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A METHOD FOR BALLOON TRAJECTORY CONTROL

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ABSTRACT

A balloon trajectory control system is discussed that is under development for use on NASA's Ultra Long Duration Balloon Project. The trajectory control system exploits the natural wind field variation with altitude to generate passive lateral control forces on a balloon using a tether-deployed aerodynamic surface below the balloon. A lifting device, such as a wing on end, is suspended on a tether well beneath the balloon to take advantage of this variation in wind velocity with altitude. The wing generates a horizontal lift force that can be directed over a wide range of angles. This force, transmitted to the balloon by a tether, alters the balloon's path providing a bias velocity of a few meters per second to the balloon drift rate. The trajectory control system enables the balloon to avoid hazards, reach targets, steer around avoidance countries and select convenient landing zones. No longer will balloons be totally at the mercy of the winds. Global Aerospace Corporation tests in April 1999 of a dynamically-scaled model of the trajectory control system were carried out in ground level winds up to 15 m/s. The size of the scale model was designed to simulate the behavior of the full scale trajectory control system operating at 20 km altitude. The model confirmed many aspects of trajectory control system performance and the results will be incorporated into future development.

INTRODUCTION

The StratoSail® TCS being developed by Global Aerospace Corporation is a new concept. No known devices have used or suggested the use of a lift-generating device, such as a wing, suspended on a long tether, to effect trajectory control of a balloon (Aaron, et. al., 1999). Figure 1 illustrates one concept for a balloon trajectory control system. The StratoSail® TCS basically consists of a wing on end connected to a rudder and a counterweight all located on a boom and suspended from a tether up to 15 km below the balloon to take advantage of the variation in wind velocity with altitude. The wing generates a horizontal lift force that can be directed over a wide range of angles. This force, transmitted to the balloon by the tether, alters the balloon's path. The TCS is scaleable over a very wide range of sizes. Obviously the magnitude of the trajectory control will depend upon the relative sizes of the balloon and the wing, coupled with the ratio of air densities and the magnitude of the wind velocity difference between the two altitudes.

Historical Background

Ever since balloons were first conceived, people have sought to control their trajectories. History books show pictures of balloons with sails and oars. Since a balloon drifts with the local winds, there is essentially no relative wind that can be used to inflate a sail and generate lift. Still, the intent and desire is clear: people wanted to control where their balloon would go.

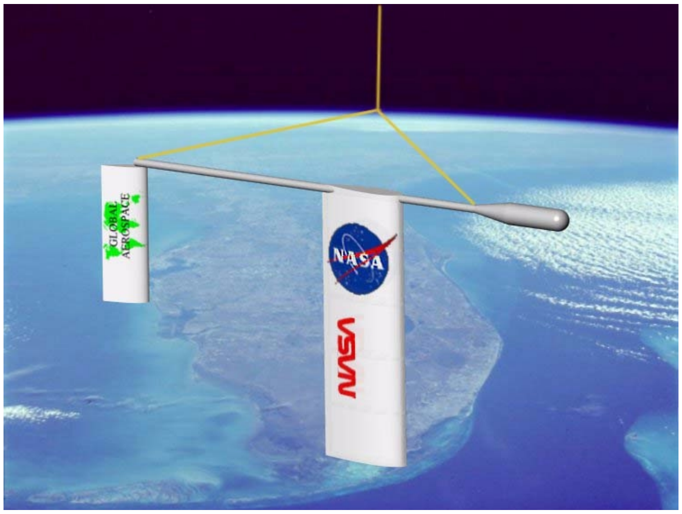

Fig. 1. StratoSail® TCS Concept

Early on, hot air balloonists discovered that by changing altitude one could reach different, sometimes more favorable, wind directions. Today, hot air balloonists compete to fly set patterns across the ground using winds aloft. Altitude change however comes with a cost. In the case of hot air balloons, the cost is fuel to heat the air in the envelope. In the case of light gas balloons it's the venting and loss of the buoyant gas itself or the dropping of ballast mass, neither of which are inexhaustible.

Other concepts for balloon altitude control are the use of so-called "anchor" balloons and phase change balloons. Unfortunately, phase change balloons do not function in the stratospheric thermal gradients. Anchor balloons utilizes a main helium balloon envelope and a sturdy fixed volume air bag which is alternately filled or emptied of high pressure ambient air in order to change buoyancy of the whole system. Richard Branson's Earthwinds, an early "around the world challenge" attempt, employed such a balloon. In a different version of the same concept, the French have also used this technique to fly meteorological balloons at constant pressure (isobars) altitudes using a ballonet inside the main helium balloon instead of a separate bag (Blamont, et. al., 1974).

Some disadvantages of pressurized air ballast concepts are the power required to pump air into the high pressure bladder, the difficulty of pumping gas at very low pressures, limited altitude change capability, and additional mass of the pumping equipment and anchor balloon or bladder. Even with detailed wind information, controlling a balloon trajectory by varying altitude is often a hit or miss type of endeavor because one is still totally at the mercy of the winds.

Propeller-driven airships obviously control their trajectories. However, the attainable altitude and payload mass for airships are quite restricted in comparison to free balloons. Airships and powered blimps use engines to turn propellers to propel themselves. The power and fuel required limit the duration of such an approach and at very high altitudes, the large required propeller size can become impractical. Some naturally-shaped balloons have also flown using propellers driven by engines suspended on tethers (Carten, 1974). A number of studies have examined high altitude airship propulsion using electric propeller systems (Vorachek, 1970; Beemer, 1975; and Perry, 1998) The power required to overcome the drag of the balloon in the stratospheric winds is significant making extended operation feasible only with large and heavy systems.

Although drag chutes on tethers have been proposed to alter the trajectory of balloons (Bourke II, 1969), no known devices have used or suggested the use of a lift-generating device, such as a wing, suspended on a long tether, to effect trajectory control of a balloon.

Ultra Long Duration Balloon (ULDB)

The Ultra Long Duration Balloon (ULDB) Project, managed by NASA/GSFC Balloon Programs Office, is planning the first ULDB demonstration flight to occur in 2000. The goal of the ULDB program is to fly up to 1000-kg science payloads above >99% of the Earth's atmosphere for at least 100 days, a factor of 7 to 30 times longer than current balloon flights. The need for trajectory control capability is driven by these longer ULDB missions which, by their nature, will have additional overflight concerns and more expensive payloads. Overflight issues will involve international discussions and agreements. There are concerns that some countries may not offer permission to enter their airspace.

The value of future ULDB payloads is expected to be significantly higher than present conventional and LDB payloads, as the ultra-long duration missions attract more scientific investigators (UNEX and other). This higher payload value puts a premium on its safe recovery. Trajectory control capabilities will mitigate overflight and safety issues and facilitate payload recovery operations. The development of balloon TCS technology is a phased activity whose initial goal is the development of a trajectory control system for use in the ULDB program.

Importance of Trajectory Control to Balloon Programs

Free balloons carrying science instruments typically drift freely in the prevailing wind at the operating altitude. In many cases, launch of such balloons must be delayed until forecast winds are projected to carry the balloon system into a region of interest, or away from a forbidden zone. Frequently, such balloon flights must be terminated prematurely to avoid flying over countries that have not given overflight permission, or to ensure that the payload descends into an appropriate landing site, or to avoid endangering densely populated regions. The ability to provide even a small amount of trajectory control could eliminate these reasons to terminate the flight early.

A TCS, arranged to provide a lateral aerodynamic force, suspended well below a balloon to take advantage of natural wind differences, can be used to control the trajectory of the balloon. Such an approach to balloon trajectory control:

- offers increased balloon operations flexibility and cost reduction,
- permits balloon to remain at fixed altitude,
- avoids overflight of uncooperative countries,
- increases number of potential landing sites,
- enables balloon to travel over desired locations,
- passively exploits natural wind conditions,
- does not require consumables,

- avoids payload disturbances caused by propulsive trajectory control methods,
- requires very little electrical power,
- operates day and night,
- offers a wide range of control directions regardless of wind conditions, and
- can be made of lightweight materials.

In summary, the TCS is important to world balloon programs because it simplifies mission operations by mitigating overflight and safety concerns, expands flight termination options, and minimizes payload recovery logistics.

TRAJECTORY CONTROL SYSTEM (TCS) CONCEPT SUMMARY

Figure 1 illustrates the current design concept for a balloon TCS. The TCS concept consists of a wing on end and a rudder connected to a boom with a counterweight. All are suspended from a tether up to 15 km below a balloon to take advantage of the variation in wind velocity with altitude. The wing generates a horizontal lift force that can be directed over a wide range of angles. This force, transmitted to the balloon by the tether, alters the balloon's flight path. The TCS is scaleable over a very wide range of sizes. Obviously, the magnitude of the trajectory control will depend upon the relative sizes of the balloon and the wing, coupled with the ratio of air densities and the magnitude of the wind velocity difference between the two altitudes. The balloon can be considered to act as the keel of a sailboat, and the wing as the sail.

The ULDB is planned to operate at altitudes near 35 km where the air density is less than 1% of the sea level value. Thus, the balloon needs to be very large to displace enough weight of air to support the payload. For balloon flights, it is very important that all payloads and support equipment be designed to keep weight to a minimum. The orientation of the wing on end naturally lends itself to lightweight construction techniques since the weight is concentrated close to the load-bearing elements. The density of the air 15-km below the balloon is about a factor of ten greater than at the balloon altitude. This allows the wing area to be significantly smaller than the balloon cross-sectional area since the aerodynamic force scales directly with air density. There is an obvious tradeoff between size (weight) and control authority. But, reasonably-sized devices can apply an appreciable force to the ULDB system.

The Use of the Natural Wind Conditions

There are significant variations in the wind speed and direction with altitude. Figure 2 displays the mean zonal wind profiles for two routinely used balloon launch sites and seasons. Significant relative winds will be available for TCS operation. For example, there is a 26 m/s relative wind between 35 and 20 km altitude for the January Alice Springs latitude and an 11 m/s relative wind for the Fairbanks latitude during July. Adding in the meridional wind component is expected to further increase these relative wind velocity estimates. The direction of the wind is not overly important since the magnitude and direction of the lift force can be varied over a substantial range by controlling the angle of attack of the wing, much like the ability of sailboats to travel in many different directions in the same wind.

TCS Design Description

The TCS is composed of three major assemblies: the TCS Wing Assembly (TWA), TCS Interface Package (TIP), and the tether. As shown in the example design in figure 1, the main lift-generating element is a wing comprising several ribs covered by a taut flexible skin. The wing is attached to a boom. A counterweight is attached to the front end of the boom and a rudder and rudder-actuator are attached to the back end of the boom. A control module is mounted in the nose. Batteries are placed in a compartment at the bottom wing tip. This compartment is shaped like an airfoil and forms an extension of the wing. The sides of this compartment are covered with solar cells. In addition, a fixed solar panel is mounted horizontally on the top of the wing. A yoke connects the boom to 15-km long tether. The upper end of the tether is attached to a winch mounted on the TIP at the gondola of a balloon. Figure 3 is an artist concept that illustrates the overall system geometry at the start of TWA reel-down.

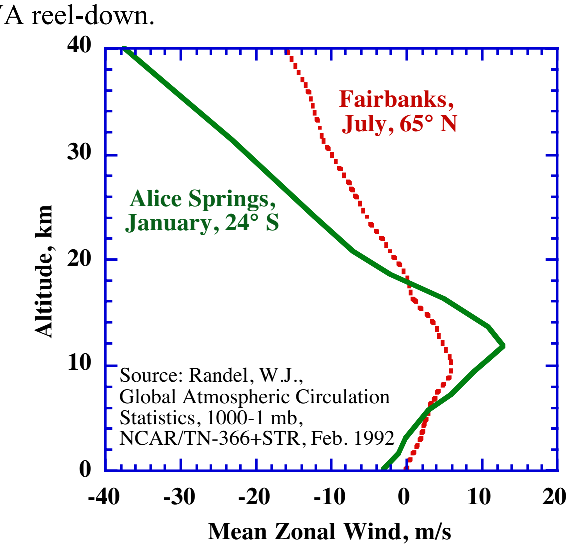

Fig. 2. Mean Zonal Wind Profiles

TCS elements that interface with and are connected to the ballooncraft are called the TCS Interface Package or TIP. The tether is unwound from a spool using an unpowered winch mounted on the TIP. The winch provides a passive means of lowering the TWA at an acceptable rate, with the weight of the TWA serving to pull out the tether. Figure 4 illustrates one possible TIP design. An option to power the winch could be used to raise or lower the TCS in altitude to reach favorable winds or to restow the device. In the current design, we have chosen to eliminate this powered reel-up option to keep weight to a minimum. Therefore the nominal plan is to cut down the TWA independently at the end of the flight by severing the tether and providing a parachute to control its rate of descent.

Depending upon the needs of a particular balloon flight, the control module may receive its commands from the balloon gondola by radio or other communication means. Alternatively, the control module may be preprogrammed prior to launch of the balloon system. For ULDB-specific TCS, we assume that TCS commands and data are relayed through the ULDB communications system. The TIP has an interface to the ULDB computer and telemetry system. Communications between the TIP and the TWA is by radio modem.

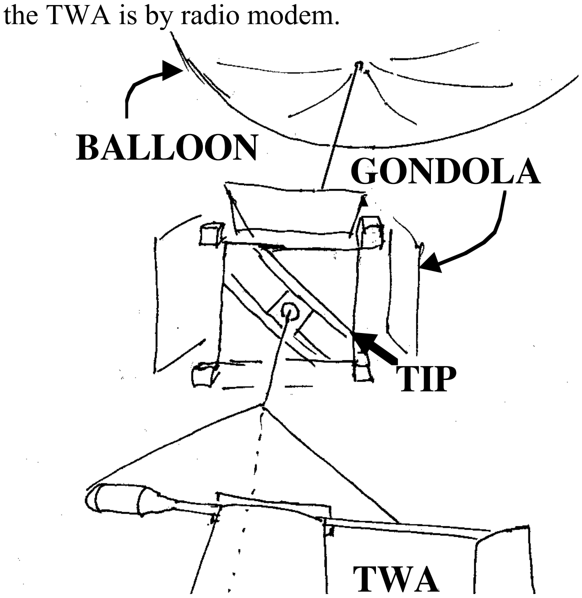

Fig. 3. Artist Conception of Overall System

One of the advantages of the TCS is that it can be operated in different modes with more or less complexity depending on the desired degree of trajectory control. For example, if the purpose is simply to provide a bias airflow past the supporting balloon to sweep away contaminants to improve the performance of sensitive instruments, then the rudder could be set at a fixed angle before the flight. This fixed angle could be selected based on a desired relative velocity coupled with prior knowledge of the expected winds at the altitudes of the balloon and the wing. For the planned ULDB float altitudes, the prevailing winds typically are in a generally easterly or westerly direction depending on the season. An ultra long duration balloon may go around the Earth several times. If the desire is to force a general drift towards the pole of the Earth (or perhaps away from the pole and toward the equator) then again the angle could be preset before launch based on the known prevailing winds and the desired drift direction. A more complex control scheme, perhaps under autonomous control, could command the wing to "tack" downwind across the wind. The wing would traverse a long zigzag pattern across the average flight path. This would increase the relative wind speed of the wing and therefore the maximum aerodynamic force too. This approach could provide significantly greater control over the trajectory direction, but would require a more complex set of control algorithms.

Global Aerospace Corporation is currently planning a prototype StratoSail® TCS flight test on a long duration balloon in the winter of 2001.

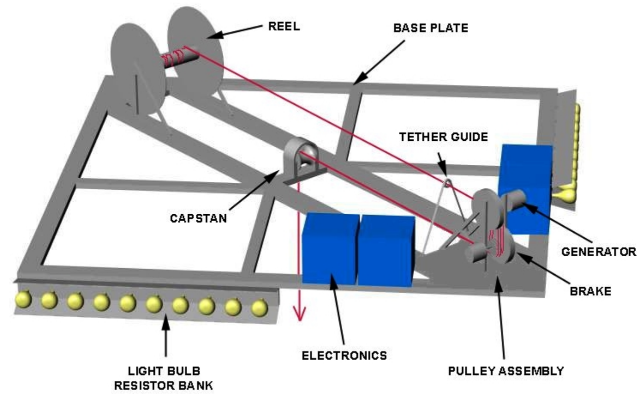

Fig. 4. Concept for TIP Assembly

Advanced StratoSail® TCS Concept

Global Aerospace Corporation has been developing an advanced StratoSail® TCS concept that has improved performance necessary for controlling global constellations of balloons. The advanced StratoSail® TCS development is under a NASA Institute for Advanced Concepts study of Global Constellations of Stratospheric Scientific Platforms. Constellation management requires the maintenance of a uniform network across all latitudes and seasons. The advanced TCS achieves higher lift than its weight, does not swing up into lower density air as lift increases, is more stable in gusts and provides greater operational flexibility. Figure 5 illustrates one concept for an advanced StratoSail® TCS.

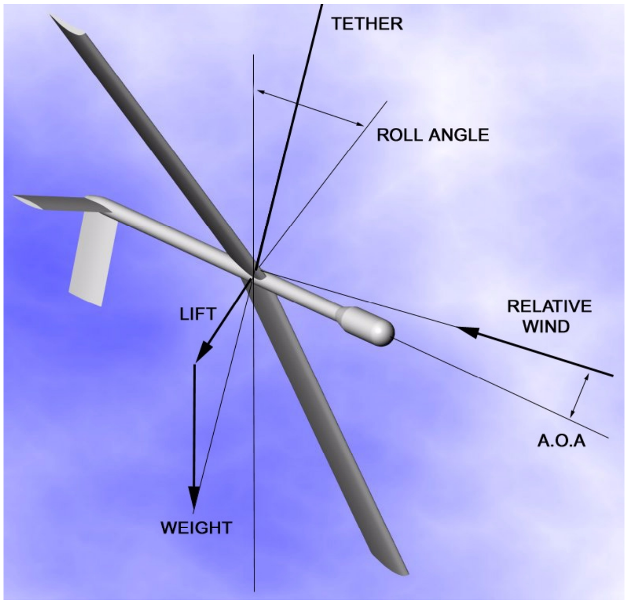

Fig. 5. Advanced TCS Design Concept

PERFORMANCE OF TCS

Figures 6 and 7 illustrate the performance of a balloon trajectory control system. Figure 6 shows a trajectory that would have been followed by a balloon launched from Alice Springs in January of 1983. Figure 7 shows the trajectory the balloon system would have followed if it had had a TCS system generating a mere 1 m/s lateral velocity of the balloon with respect to the winds in which it was floating. This particular set of wind data was selected because it showed a dramatic departure from more typical trajectories. Yet even with such an extreme case, a relatively small amount of trajectory control could easily negate the undesirable wandering of the balloon. For typical conditions, a greater drift velocity is predicted using the StratoSail® TCS. It is clear that even a very modest amount of control acting over long periods of time can yield dramatic improvements to the trajectory, negating undesirable latitude excursions.

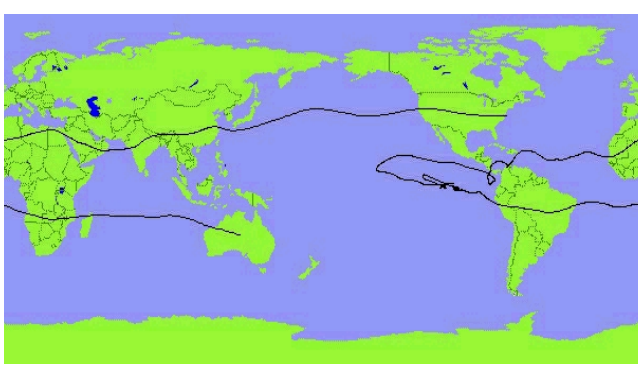

Fig. 6. Simulated Uncontrolled Free-Flight Trajectory

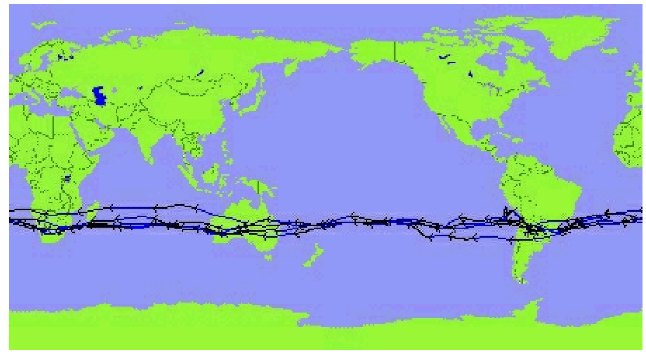

Fig. 7. Controlled Trajectory with Wind Field Identical to Fig. 6 using 1 m/s Control Authority

Figure 8 illustrates an example ULDB mission application of a StratoSail® TCS for a balloon launching from Christchurch, New Zealand, flying to –70° latitude, then returning to Alice Springs, Australia within 100 days flighttime. This is a detailed simulation that assumes real polar wind conditions (historical winds starting in mid-November 1988), a 5-m^2 TCS wing area, and a simple control algorithm.

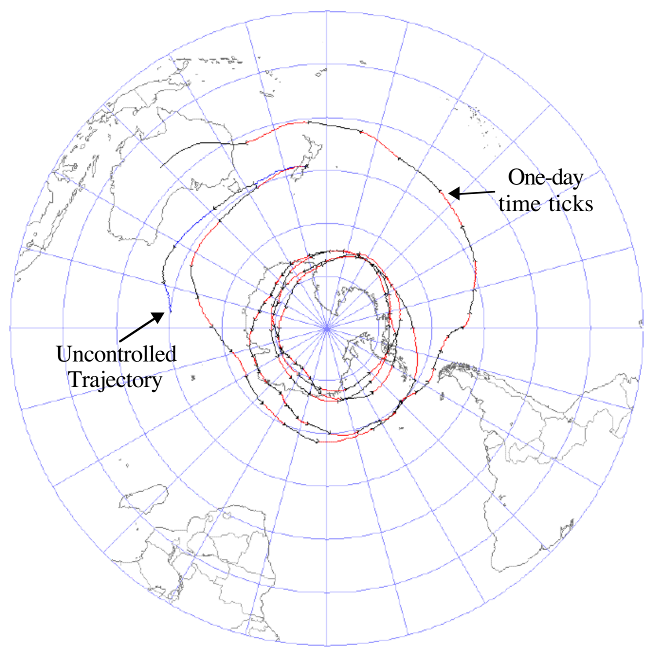

Fig. 8. Simulated StratoSail® TCS Performance

DYNAMICALLY-SCALED TEST FLIGHT

The field-tests for the dynamically-scaled test model of the StratoSail® TCS were carried out in April 1999. The model tested is about a 1/4th scale of the full-scale model. The model was tested near ground level at a site 1000 m above seal level in winds up to 15 m/s. The design and size of the scale model were intended to simulate, to the greatest extent possible, the behavior of the full scale TCS operating at 20-km altitude. The model was suspended about 60 m below a small, tethered blimp, which was floating about 70 m above the ground. Its behavior was observed and measured in the near surface winds.

Fig. 9. Dynamically-scaled StratoSail® TCS Test

Overall, the dynamically-scaled model testing was very successful. It verified that the TCS behaves essentially like an aircraft in pitch, as expected. It allowed investigation of some dynamic behavior that could not readily be modeled or predicted. We gained important insights into the operation and design of the TCS. Because of the testing, some refinements and adjustments were made to the design. The testing has made us very confident about moving ahead with the development of this system.

SUMMARY AND CONCLUSIONS

The StratoSail® Balloon Trajectory Control System being developed by Global Aerospace Corporation has been described, its performance discussed and its value to balloon programs delineated. A StratoSail® TCS, which employs a wing on end to generate a lateral lift force, is used to alter the path of the balloon system. The wing assembly is suspended on a long tether to take advantage of the wind variations with altitude. This approach has been contrasted with previous approaches and found to be quite promising. Recent testing has confirmed the expected behavior of the approach, although further development is required to develop the full system. A balloon TCS may be of significant value to balloon programs because it simplifies mission operations by mitigating overflight and safety concerns, expands flight termination options, and minimizes payload recovery logistics. Finally, advanced TCS designs are on the drawing board that can be used for more ambitious global balloon constellation geometry control (Nock, 2000) in the future.

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