A METHOD FOR PLANETARY BALLOON FLIGHT PATH GUIDANCE

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ABSTRACT

In this paper, we describe the operation, performance, and benefits of a Balloon Guidance System (BGS) for operation at Mars. Balloon guidance systems have been under development by Global Aerospace Corporation (GAC) for use in NASA's scientific balloon program. In addition, several NASA-funded studies have explored the use of BGSs for guiding scientific balloons on Earth, Mars, Venus and Titan. A scaled flight test validated the aerodynamics, stability, control, and operation of a balloon guidance system for high-altitude scientific balloon applications. These tests were carried out in a relevant environment giving high confidence that a full-scale system will perform as expected on stratospheric Earth balloons. In addition, scale model testing along with performance analysis provides assurance that planetary balloon guidance systems will perform well in the relevant atmospheres.

1. INTRODUCTION

Systems capable of modifying the trajectory of high altitude scientific balloons at Earth have been under development by GAC since about 1997 [1-4]. In 2002, GAC began developing concepts for guiding planetary balloon platforms [5, 6]. One embodiment of a Balloon Guidance System (BGS) uses a wing suspended several kilometers below the balloon on a very long tether. In planetary atmospheres, there is generally a vector wind difference between balloon and wing altitudes (separated by a few kilometers) that results in a relative wind at the wing, allowing it to generate a lift force. This lift force can be directed horizontally across the natural flight path of the balloon. This force is transmitted by the tether to the balloon, causing the balloon to drift across the winds at its altitude. This force, acting over long durations (days), can cause the balloon to depart hundreds to thousands of kilometers away from its natural drift trajectory. In the next several sections, we will discuss the aerodynamics, performance modeling, design, and simulation of a low-cost, low-risk, passive, planetary balloon flight path guidance concept with a focus on the Mars application.

2. SYSTEM CONCEPT OF OPERATION

In the past, the inability to control the path of planetary balloons had limited their usefulness and, therefore, scientific interest in their use. This statement is particularly true for Mars: without flight path guidance technology, a Mars balloon cannot observe desired regions of interest, and it has a high probability of impacting mountainous territory. The BGS vastly expands the capabilities of balloons for Mars exploration by providing the means to control their balloon trajectories in the Martian atmosphere to observe regions of interest, to drop surface probes in desired targets, and to reduce the risk of mission failure by avoiding terrain with high topography.

2.1 Principle of Operation

A BGS 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. A BGS consists of an aerodynamic system or "BGS wing" (e.g. near vertical wing, support boom, and rudder) below the balloon, a kilometers long tether and a winch system for lowering and, sometimes raising, the BGS wing. A variety of concepts for the aerodynamic system have been studied including kites, dual wing airfoils, and whirligigs [1]. Fig. 1 illustrates the principle of operation of a single-wing BGS. For the Mars application, the balloon would typically be at 10 km altitude and the BGS main wing at 3 km altitude. Generally there is a wind difference between altitudes that translates to a relative wind on the BGS wing as it is dragged along by the balloon. This relative wind can generate a lift and drag force at the wing, resulting in a horizontal force. Changing the angle of attack of the wing by use of the rudder can modify the direction and magnitude of this force. 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.

A BGS enables a balloon to fly over surface targets for high-resolution reconnaissance or for deployment of microprobes, to steer around mountains to avoid collisions, to sample the atmosphere to map the abundance of trace gases that could lead to locating possible surface sources of these gases, and to explore a planet on regional and global scales. No longer are planetary balloons completely at the mercy of the winds.

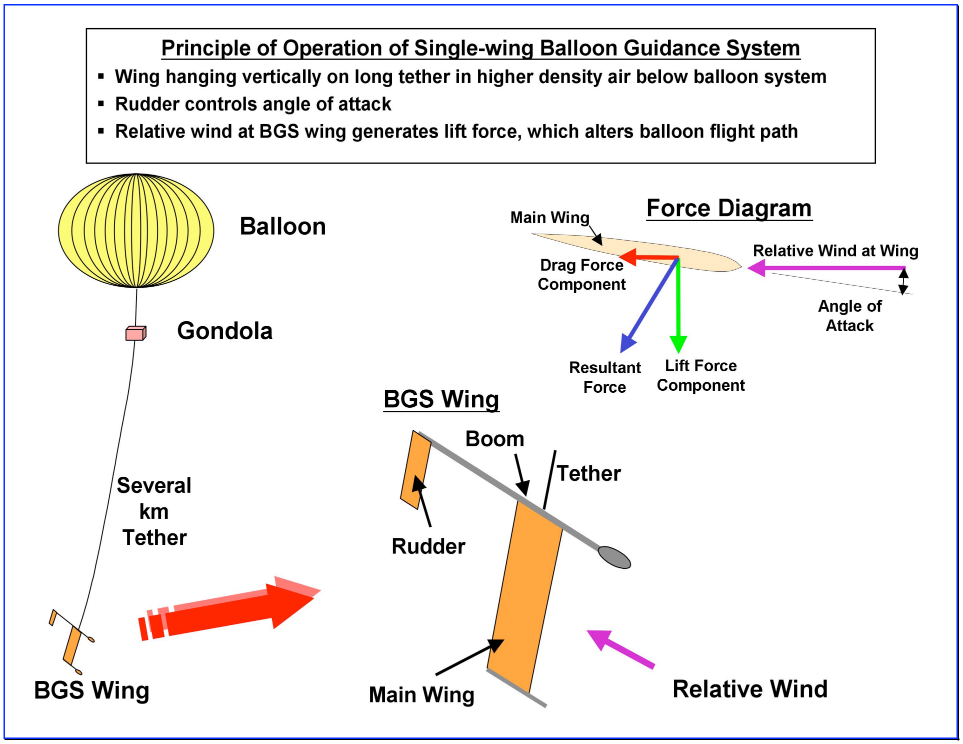

Fig. 1. Principle of operation of single-wing balloon guidance system.

Features of a BGS include the ability to:

- Passively exploit natural wind conditions
- Operate day and night
- Control direction of balloon flight path in various wind conditions
- Be made of lightweight materials and inflatable structures
- Operate with very little power and without consumables

In usual wind circumstances with conventional designs, a balloon with a BGS cannot keep station over a given location. However, advanced BGS design concepts being studied by Global Aerospace can station-keep stratospheric airships.

2.2 Physics of Operation

Fig. 2 shows a vector diagram illustrating the wind vectors and dominant forces during operation of the BGS. The definitions of the various vectors are described in Table 1. The view is looking down from above the balloon and the BGS and is not to scale. The BGS (represented as an airfoil section) is at a much lower altitude than the balloon (represented by the circle). For illustration purposes, the BGS wing is shown much larger than it would be in proportion to the balloon. The upper portion of the figure shows expanded views of some small vector details.

Table 1. Notation for vectors in shown in Fig. 2.

V_{10}	Wind Velocity (relative to the ground) at Balloon altitude (~10 km on Mars)
V_3	Wind Velocity at BGS altitude (~3 km on Mars)
V_B	Velocity of Balloon relative to the ground = Velocity of all parts of the system
V_{DRIFT}	Drift Velocity of the balloon due to action of the BGS = V_B - V_{10}
V_{REL}	Relative Wind Velocity at the BGS = $V_B - V_3$
V_{DF}	Vector Difference between Winds at Balloon and at BGS = V_3 - V_{10} (used in an even simpler analysis, but not used here)
V_{CT}	Cross-Track Velocity Component of V_{DRIFT} (perpendicular to V_{10})
V_{BT}	Back-Track Velocity Component of V_{DRIFT} (parallel to V_{10})
F_L	Lift Force on BGS (acts horizontally and is perpendicular to V_{REL})
F_D	Drag Force on BGS (acts horizontally and is parallel to V_{REL})
F_R	Resultant force on BGS = F_L + F_D ~ Drag force on balloon
F_{DRIFT}	Drag Force on balloon due to V_{DRIFT} ~ F_R

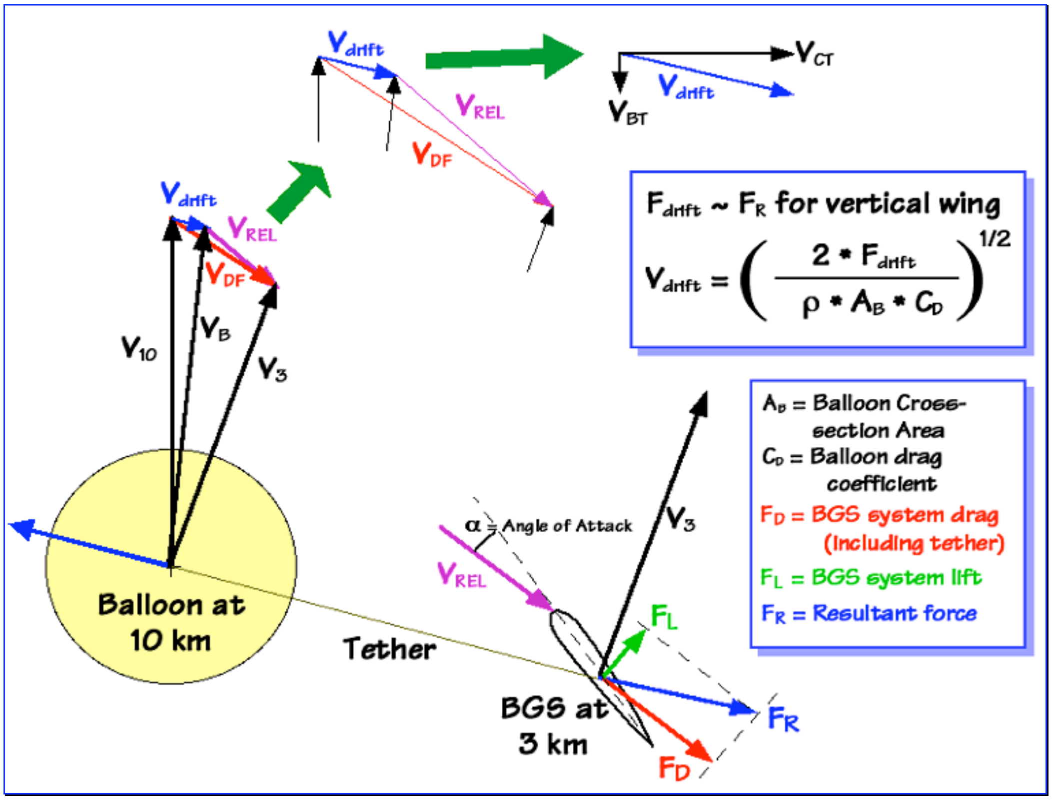

Fig. 2. Balloon guidance system vector wind and force diagrams at Mars.

Many simplifying assumptions are present in Fig. 2; however, the complex models that have been developed to characterize and simulate the BGS behavior do not share these limitations. For example, the tether is shown here as a straight line. In reality, due to the variation in relative wind and atmospheric density along its length, the drag forces on the tether will cause it to have a gentle curvature. The detailed models include this effect by breaking the tether down into shorter segments over which conditions are treated as being constant. In Fig. 2, the tether drag force is shown to act at the BGS. This is not a bad assumption since the drag on the lower 10% or so of the tether dominates the rest of the tether because the atmospheric density is greatest and the relative wind is also greatest here. The wing is assumed to be exactly vertical so the lift and drag forces act in a horizontal plane. In actual operation, the wing will hang with some tilt to the side and backwards. Our detailed models resolve the forces in three dimensions and include this effect.

The system is assumed to be in equilibrium, so the vector sum of the forces must equal zero. In the vertical direction, the buoyancy force provided by the balloon exactly equals the weight of the system. These vertical forces are not shown. The aerodynamic drag force on the balloon is equal to and opposite to the resultant aerodynamic force on the BGS (including the tether drag force). With this simplification, one can calculate the drift velocity of the balloon (inset box in figure) in which A_B is the projected area of the balloon (as viewed from the side), C_D is the drag coefficient of the balloon (for flow from the side), and ρ is the atmospheric density at the altitude of the balloon. The angle of attack, α, of the BGS wing is controlled by adjusting the incidence angle of the rudder (not shown), and is usually arranged to produce close to the maximum lift coefficient for the wing as this typically produces maximum useful control effect for the system. A small amount of iteration is required to determine the drift velocity vector that balances the forces, thereby making the system self-consistent or in equilibrium. The diagram in Fig. 2 is drawn to illustrate an equilibrium solution.

3. SCALE MODEL TESTING

To gain confidence in the ability of the BGS to perform properly for NASA stratospheric balloon applications we carried out two scale model tests. We built and tested a 1/4-scale model (see Fig. 3) of the BGS wing assembly. The scale model BGS uses a 0.31-m chord by 1.41-m long, NACA 0015 airfoil for its main wing. The rudder used a scaled down version of the same airfoil. It was scaled down from a full-scale system intended for operation in the Earth's stratosphere. The scale model actually tested is lighter and has lower moments of inertia than an ideal dynamically-scaled model making it more responsive than an ideal scale model, thus emphasizing any instabilities that might exist in the design.

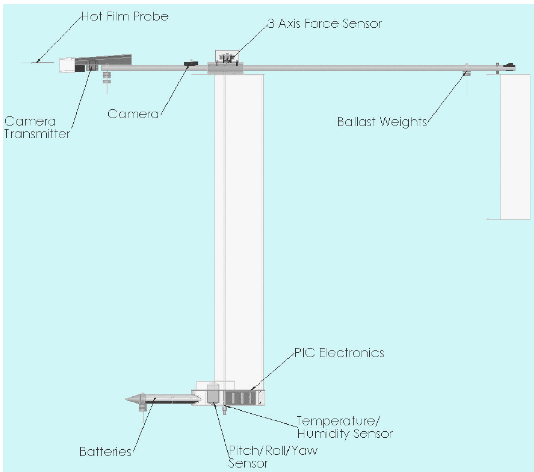

Fig. 3. Scale model BGS configuration.

In April 2001, GAC conducted the second of two scale model flight tests from a tethered blimp at El Mirage Dry Lake in California, which is discussed below.

3.1 Test Objectives

The objectives of this test were to acquire quantitative data to verify aerodynamic performance predictions, to investigate effects of center of gravity (CG) location on dynamic behavior, validate stability and control requirements, and to gain experience with instrumentation applicable to full-scale test.

3.2 Scale Model Instrumentation

We carried an array of instruments aboard the scale model to make measurements of its performance and behavior. These instruments included:

- Hot Film X-probe (velocity and alpha)
- 3-axis tether force transducer (strain gage)
- Accelerometer-based Pitch Roll sensor
- Magnetometers
- Temperature and humidity
- Rudder position encoder
- On board video camera

In addition, we had an onboard data acquisition and transmission system that sent data to a laptop computer for real-time evaluation.

3.3 Dynamic Scaling

In the 2001 testing, we matched full-scale aerodynamic parameters as well as possible, including Reynolds number (Re). The 1/4 scale prototype system simulated the performance of the full-scale system, which has a 5-m long wing, at 20 km altitude in the Earth atmosphere. During scale model testing, the Reynolds number varied, due to wind speed changes, between 38,000 and 227,000. This range encompasses much of the operating range of the Earth full-scale system. The average Re throughout the test was about 72,000 versus the nominal 69,000 expected for the full-scale system at 20 km altitude for one likely set of wind conditions (Latitude –24° in January). This fit of average Re is really quite a good match for scaled experiments. And, we collected many data points on either side of Re =69,000.

3.4 Results of Scale Model Testing

Data from scale model testing indicates that the horizontal lift force was somewhat better (10-20%) than expected. Analysis of the data (see Fig. 4) indicates that the maximum lift coefficient point, 1.2 at an angle of attack (α) of about 12°, was obtained when the Re was 45,000, which is somewhat lower than the test average (72,000). This result indicates that the measured lift coefficient underestimates the expected performance at full-scale flight altitudes in higher winds. The scale model tests occurred at low altitude where turbulence is expected to improve apparent performance, which means that the performance of the full-scale system could have been overestimated by 10-20%. Note, the BGS tested was not just a single airfoil; i.e. the boom, forebody, and rudder all contribute to the lift, which means that the measured lift coefficient could easily be greater than the airfoil alone.

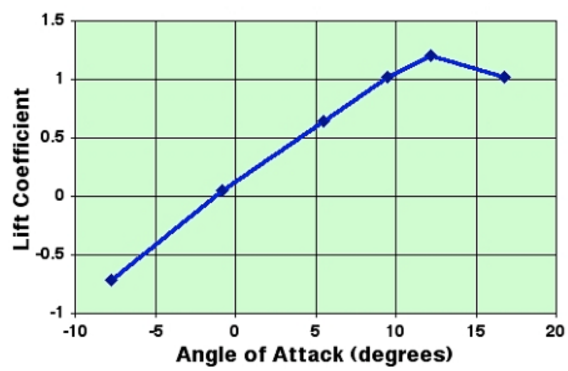

Fig. 4. Scale model lift coefficient as a function of angle of attack.

Over the Reynolds number range flown, we did not observe any changes in flight characteristics nor was any instability encountered despite attempts to induce instabilities by (a) significant shifts in the CG location both behind and above its preferred location and (b) by driving large-amplitude oscillations that could excite unstable dynamics in the system.

In this, the instrumentation worked perfectly which set the stage for development of instrumentation for full-scale tests and operational flights. This scale model testing gives us high confidence that the full-scale version will perform well at Earth. In addition, this test suggests that BGSs will be able to provide the needed guidance for balloon missions on most planets. Mars is a special challenge, however, as we discuss in the next section.

4. MARS BALLOON GUIDANCE SYSTEM

In this section we discuss low Reynolds number airfoils, their performance in real Martian winds, and conceptual Mars BGS system designs.

4.1 Low Reynolds Number Airfoils

In this section we discuss (a) low Reynolds number airfoils, their performance in Martian winds and (b) conceptual Mars BGS system designs.

4.2 Low Reynolds Number Airfoils

The aerodynamic surface of a Mars BGS will be operating at low Reynolds numbers (Re the order of ~1000). For example, during seasons near an Ls of 150°, BGS Re will typically vary, globally, between 400-6000 for wind differences between 4 and 10 km [7]. For these low Reynolds numbers, drag coefficients are significantly higher and maximum lift coefficients are a little lower than for higher Reynolds number operation (e.g. above 50,000). In recognition that operation in the Martian environment would result in fairly low Reynolds numbers, we reviewed existing literature on wings designed for low Re operation. Although there have been some studies in this regime, there are far fewer sources of data or modelling results than for the higher Reynolds numbers typical of normal aircraft flight. It is clear that for these low Reynolds numbers, drag coefficients are higher and maximum lift coefficients are a little lower than for higher Reynolds number operation, as studied by Sunada in 2002 [8].

The reduced lift-to-drag ratio (L/D) during low Re operation is quite a challenge for flight systems, such as airplanes, that use aerodynamic lift to support system weight and provide thrust to overcome the drag. However, for a BGS, the weight is supported by buoyancy and thrust is not required to overcome drag. The “lift” from the wing is directed close to horizontal and predominantly across the flight path of the balloon. The drag acts mostly to slow down the balloon, and is relatively unimportant to the operation of the BGS. In fact, tether drag is typically much greater than BGS wing drag. The forces generated by the BGS are very low (of order 1 N). However, the drag on even a large balloon moving at only 1 m/s in the Martian atmosphere is also very small.

In Fig. 5, airfoils #5-12 (red boxes) are likely candidates for the Mars BGS wing design.

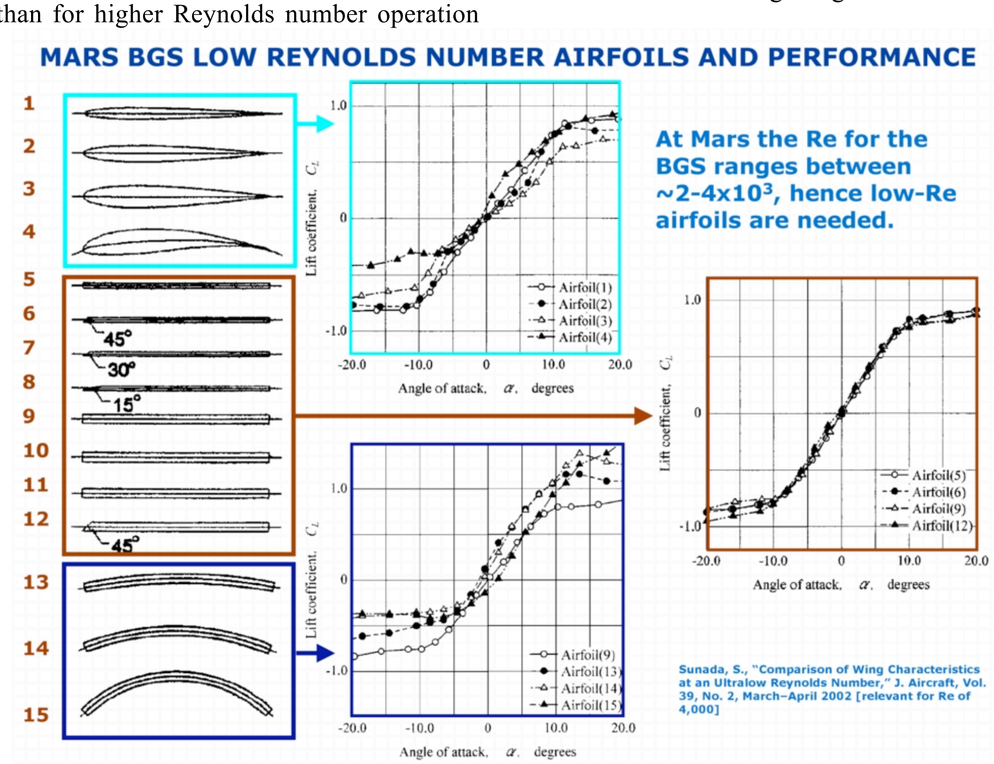

Fig. 5 Low Reynolds number airfoils and their performance.

4.3 BGS Performance in Mars Winds

The difference in winds at different altitudes in the atmosphere creates a relative wind at the altitude of the wing (stronger winds are usually found at higher altitudes on Mars). An example of a wind profile at Mars is shown on Fig. 6 (from Mars-GRAM 2001 [9]) for southern mid-latitudes at an Ls = 150°. This wind profile shows the high relative winds available during this season and latitude.

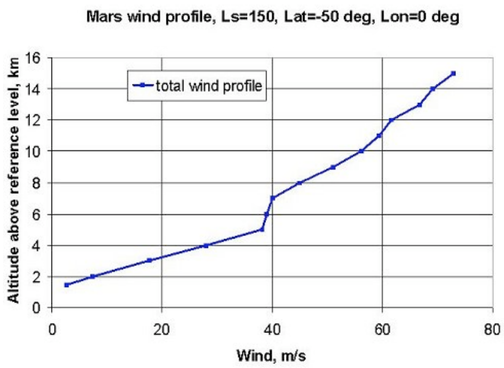

Fig. 6. Mars atmospheric wind profile.

The horizontal component of the total force produced by the wing can be used to change the path of a balloon in the winds. For this example wind profile, the wind at 10 km altitude, where the balloon would be floating, is about 56 m/s while the wind at 3 km, where the BGS would be situated, is about 18 m/s. The resultant relative wind is therefore 38 m/s. This level of relative wind could apply a cross-wind delta-V to the balloon of the order of 4 m/s for an 8 m^2 wing operating with a lift coefficient of 0.8.

Having developed and tested the numerical model of the BGS, a study was carried out of its performance in different wind regimes characterized by strong or weak vertical wind gradients, varied tether length and balloon sizes. The model solves for the equilibrium solution that maximizes the cross-track velocity of the balloon (the velocity in the direction perpendicular to the direction of the prevailing winds).

Example of model solutions are illustrated in the next two figures. The model run for the first case shown in Fig. 7 takes place at about equinox (Ls=6°). The corresponding date is August 13, 2013 – within a month of the 2013 Mars arrival window of opportunity for a Mars Network Emplacement Mission.

The location of the model run is on the southern edge of the zonal jet in the northern hemisphere. The action of the BGS in this case changes the velocity of the platform by 2.5 m/s. The BGS velocity vector is close to the southwest direction. The solution for the tether configuration and the relative winds are shown in Fig. 7. Note the different scales in the U (zonal) and V (meridional) directions. And the scales in U and V directions are different from the vertical scales to better illustrate the tether shape. The deflection of the tether from the straight down configuration in the U direction is due to the drag of the tether in the strong relative U wind. The deflection from the vertical configuration in the V direction is primarily due to the sideways lifting force generated by the BGS.

The platform continues to be embedded into the zonal flow (ground speed U=45.7 m/s) with a slight southward drift more than 50% of which is due to the action of the BGS (ground speed V=-2.7 m/s, BGS U=-1.84 m/s, BGS V=-1.83 m/s).

For the weak flow case shown in Fig. 8, the relative wind at the wing altitude is much smaller than before – just about 1 m/s in the zonal direction. Interestingly, the total BGS velocity is of the same order of magnitude as the relative wind at the altitude of the wing ~9 m/s. The tether deflection shown in the figure is due to the tether drag (note different spatial scales on all three plots). This analysis illustrates the worst case for the BGS performance – in low relative wind at the wing altitude, the cross-track component of the BGS velocity is negligibly small. However, the conditions described in this analysis do not persist long at Mars. Simulations for a different longitude at the equator at the same time (different local time, not shown) show an increase in relative wind and a corresponding increase in the cross-track component of the BGS velocity (1 m/s for relative wind of 9 m/s). Hence, our analysis indicates that the BGS will enable balloon steering capabilities for the wide range of atmospheric conditions that can be encountered at Mars.

4.4 Example Mars Balloon Guidance System

The Mars BGS consists of the main wing, the winch system at the gondola and the long tether. An example Mars BGS wing system design is displayed in Fig. 9. It is characterized by a long, vertical wing below which is a support boom and rudder. The Mars BGS is attached to the gondola via a very strong, 3-8 km long tether. The BGS requires very little power (about 1 W on average) to operate, when it is not being reeled up to avoid terrain obstacles, and it can be made very light. This Mars BGS is expected to incorporate low-Reynolds number airfoil designs. The science payload could be split between the gondola and the BGS, e.g. the BGS in Fig. 9 illustrates cameras attached to it just below the large wing structure. Also shown is the narrow solar array on the top of the boom that supplies power to the BGS systems.

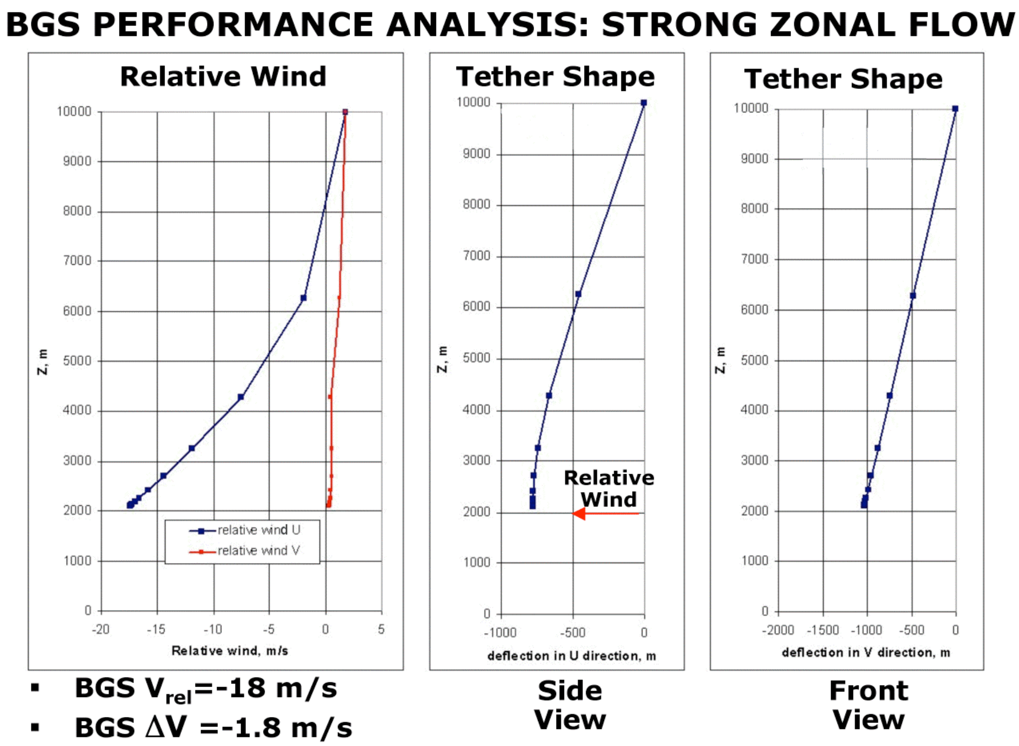

Fig. 7. BGS Performance in strong zonal flow.

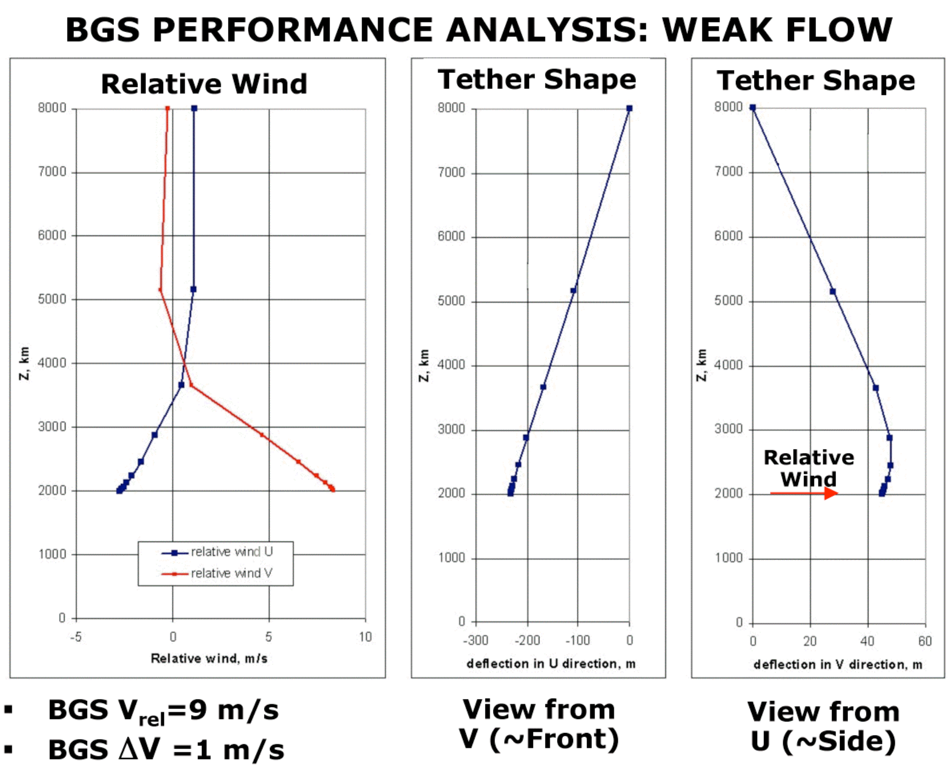

Fig. 8. BGS Performance in weak wind flow.

In this example, the main wing is 8 m in length and 1 m in chord for a total of 8.0 m^2 in wing area. The assumed wing coefficient of lift is 0.8 with a corresponding drag coefficient of 0.2. The estimated mass of this wing system, including the support boom, rudder, and power and computer elements is 8.7 kg. The tether mass is estimated at 1.0 kg (only 125 g/km) while the winch mass is estimated at 2.0 kg. The total suspended mass of the BGS system is therefore only 11.7 kg. Designing a lightweight BGS can easily be achieved by the use of advanced structures technology including inflatable structures [7].

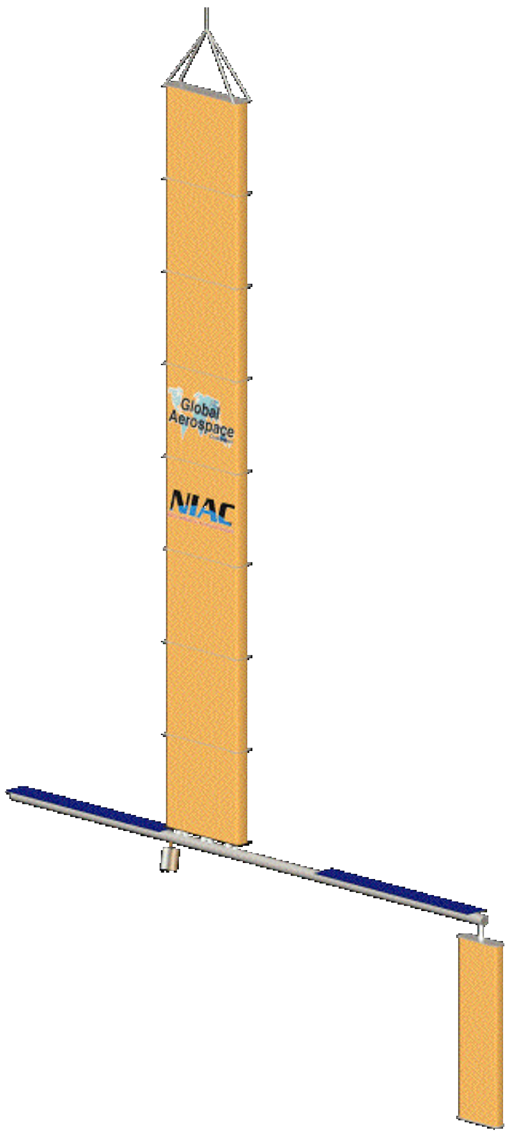

Fig. 9. Example BGS main wing system design.

5. SUMMARY

A Balloon Guidance System (BGS) provides flight path control so that balloons can be directed instead of being completely at the mercy of the prevailing winds. A BGS can be designed and fabricated out of very light materials, including inflatable structures. Earth-based scale model BGS testing provides high confidence in operation in relevant atmospheric conditions. Flight operations have been simulated at Mars using comprehensive aerodynamic and atmospheric models. In addition, the BGS concept is appropriate for near-term applications at Mars and other planets with atmospheres.

A BGS enables a number of science capabilities not otherwise available to Mars explorers. Global planetary coverage from within the atmosphere is possible. Targeted overflight of surface sites and more accurate delivery of science probes can occur. High-resolution imaging, elemental, magnetic and gravity surveys not possible or very challenging from orbit are enabled. Finally, robotic and crewed landing sites can be investigated at close range and navigation beacons deployed.

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