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COMPUTER SIMULATIONS OF GLOBAL NETWORKS OF STRATOSPHERIC SATELLITES

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ABSTRACT

This paper presents simulation technology and results for a revolutionary concept for a global constellation and network of hundreds of stratospheric superpressure balloons, called StratoSat™ platforms, that can address major scientific questions relating to Earth science and meteorology. Applications of such a network include in-situ atmospheric profiling for weather forecasting, hurricane tracking and prediction, hazard detection and monitoring, and global distribution of ozone. Simulations show the amount and extent of surface coverage and the effectiveness of using trajectory controlled balloons for adaptive sampling.

1 INTRODUCTION

Global Aerospace Corporation (GAC) is studying, under NASA Institute for Advanced Concepts (NIAC) funding, a new generation of low-cost stratospheric platforms, called *StratoSat™ platforms*, based on advances in NASA's Ultra Long Duration Balloon (ULDB) technology currently under development. StratoSat™ networks and constellations can address issues of high interest to the Earth science community including global change, especially tropical circulation and radiation balance; global and polar ozone; hurricane forecasting and tracking; global circulation; and global ocean productivity [Nock 2000, Nock 2001]. Regional and global constellations of stratospheric superpressure balloons can measure stratospheric gases, collect data on atmospheric circulation, observe the Earth's surface, and detect and monitor weather and environmental hazards. The following figure shows an example StratoSat™ platform and a network of 100 stratospheric balloons distributed evenly around the globe.

Low-cost StratoSat™ platform constellations could provide good diurnal coverage of the entire globe or specific regions, improve resolution and/or signal-to-noise ratios of measurements due to their low altitude observations, enable new observational techniques because of their low speed, provide frequent to continuous measurements of geographic locations, measure horizontal gradients in addition to vertical profiles, and operate for an extended duration of 3-10 years. StratoSat™ platforms can provide a cost effective method for science and satellite validation, verification, and calibration.

StratoSat™ platform constellations operating at a 35-km altitude and for 3 to 10-years in duration could augment and complement satellite measurements and possibly replace satellites for making some environmental measurements. The keys to this new concept are (a) affordable, long-duration balloon systems, (b) balloon trajectory control capability, and (c) a global communications infrastructure. GAC will summarize the development of technology for these very long-duration and guided stratospheric balloons that enable affordable global and regional constellations of formation-flying, stratospheric platforms.

2 CONSTELLATION TRAJECTORY CONTROL CAPABILITY

The following figure illustrates one concept for a balloon trajectory control system. The StratoSail® TCS 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 [Aaron 1999, Aaron 2000]. 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. The magnitude of the trajectory control capability depends on 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.

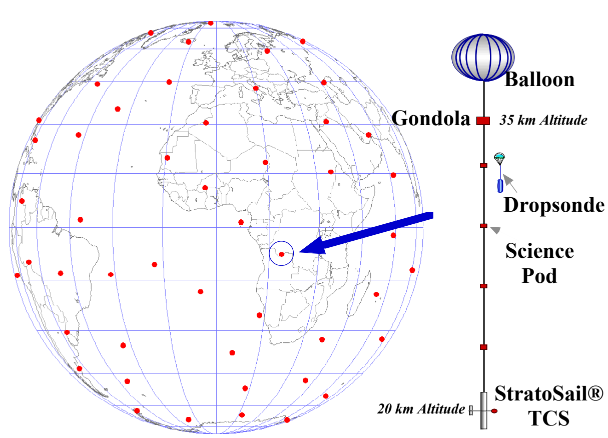

Figure 1. Example Global Constellation of 100 Stratospheric Balloons.

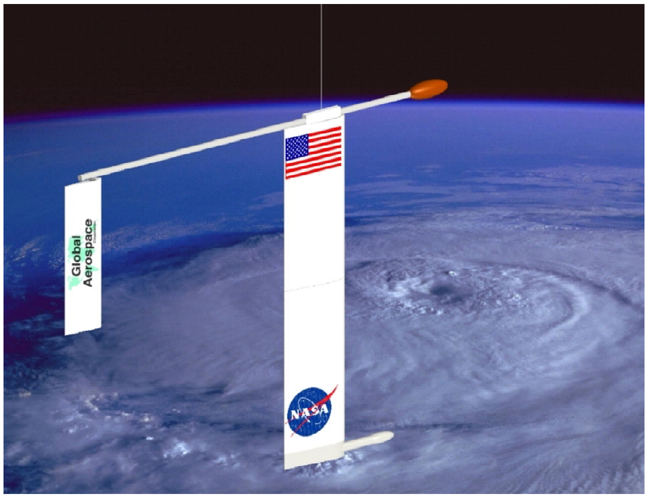

Figure 2. StratoSail® Trajectory Control System.

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.

A StratoSail® TCS provides a sideways (lateral) lift force and has a backward drag force. These forces are applied at the wing. The following figure illustrates the model of the lift and drag forces used to simulate the performance of the StratoSail® TCS. The drag force is essentially constant and in the same direction as the relative wind at the wing. The lateral force can be directed to the left or right of the relative wind at the wing. And, the lateral forces vary in magnitude as a function of the angle of attack of the wing.

The StratoSail® TCS is an example of a bounded and underactuated control system. A bounded control system is one in which control inputs have bounded magnitude; in this case the bound is less than typical external forces (winds). An underactuated control system is one in which control forces cannot be applied in all desired directions. The StratoSail® TCS is both bounded (because it cannot fight the winds to maintain station) and underactuated (because it provides control forces over about 90° of the full circle).

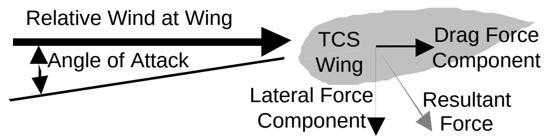

Figure 3. Lateral (Lift) and Drag Force Components on StratoSail® TCS.

3 WEAK STABILITY BOUNDARY THEORY

Weak Stability Boundary (WSB) theory is a way to predict where sensitive (or chaotic) motion will occur as an object is moving under the influence of various forces. It will also analytically approximate the regions of sensitive motion. These regions are termed weak stability boundaries. The sensitive nature of the motion can be exploited to minimize trajectory control requirements, depending on the application. This theory was originally developed in 1986 for the application to the motion of spacecraft [Belbruno 1987]. It was used to salvage the Japanese spacecraft Hiten and enabled it to reach the Moon on October 2, 1991. This was the first operational proof of WSB theory [Belbruno 1993, Frank].

An important result of this work is analysis that shows that WSB theory can be applied to control the motion of balloons in the stratosphere. By modeling stratospheric vortices as Newtonian potentials, WSB regions can potentially be identified near these vortices. Balloons moving near these locations will move in a sensitive manner which can be exploited to minimize control effort for maintaining the nominal path of the balloon and to also change its path.

An example WSB surface and an illustration of how it is used is shown in the three-dimensional plot in Figure 4. In this example, there is a pair of cyclones, one modeled as a source and one as a sink. In the plot the xy-plane corresponds to the physical plane where x is a local coordinate for latitude and y a local coordinate for longitude. The z-axis represents the energy associated with the surface. This energy is a measure of the velocity a balloon can have at a given value of x and y while being on the WSB surface. The higher the surface, the greater the range of velocities the balloon can have at a given point (x; y). This means that there is a larger range of possible velocity values to choose from in order to be on the boundary, giving more flexibility in the control of the balloon's motion. The control is achieved by applying small maneuvers to achieve large changes in the trajectory. In Figure 4, the balloon trajectory is seen to start in Region I at x=.5, y=-4. It

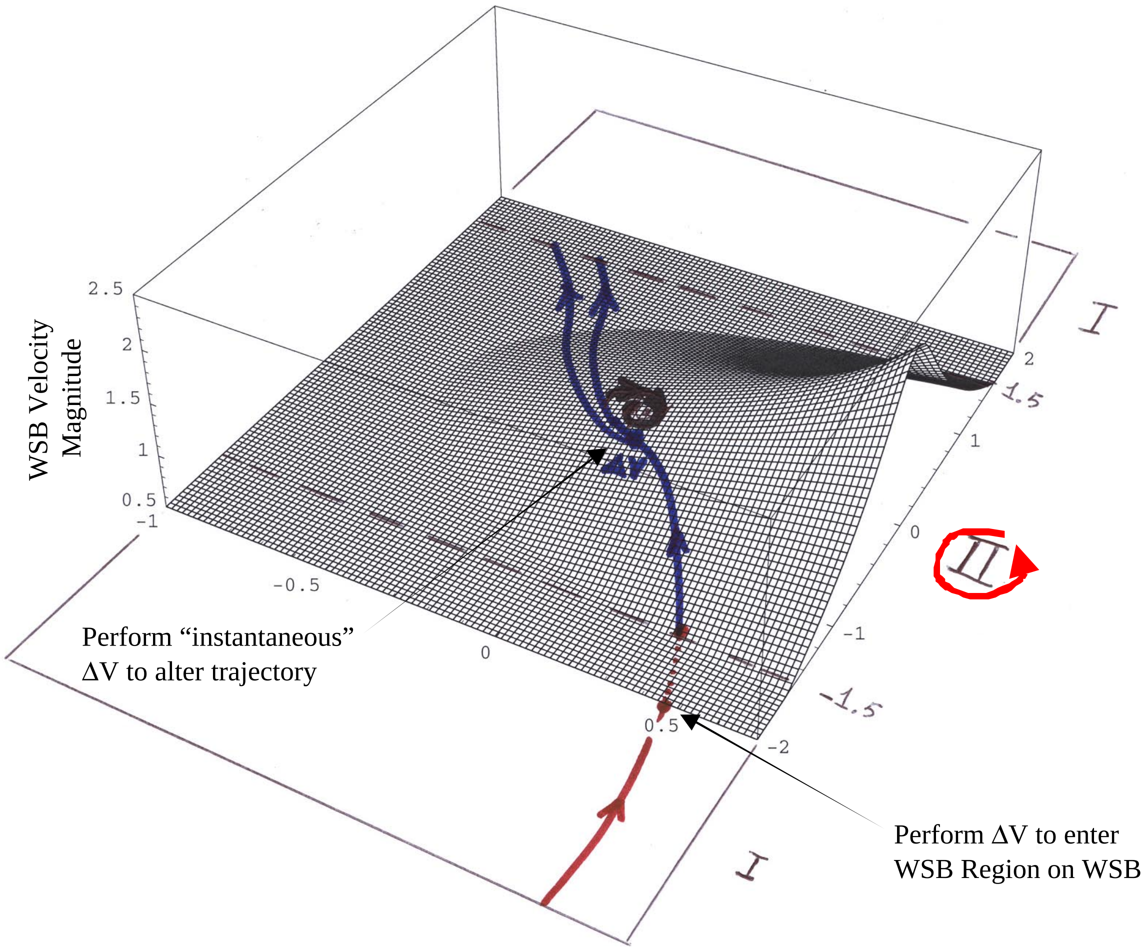

Figure 4. Example Use of WSB Theory to Alter Balloon Trajectories.

moves with no delta-V until it gets to the threshold of Region II at the position x=.5, y=-2. There a delta-V is applied so that the velocity at this point corresponds to one in which the balloon will be able to enter Region II and be approximately at the WSB. After this point the balloon moves with no delta-V across Region II and remains on the WSB. Moving on the WSB implies that its motion should be sensitive to small maneuvers (delta-V's). This fact is demonstrated when the balloon is approximately at the middle of the WSB region at the position x=-.2, y=0. This point is slightly below one of the cyclones (the one that is modeled as a source) which has its origin at x=0, y=0. Here, a small maneuver is performed. For comparison, in the case in which no maneuver is performed, the trajectory freely moves on the path to the right. When the maneuver is performed, the path to the left is shown. Since 1 unit in the xy-plane corresponds to 5,000 km, a significant deviation is obtained, as is shown. The maneuvered trajectory is the path of a balloon which is given a delta-V of –5 m/s tangential to its path in the WSB region. This causes a shift of 2000 km in 12 days. It would require a higher control effort to cause this amount of shift were the control effort applied elsewhere along the trajectory of the balloon. It is expected that applying delta-V's at more places or continuously along the trajectory would cause a much greater shift.

4 ARTIFICIAL POTENTIAL (AP) THEORY

Biologists who study animal aggregations such as swarms, flocks, schools, and herds have observed the remarkable group-level characteristics that are exhibited as “emergent” properties from individual-level behaviors [Parrish 1997, Okubo]. These include the ability to make very fast and efficient coordinated maneuvers [Parrish 1999], the ability to quickly process data, and a significantly improved decision making ability (as compared to individuals) [Khatib 1980]. The following figure illustrates these natural behaviors with a pod of dolphins.

Figure 5. Example Biological Group: Pod of Dolphins.

The use of artificial potentials to generate control laws that emulate schooling behavior is inspired by the observations and models of the biologists. Groups in nature make use of a distributed control architecture whereby individuals respond to their sensed environment but are constrained by the behavior of their neighbors. Biologists suggest that the following elements are basic to maintaining a group structure: (1) attraction to distant neighbors up to a maximum distance, (2) repulsion from neighbors that are too close and (3) alignment or velocity matching with neighbors [Okubo]. In our control synthesis framework, these local traffic rules are encoded by means of (local) artificial potentials that define interaction forces between neighboring vehicles. Each of these potentials is a function of the relative distance between a pair of neighbors [Leonard 2001]. Using such a method, the control forces drive the vehicles to the minimum of the total potential. Artificial potentials can also be defined as a function of relative orientation in order to produce control laws to align neighboring vehicles [Smith].

In robotics, artificial potentials have been used extensively to produce feedback control laws [Khatib 1980, Khatib 1986, Khosla, Rimon] that avoid stationary obstacles as well as obstacles in motion [Newman] and have been used in motion planning [Barraquand, Warren]. Potential shaping has also been used successfully for stabilization of mechanical systems [van der Schaft, Ortega, Leonard 1997, Bloch, Bullo]. Progress has been made in using artificial potentials in group tasks such as in addressing the problem of autonomous robot assembly [Koditschek] and the coordination of a constellation of spacecraft [McInnes]. In the artificial intelligence and computer animation industries, heuristic traffic rules are imposed of a similar sort in order to yield life-like coordinated behaviors [Reynolds]. In recent work, the artificial potentials framework has been considered to enable vehicle groups to efficiently climb gradients in a spatial distribution [Bachmayer].

5 GLOBAL CONSTELLATION GEOMETRY MANAGEMENT WITH ARTIFICIAL POTENTIALS FOR SURFACE REMOTE SENSING

We have successfully utilized artificial potentials to control constellations of hundreds of stratospheric balloons for simulated constellations doing surface remote sensing. This is the first known application of AP theory for bounded and underactuated control systems (StratoSail® TCSs) in the presence of a non-uniform external flow field (stratospheric winds).

We assume that science data is to be collected by remote observation of the surface of the earth. Emission angles greater than 2° are acceptable, so the “footprint” for one balloon includes all points on the globe that can view the balloon with 2° elevation angle or higher. For this application, it is desired to have uniform coverage over the entire region of interest. The StratoSail® TCS, being a bounded control system, does not provide station-keeping capabilities, so we choose to utilize enough balloons to cover the latitude band in which the desired region lies. For the case of uniform coverage in the Northern Hemisphere (+15° latitude to the pole), 383 balloons are sufficient.

Figure 6 shows an example constellation of balloons for this application. Note that balloon locations are shown as red dots, the coverage zone for each balloon is shown as a yellow circle, and overlapping coverage regions are shown in green.

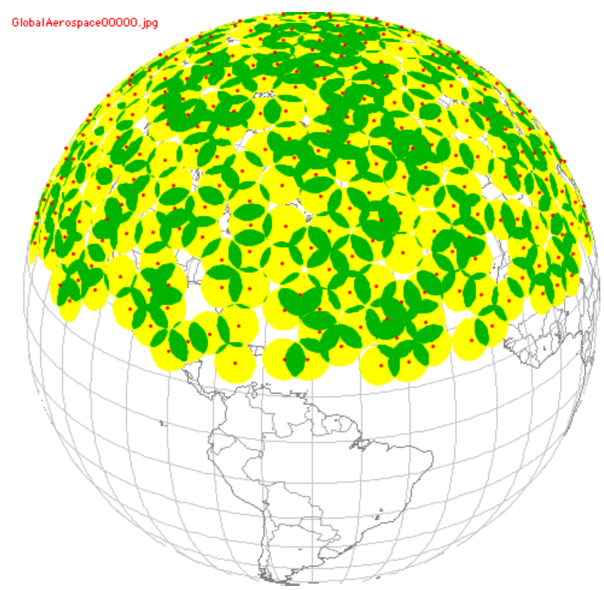

Figure 6. Northern Hemisphere Constellation of 383 Stratospheric Balloons.

For these simulations, we used the artificial potential (AP) theory to set the desired magnitude and direction of the forces applied by the trajectory control system. In cases where the desired velocity vector is not achievable by the TCS, we choose to preserve the lateral component (as shown in Figure 3) of the desired velocity vector (up to the maximum lateral magnitude).

5.1 Results

5.1.1 Simulation process

We simulated a 383-balloon constellation covering the area from +15° latitude to the north pole. The start of the simulation is at 2000-06-01T00:00:00. Historical wind conditions for the period of the simulation were supplied by the United Kingdom Meteorological Office (UKMO). The integration time step for the simulation is 1 hour, and the TCS control directions are reset at each time step. The balloons float at 35 km ± 1 km. The altitudes of the balloons are randomized in that range at that beginning of the simulation. The balloons remain at their initial altitude throughout the simulation. The simulation ran for more than 1 year.

Without the use of trajectory control, the balloons tend to cluster together in low-pressure regions. Figure 7 illustrates this clustering behavior with a smaller network of balloons (from +15° to +55° latitude) operating without trajectory control within the latitude band. (The initial condition is an evenly-distributed network.) Undesirable voids and clusters appear in the network after 76 days of the simulation.

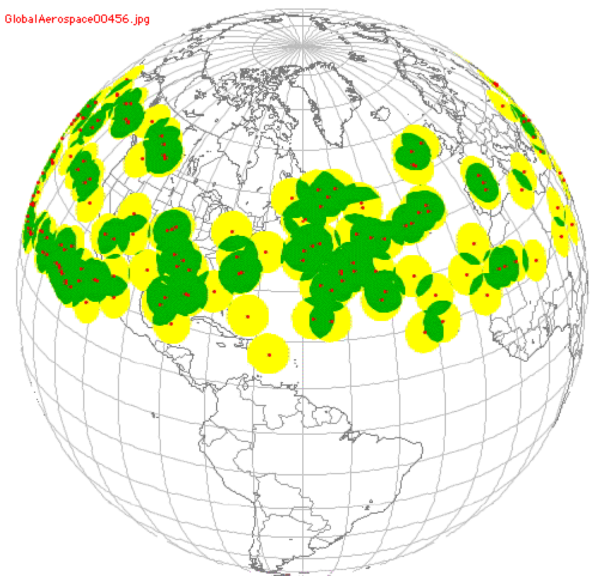

Figure 7. Uncontrolled Constellation.

However, with the artificial potential trajectory control algorithm operating, near-uniform coverage is obtained as shown in the following figure 277 days into the simulation. As a whole, the constellation of balloons acts in a manner analogous to biological groups (flocks of birds, for example). By using simple control laws for individuals in the network, we see emergent group behavior (intelligence) that is more interesting and important for science data collection than the behavior of each individual.

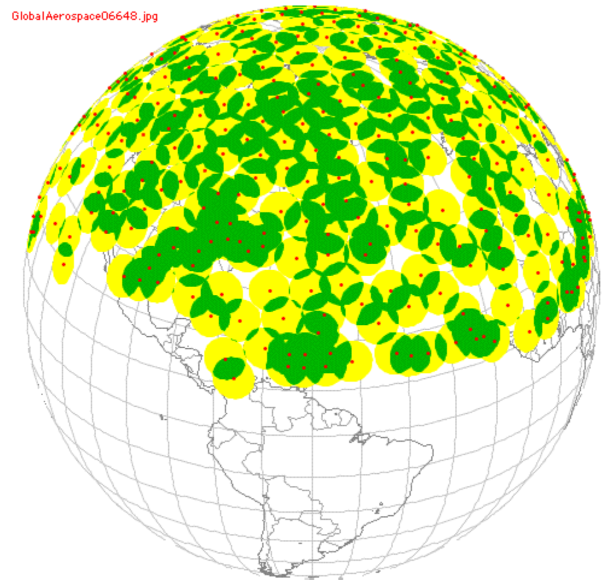

Figure 8. Constellation with AP Control (277 Days into the Simulation).

5.1.2 Coverage ratio statistics

To evaluate the quality of coverage provided by such a network, we selected 100 random sites in the United States and plotted the ratio of the number of sites that are covered by at least one balloon to the total number of sites as a function of time. Figure 9 shows that excellent coverage is afforded throughout the year. Note that the period from 210 to 240 days from launch includes significant activity of the polar vortex. The vortex is bifurcated and offset from the north pole. Despite the challenging conditions presented by the non-uniform external flow field, the coverage ratio remains high.

5.1.3 Outage and recovery duration distributions and percentiles

Another way to evaluate the quality of coverage is to examine the distribution of outage durations at the 100 US sites. An outage is defined as a period of time during which a site on the ground cannot emit to any balloon in the constellation at greater than 2° elevation angle. The outage duration is the length of time that the outage persists. We see from Figure 10 that a plurality of the outages experienced in the simulation have durations equivalent to the time step of the integration (1 hour) in the simulation. Thus, we conclude that outages are expected to be 1 hour or less in duration.

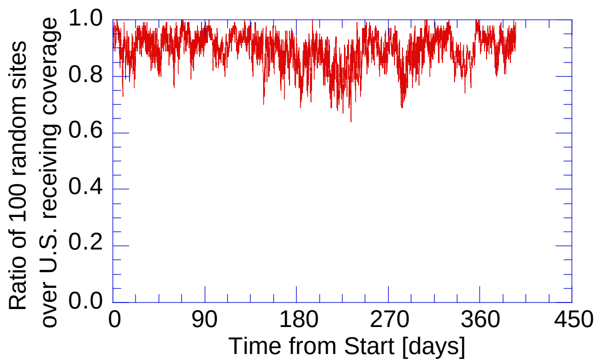

Figure 9. Coverage Ratio as a Function of Time (Controlled Constellation).

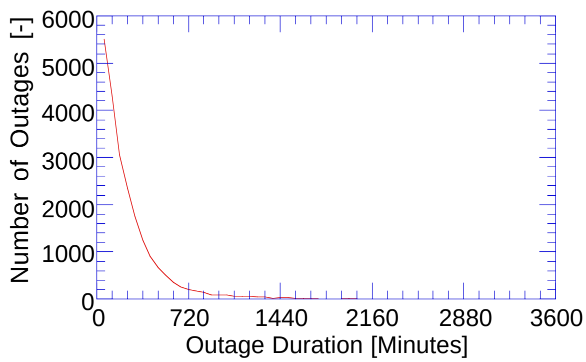

Figure 10. Outage Duration Distribution (Controlled Constellation).

One can also determine the distribution of recovery durations. A recovery is defined as the return of emission at greater than 2° elevation angle after an outage. The duration of the recovery is the length of time that the recovered condition persists. The following figure shows that the most frequent recovery duration time is 13 hours (780 minutes) and indicates that there will be sufficient opportunities for data transmission upon recovery. Furthermore, the distribution has a significantly large tail toward longer recovery times.

6 CONTROL OF BALLOONS FOR ADAPTIVE SAMPLING

We have also simulated the trajectories of individual balloons that could be part of a constellation that provides data for adaptive observing systems that focus on regions with high sensitivity for meteorological forecast accuracy. Data are collected by dropping sondes from balloons at desired locations. The region of high sensitivity is assumed to be the northern Pacific Ocean. Thus, the goal is to maximize the number of dropsonde opportunities in that region.

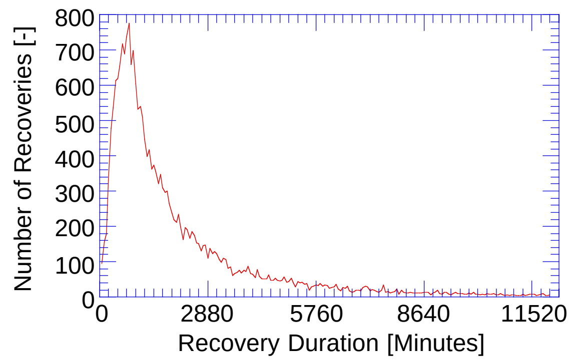

Figure 11. Recovery Duration Distribution (Controlled Constellation).

Figure 12 shows a 15-day snapshot of a simulation that demonstrates the advantage of trajectory control for such targeted observations. The **red** trajectory shows an uncontrolled balloon floating at 35 km. The **green** trajectory represents a “simple control” balloon at 35 km whose trajectory is being controlled by a StratoSail® TCS at 20 km. The objective of the simple trajectory control algorithm for the **green** balloon is to maintain 45°-north longitude at all times. Thus, when the balloon is south of 45°, the TCS pushes north if possible, and vice versa. The **blue** trajectory shows a balloon at 35 km with the same 20-km StratoSail® TCS as the green balloon. However, the **blue** balloon uses a sophisticated trajectory control algorithm. At various times throughout the flight, the **blue** balloon is commanded to maintain latitude or to move toward or away from the center of an observed vortex. Control actions are taken based on the structure of the wind field at the time the control decision is made. No forecast information is utilized. We assume that there is an opportunity to change the StratoSail® TCS command every four hours.

The complete simulation begins at November 1, 2000 and ends on March 1, 2001, 120 days in duration. Only 15 days of the trajectories (starting from December 1, 2000) are shown in figure 6 for clarity. The arrows on the trajectories indicate direction of travel and are spaced at 6-hour intervals to demonstrate locations of possible sonde drops. Stratospheric winds are provided by United Kingdom Meteorological Office (UKMO) assimilations.

Table 1 gives the number of dropsonde observations in the region of interest over the 120 days of simulation.

7 NEXT STEPS

There are several future directions for this research. First, we want to integrate the AP and WSB theories into

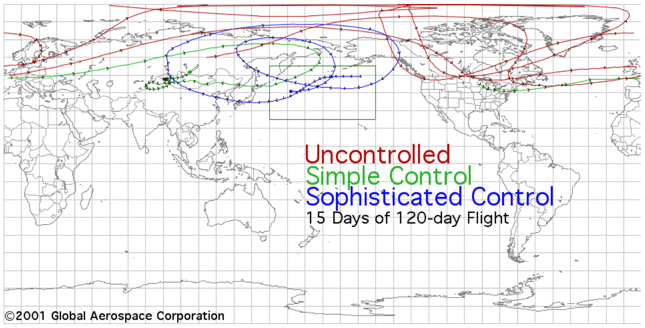

Figure 12. A 15-day Snapshot of an Example Adaptive Sampling 120-day Simulation.

Table 1. Observations "in the box" of Figure 12.

Trajectory	# of Sonde Drops in High-Sensitivity Region
Uncontrolled (red)	12
Simple Control (45°) (green)	107
Sophisticated (blue)	175

a unified framework so that we can utilize all available trajectory control options near meteorological features such as vortices. We need to incorporate the capability to recognize these meteorological features from the atmospheric data. We can further use that information in prescribing desirable control actions to achieve constellation geometry objectives. When features such as vortices or jets are identified, modified control laws can be applied in a coordinate system local to the meteorological feature. The primary benefit to these developments may be reduction of the number of balloons required for a constellation. Finally, we are interested in continuing the work on balloon constellations for adaptive sampling for specific science or meteorological objectives. Such adaptive constellations could make use of “virtual” members of a constellation that attract balloons to a desired area or repel balloons from other regions. Another possibility is using the schooling approach for gradient climbing as discussed earlier.

8 OTHER POTENTIAL APPLICATIONS

There are other potential applications for the work presented here. For example, the control actions of small or micro satellites in an orbital constellation could be determined by the Artificial Potential and Weak Stability Boundary theories. Such systems are often discussed for Earth and planetary science applications. Another example application is adaptive ocean sampling using underwater ocean vehicles that carry science instruments and utilize buoyancy changes and mass redistribution to generate sideways trajectory control forces. Such systems meet the definition of bounded and underactuated control systems. Furthermore, these underwater systems operate in the presence of non-uniform external flow fields (ocean currents). Schools of these systems could benefit from the algorithms discussed here. Details on the progress of these activities can be found at http://www.gaerospace.com/publicPages/projectPages/StratCon/index.html.

9 CONCLUSION

We studied options and theories for the control of a constellation of stratospheric balloons. We found that behavior analogous to that of natural biological groups (flocks of birds and schools of fish) can be obtained for vehicles with bounded and underactuated control systems in the presence of non-uniform external flow fields. We successfully demonstrated for the first time the use of Artificial Potential theory for this application.

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