Stratospheric Satellites for Earth Science Applications

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Abstract - We present a concept for global and regional constellations of low cost stratospheric satellites based on Ultra Long Duration Balloon (ULDB) and StratoSail® Trajectory Control System (TCS) technologies. Stratospheric Satellites (StratoSat™ platforms) will be moved around the globe by stratospheric winds (at the height of 35 km – above 99% of the Earth's atmosphere, virtually "at the edge of space"), have some maneuvering capabilities, and have a multitude of Earth Science applications, such as measuring profiles of concentrations of ozone and trace constituents, monitoring Earth magnetic field and radiative fluxes, tracking hurricanes, and monitoring global weather and climate. Networks of StratoSat™ platforms can be configured to provide independent observations and to validate observations of other sensors within the SensorWeb paradigm of the NASA Earth Science Vision. The StratoSat™ platforms utilize a small amount of trajectory control to meet observation objectives. This capability allows for rapid adaptation of network configuration to observational needs. The network can be configured to provide observations with a desired frequency over specific target areas, such as the tropics or Polar Regions. We describe the design of StratoSat™ platforms, potential mission scenarios and payloads, and potential network configurations.

I. Introduction

Global Aerospace Corporation (GAC) is developing, under NASA Institute of Advanced Concepts (NIAC) funding, a revolutionary concept for a low-cost adaptive observing system comprising a global constellation and network of perhaps tens to hundreds of stratospheric satellites (StratoSat™ platforms). At the heart of the StratoSat™ platform is a superpressure balloon based on NASA's Ultra Long Duration Balloon (ULDB) technology currently under development. The balloon maintains its constant altitude of 35 km throughout a flight and can potentially remain afloat for several years. The StratoSail® trajectory control system (TCS) is suspended on a tether 15 km below the balloon altitude. The StratoSail® TCS is essentially a wing that hangs on end so that the relative winds at the altitude of the TCS create a horizontal "lifting" force. This force "nudges" the balloon in the crosswind direction to considerably alter balloon trajectory. Even though the size and direction of the available force are limited, it can be applied constantly, and the system requires virtually no consumables. The application of novel trajectory control methodologies based on chaos theory and on the behavior of biological groups (flocks of birds, schools of fish) to constellations of balloons provides the potential for radically new observational approaches to many Earth Science problems. Fig. 1 shows an example StratoSat™ platform and a network of 100 stratospheric balloons distributed evenly around the globe. The detailed description of the concept can be found in [1] and at http://www.gaerospace.com/publicPages/projectPages/StratCon/index.html.

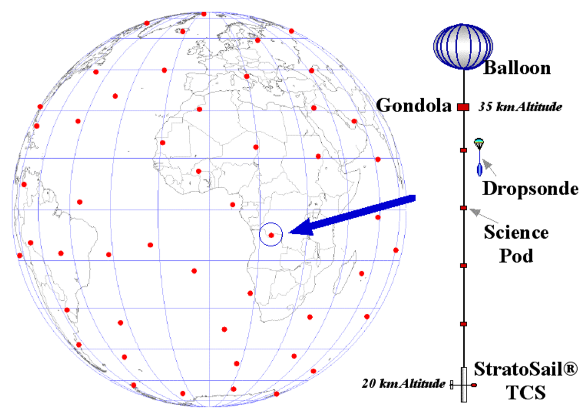

Fig. 1. Global constellation of StratoSat™ platforms

Low-cost StratoSat™ platform constellations could provide good diurnal coverage of the entire globe or specific regions, improve the resolution and/or signal-to-noise ratio 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.

In the following sections we describe several potential Earth Science applications for constellations of StratoSat™ platforms and show how the StratoSail® TCS trajectory control capabilities can be utilized in the context of these applications.

II. EARTH SCIENCE APPLICATIONS

A. *Atmospheric Chemistry and Weather*

Stratospheric balloons present a unique opportunity for continuous *in situ* and remote measurements of atmospheric constituents (e.g. ozone, trace constituents). These observations are necessary to (a) answer the question of how the concentration of ozone is changing in the atmosphere and (b) study tropical and global circulation. Instruments can be positioned on the gondola and also on the tether for measurements of vertical profiles. The same payload can carry a number of meteorological dropsondes, which can be deployed coincident with *in situ* and remote sensing measurements, or independently. Balloon constellations can be deployed globally or regionally – in the tropics or in the Polar Regions. Trajectory control would maintain a uniform distribution of balloons within a global constellation (Fig. 5) or provide the option of performing targeted observation of data sparse regions (Fig. 2) or severe weather events with a smaller constellation (Fig. 3).

B. *Earth's Magnetic Field*

Measurements of the Earth's magnetic field are required globally and on a regular basis, but many areas (e.g. oceans) lack observations. Observations from satellites have low signal-to-noise ratio because of their high altitude and influence of the ionosphere, while high-cost surface, aircraft, and vessel observations do not provide global coverage. Constellations of stratospheric balloons can achieve global coverage (Fig. 5) and provide measurements with higher signal-to-noise ratio and higher spatial resolution than satellites, as the size of the sampling footprint on the ground is proportional to altitude. In addition, balloons offer an unprecedented opportunity for measurements of magnetic field vertical gradients, which are more sensitive to the position of magnetic field sources than measurements of the total field. Magnetometers are light instruments (1 kg) and can be positioned at several kilometer intervals along the tether that supports the TCS. Magnetic field gradient measurements from global constellations of StratoSat™ platforms would provide detailed maps of crustal sources of the magnetic field and resolve diurnal variations of the field. Long duration flights could investigate magma displacements in the Earth's interior and the dynamics of the Earth's dynamo by measuring variations of the magnetic field on longer timescales (years).

C. *Radiative Fluxes*

The difference between incoming solar radiation and outgoing Earth's infrared radiation controls Earth's climate and weather. Even small changes in those radiative fluxes (of order of several percent) can lead to significant global climate change. Currently, fluxes are monitored by satellite instruments that measure radiances, which are post-processed into fluxes. The conversion process introduces an uncertainty of about 4 percent to flux measurements, which is significant in terms of climate change. Instruments on stratospheric balloons can measure fluxes directly at the height of 35 km (top of the atmosphere or TOA), thus eliminating the uncertainty of satellite measurements due to the radiance-to-flux conversion process. In addition, balloon measurements would have higher spatial resolution than satellite measurements because of the balloon's lower altitude. It would also be possible to capture diurnal variations of TOA fluxes over relatively small (1000 km) areas with slow moving (1 percent as fast as satellites) balloons. Global constellations of guided balloons could provide coverage comparable to that of the satellites (see Fig. 5). Each balloon would carry up to four Active Cavity Radiometers to measure total and short wave fluxes with narrow and wide fields of view.

III. TRAJECTORY CONTROL CAPABILITES

In this section we show numerical simulations of trajectory control capabilities of singular balloons and constellations. In all simulations real winds from the UKMO assimilation model were used. The control force provided by the StratoSail® TCS depends on the winds at the balloon altitude (35 km) and on the winds at the altitude of the TCS (20 km).

A. *Single Balloon Control*

This simulation illustrates how trajectory control can be implemented for targeted observations. It is currently believed that targeted observations of data sparse and sensitive areas can lead to improvement of short range (3-5 days) and medium range (8 days) weather forecasts. The Observing system Research and Predictability Experiment (THOR*pex*) seeks to prove this hypothesis [2]. The accuracy of Continental U.S. weather forecasts is strongly dependent on measurements in North Pacific, within a region that is schematically marked by a box on Fig. 2.

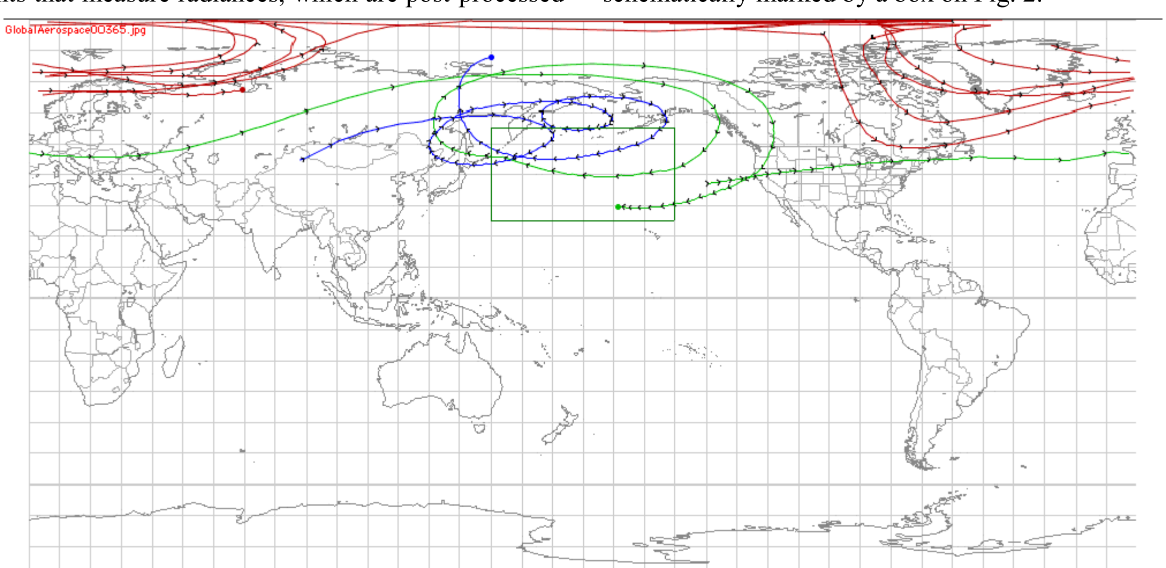

Fig. 2. A 15-day snapshot of example THOR*pex* targeting simulation

The goal of the simulation is to direct a balloon inside the box where it would deploy dropsondes or perform other observations. The simulation compares trajectories of three balloons, if they were all launched from Palestine, TX on January 1, 2000. The first balloon (red) does not have any trajectory control. The second balloon (green) is always directed towards 45°N latitude, so that it would cross the middle of the box. The third balloon (blue) "looks" for vortices and uses their rotating wind patterns to change direction and revisit the box. If there are no vortices nearby, it uses the same strategy as the green balloon. Fig. 2 shows a snapshot in the middle of the 120-day simulation. The "tails" of the balloons are 15 days long and the arrows on the "tails" indicate dropsonde deployment times (every 6 hours). Fig. 2 shows the uncontrolled balloon spending most of the time in the polar vortex over Greenland, while the controlled balloons overfly the forecast sensitivity region. By the end of this 120-day simulation, the uncontrolled balloon deploys 12 dropsondes inside the sensitivity region, while the controlled green and blue balloons deliver an order of magnitude larger number of dropsondes - 107 and 175, respectively.

B. Linear Constellation Control

This simulation illustrates how trajectory control within a small constellation can be used to achieve almost continuous observation of a localized and moving phenomenon (hurricane) – what we call "virtual station keeping." The constellation consists of 20 StratoSat™ platforms deployed in a linear constellation in the tropics. When the balloons are within 90° longitude of the hurricane, they are directed toward the eye of the storm. Otherwise, they are commanded to maintain the latitude of the storm. Fig. 3 shows a snapshot of the simulation with a blue circle indicating hurricane Alberto and red dots indicating balloons with 1-day "tails". One balloon is seen leaving the hurricane, with the nearest incoming balloon about 10° from the hurricane, and the geometry of the constellation is modified in response to the movements of the hurricane.

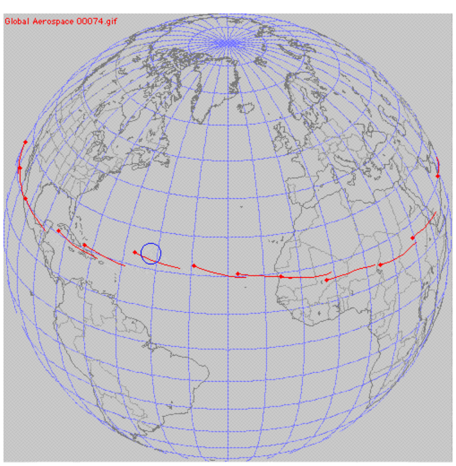

Fig. 3. Example of hurricane overfly with linear constellation

C. Global (Hemispheric) Control

The final simulation compares the evolution of two 383-balloon constellations with and without trajectory control during Northern Hemisphere winter. The goal for the controlled constellation is to maintain close to uniform distribution in the latitudinal band between 15° and 55°. The trajectory control methodology for the controlled constellation is based upon the dynamics of biological groups in nature, such as flocks or schools of fish. Balloons in the controlled constellation maintain a coherent structure after 120 days (Fig. 5), while balloons in the uncontrolled constellation are thrown chaotically around the globe or trapped on the circumference of the vortex (Fig. 4).

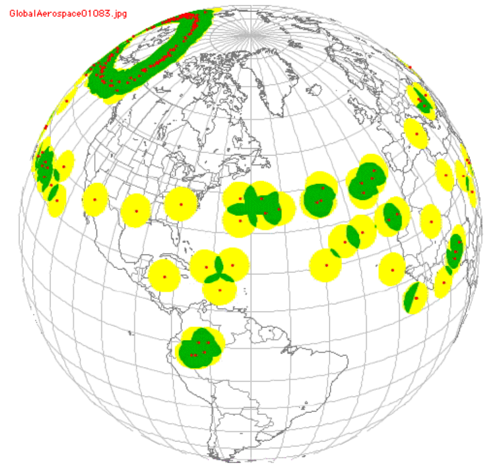

Fig. 4. Constellation without control

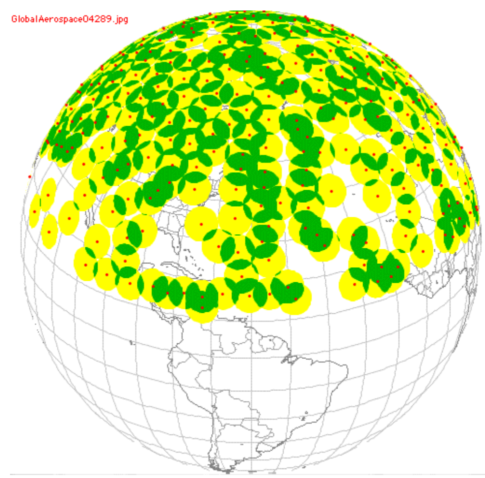

Fig. 5. Constellation with control

References

[1] M. K. Heun, "Stratospheric balloon constellations for Earth science and meteorology," *5th Symposium on Integrated Observing Systems, Amer. Met. Soc.,* pp. 210-217, 2001.

[2] http://www.nrlmry.navy.mil/~langland/THORPEX_document/Thorpex_plan.htm