of angles relative to the wind direction.

The combination of a semi-steerable LTA airship and a maneuverable drone-like tug with variable lift capability could allow the system to keep station in a variety of
wind combinations. It could even maneuver to find better wind conditions, and climb and descend to some degree as needed.

The tug will need to be able to generate its own power to serve its operating flight systems and possibly to be self-propelled to some extent. In addition to solar PV power stored in batteries, the tug could be equipped with a propeller to serve as a variable drag device and power from the propeller could be used to generate electricity both day and night.

A cruder wind force balancing scheme was proposed in 1969 by R. Bourke [7] in a Raytheon Company report. He described a concept in which a conventional balloon floating in the stratospheric easterlies could deploy a parachute into the lower stratospheric westerlies to provide a drag force to overcome the balloon’s drift.

Using available wind data available at the time, Bourke concluded that this arrangement could work for certain months of the year, mainly during summer months at mid-latitudes. But he also found that the altitude and latitude of the lowest stratospheric winds varied seasonally leading to difficulties in maintaining accurate station keeping. Nonetheless, he viewed the concept as “provocative in its intrinsic simplicity”. However, to our knowledge no high-altitude balloon plus drag chute system was ever deployed and tested by Raytheon or anyone else.

Our scheme differs substantially from that proposed by Bourke. He suggested that the upper altitude balloon have self-propulsion capabilities and proposed a simple drag chute lowered from the balloon using a winch only as a supplemental element to aid the airship’s station-keeping ability. In contrast, our concept consists of a passive and ideally aerodynamically-shaped, stratospheric balloon or airship tethered to a lower altitude robotic tug vehicle that can precisely control its aerodynamic wind forces. Our stratospheric airship would have no self-propulsion element but could have some directional steering capabilities much like that demonstrated in a high altitude wing guidance system [29]. Bourke’s use of a winch-lowered drag chute may have been an attempt to simplify the balloon launch. Our scheme could also include some sort of tether storage system possibly attached to the tug vehicle in an effort to better control deployment and recovery of both upper and lower vehicles.

7 Astronomical Uses of a High Altitude Platform

One application for a stratospheric platform would be wide-field, high resolution optical and near-infrared imaging of astronomical targets. The value of high angular resolution imaging for astronomy cannot be overstated. The chief reason for the enormous impact of the Hubble Space Telescope (HST) across a wide spectrum of research topics despite its modest size mirror (2.4 m) has been its ability to obtain diffraction-limited imaging due to its location above Earth’s atmosphere.

However, with no repair or refurbishment missions currently planned, Hubble’s expected useful lifetime will probably end before the year 2020 due instrument failures or degradation of its batteries, solar panels, pointing gyros, and associated equipment [27]. With no present follow-up optical/UV space mission to Hubble, its loss may mean astronomical high-resolution imaging might be confined for the near future to small space telescopes or ground-based adaptive optics (AO) instruments which
employ one or more natural or laser guide stars to correct for atmospheric turbulence. Unfortunately, AO instruments work best in the infrared and under good seeing conditions and provide limited field-of-view (< 1 arcmin) with Strehl ratios less than 60%.

A reliable LTA platform situated at an altitude of 20 km or higher should, if properly equipped, provide image quality competitive with space-based telescopes. Such an observatory could provide sub-arcsecond imaging with short response times at a much lower cost than a comparable space-based telescope.

For example, at an altitude of 24 km (80 kft) an astronomical telescope would be above the weather and all but \( \approx 2.5\% \) of the atmosphere. It would experience virtually perfectly clear skies every night with image quality at or approaching the diffraction limit of the main aperture. Thus, an optical telescope located at such stratospheric altitudes with a mirror just 0.5 m in diameter (20-inch) with sufficient pointing stability and large CCD arrays could provide wide-field images with FWHM = 0.25 arcsecond at 500 nm, making it virtually superior to any ground-based imaging system.

Being above the weather, it could provide such data quality night after night for as long as the platform remained at this altitude. The lack of appreciable water vapor, dust and other particulates in the remaining atmosphere above these altitudes such a platform would also enjoy excellent atmospheric transmission.

Light scattering from moonlight would be expected to be minimal and not a major factor in scheduling faint target observations, making most observing time effectively astronomical “dark time.” This feature would greatly enhance the platform’s ability to respond rapidly to opportunities for observations of faint transient targets such as supernovae and gamma-ray bursters.

Also, unlike low Earth orbit (LEO) satellites such as HST, data transfer to and from a high-altitude station-keeping observatory could involve simple line-of-sight communications running continuously to a single ground station. Finally, a stratospheric astronomical observatory could also provide reliable science support for a host of space-based missions at an estimated cost of a few percent of a conventional LEO satellite.

8 Conclusions

We have described a new method for establishing a near station keeping, stratospheric LTA vehicle at low and mid-latitudes. This concept uses the naturally occurring seasonal wind shear between upper and lower layers of the stratosphere to provide forces that counter platform wind drift and allow it to keep station over a specified geographical location. We have necessarily left out many details about the architecture. These include platform migration issues in order to follow seasonal variations in latitude where optimal stratospheric wind shears are found, launch and recovery problems and solutions, specific airship and tug design constraints, and science payload arrangements to permit unobscured horizon-to-horizon observations.

If this method is shown to be practical, then the quest for the long-sought method of station keeping a scientific HALE platform may finally be realized, within season and latitude restrictions. This concept could provide the means for obtaining high
quality data rivaling space-based platforms but at a small fraction of the cost. The development of an affordable stratospheric platform that could keep station for weeks or months would be a powerful new tool for a variety of users and could be a game-changer for astronomical, atmospheric, and Earth-science research, as well as for a host of other applications including military surveillance and civil telecommunications services.

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