STRATOSPHERIC SATELLITES IN THORPEX

Global Aerospace Corporation
711 West Woodbury Road
Altadena, CA 91011

Prepared by
Dr. Matthew Kuperus Heun
Dr. Alexey A. Pankine
Kerry T. Nock

September 15, 2001

Concept

Stratospheric satellites (StratoSat™ platforms) are envisioned as autonomous low-cost observing platforms that float (with some trajectory control capability) in stratospheric winds. A global constellation and network of tens to hundreds StratoSat™ platforms, as depicted in Figure 1, can address major observational needs for weather prediction and climate monitoring by providing global data coverage with an array of in situ and remote sensing instruments. The in situ data include GPS dropsonde profiles through the lower stratosphere and troposphere, as well as continuous measurements by onboard sensors in the region of the stratosphere between 20 and 35 kilometers. The suite of remote sensing instruments may include high-resolution cameras, wind Lidars, and precipitation radars.

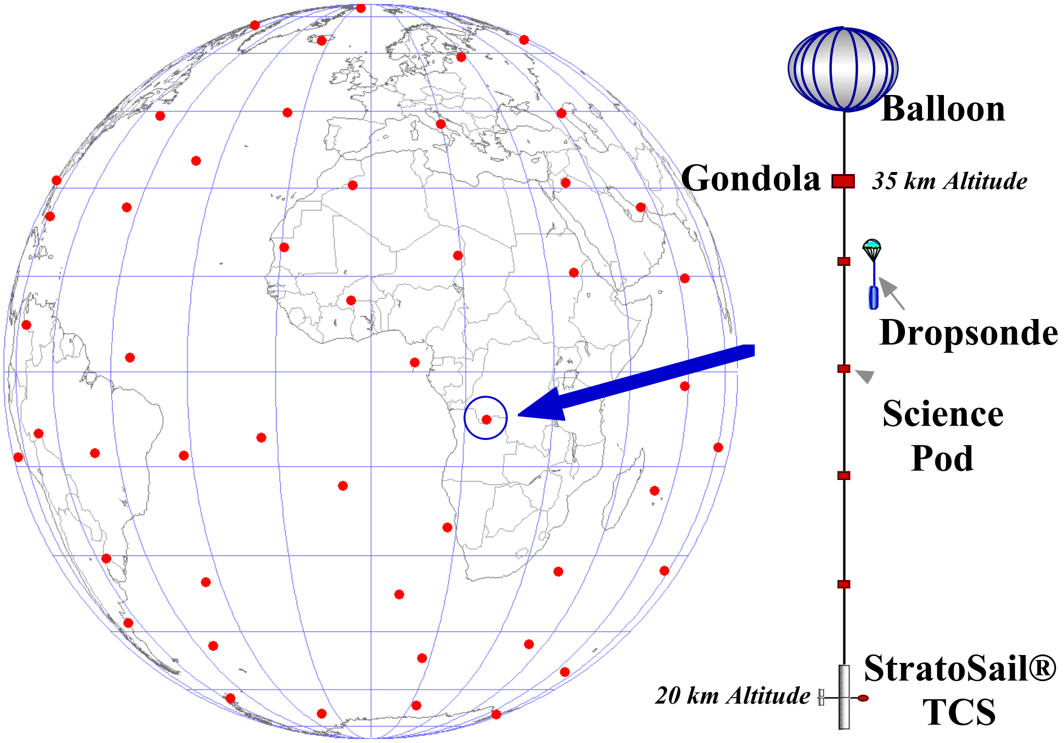

Figure 1 Global Constellation of StratoSat™ Platforms

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 high frequency over specific target areas, such as areas of initial condition sensitivity for weather forecasts, data sparse regions, and storm tracks. Once deployed, the StratoSat™ platforms could operate for up to 10 years providing a means for low cost and adaptive atmospheric sampling. Estimates of the cost per sounding profile range from $200-300 or less, depending upon how many weather forecast zones of the world are targeted.

Platform Description

A StratoSat™ platform consists of a small (~70,000 m^3) super-pressure stratospheric balloon; a gondola containing science packages, dropsonde system, communications, power, computing, flight safety, and recovery subsystems; and a flight path or trajectory control system (TCS).

The balloon is an Euler Elastica, or "Pumpkin" shaped envelope based on advancements of the NASA Ultra Long Duration Balloon (ULDB) currently undergoing testing. Figure 2 shows an artist's view of the NASA ULDB (See http://www.wff.nasa.gov/~uldb/index.html). The NASA ULDB is a superpressure polyethylene pumpkin-shaped balloon capable of carrying a payload of 2045 kg (4500 lbs.) to 34-km float altitude. At the successful June 2000 test, the scaled version (1/10 volume) of the ULDB reached 28-km altitude and carried a 777-kg payload (see Figure 3). The ultimate StratoSat™ platform design uses a smaller, advanced technology version of the scaled balloon capable of carrying a payload of at least 250 kg.

Figure 2 Artist Drawing of NASA ULDB

The gondola is based on lightweight mechanical designs and low-power lightweight electronics hardware. A lightweight, modular solar array, currently under development by Global Aerospace Corporation (GAC) with NASA funding, provides 2 kW or more of power to gondola subsystems. An advanced battery or lightweight hydrogen fuel cell subsystem supplies nighttime energy. A flight path control system based on Global Aerospace Corporation's StratoSail® trajectory control system (TCS) provides the flight path guidance required to maintain constellation geometry.

The nominal flight level of StratoSat™ platforms is well above controlled airspace: they do not present a hazard to aviation. After termination of the flight, the payload is delivered to the designated area by autonomous precision-guided parafoil similar to that being developed by ITS Aerospace for the French balloon program (see Figure 4 for a version developed for NASA).

Figure 3 Successful ULDB test, June 2000 (courtesy of NASA)

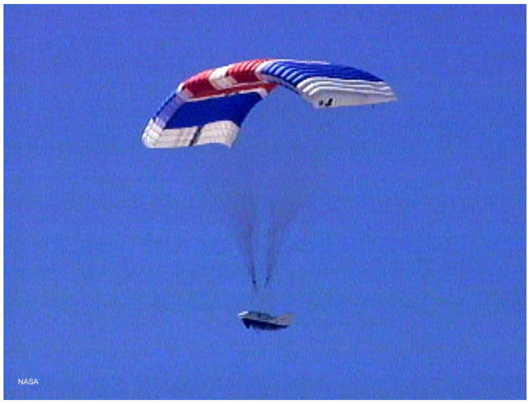

Figure 4 The ORION™ NGCS Guiding the X-38 to a Safe Landing

The first generation StratoSail® TCS, as shown depicted in Figure 5, is designed to alter the flight path of balloons. The StratoSail® TCS takes advantage of the natural difference in wind speed and direction at different altitudes in the atmosphere. A wing is suspended several kilometers below the balloon gondola using a long thin tether. The wing hangs on end, so its "lift" acts sideways rather than upward as in an airplane. This sideways lift force is used to drag the balloon across the relative wind. This allows the balloon to be maneuvered towards regions of interest for atmospheric sampling and weather data collection. Global Aerospace Corporation is developing a first generation StratoSail® TCS under the NASA Small Business Innovation Research (SBIR) Program. We are currently in Phase II of this development. We successfully flight-tested a 1/4-scale model of the TCS in April 2001 as shown in Figure 6 (See http://www.gaerospace.com/publicPages/projectPages/StratoSail/index.html). In March of 2002 we are planning to complete a full scale TCS Wing Assembly (TWA), a testbed of our TWA winch-down system and the flight ready tether. Global Aerospace Corporation is currently fabricating the full-scale wing and rudder assemblies and the flight tether through subcontractors. The full-scale wing assembly, which is less than 10 kg, is shown in Figure 7. A scaled TCS model was successfully tested in April 2001. Figure 6 is a picture from the test.

Figure 5 Artist rendition of First Generation StratoSail® TCS in flight.

Figure 6 StratoSail® TCS Scale Model Test

Figure 7 Full-scale TCS Wing

In the ultimate StratoSat™ platform, an advanced TCS design using a dual, cambered wing is employed in order to obtain higher trajectory control forces on the balloon. This design, shown in Figure 8, allows the lift forces to be higher than the weight of the system and enables the system to stay down in denser air thereby providing greater performance. Global Aerospace Corporation has begun the design of the advanced TCS under NASA Institute for Advanced Concepts (NIAC) funding.

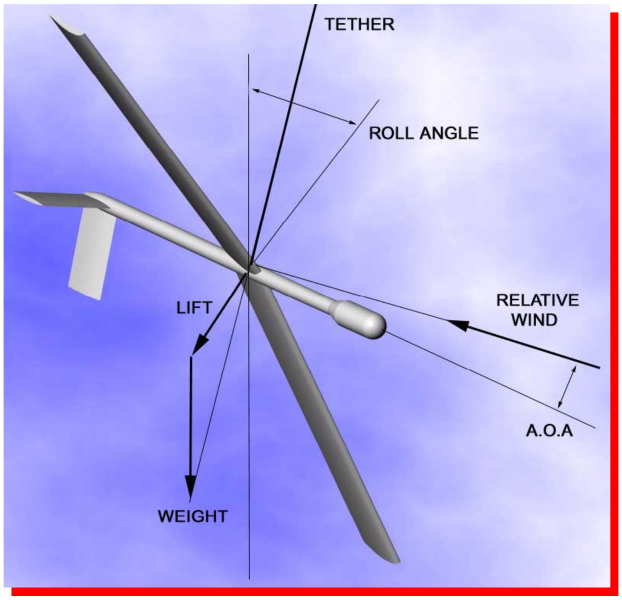

Figure 8 Advanced TCS Design

Operation

The StratoSat™ platform ascends to the altitude of 35 km (~5 mb), deploys the StratoSail® TCS and then drifts in ambient stratospheric flow, adjusting its trajectory according to the observational strategy. The StratoSat™ platforms relay information to a ground station via communication satellite or using their own overflight opportunities. The ground controller issues instructions for trajectory correction. A network of StratoSat™ platforms may also operate autonomously relying on "artificial intelligence" controls, whereby StratoSat™ platforms adjust their positions according to an algorithm based on network configuration information, atmospheric winds, and observation objectives. Algorithms based on the studies of natural grouping behavior (flocks of birds and schools of fish) and optimal control theory are currently being develop that would allow for "intelligent" group behavior of the network. See http://www.gaerospace.com/publicPages/projectPages/StratCon/index.html for more on this work.

An ultimate StratoSat™ platform could be capable of carrying at least 300 GPS dropsondes (assuming the 0.3 kg dropsonde currently being developed by NCAR) for tropospheric and lower stratospheric profiling. In the future, dropsonde mass could possibly be reduced to 10-25 g by application of advanced microelectronics (multichip module [MCM] design) and advanced packaging technology. Thus dropsonde mass reduction will allow each StratoSat™ platform to carry thousands of dropsondes to be used in adaptive sampling over the course of a 10-year life. Science pods positioned every 2-3 km on the TCS tether could provide continuous *in situ* measurements in the lower stratosphere (20-35 km). The StratoSat™ platform may also carry high-resolution wind Lidars and precipitation radars, radiometers, cameras and other instruments. A low-earth satellite (LEO) will relay the collected data to the ground station.

THORPEX Tests

The balloon vehicles for THORPEX test missions do not have to be the ultimate StratoSat™ platforms, i.e. it is not necessary to wait for all the relevant technologies to become available. For these initial tests, we propose using a scaled ULDB, a prototype first generation StratoSail® TCS and a gondola of conventional design. The initial testing of early StratoSat™ platforms could demonstrate the following key characteristics of the concept:

- Targeting – demonstrate system maneuverability utilizing the StratoSail® TCS.
- Networking – demonstrate advantages of cooperative behavior of several StratoSat™ platforms.

Depending on the level of funding available, targeting and/or networking capabilities can be tested. A Targeting Mission test can be done with a single StratoSat™ platform. The primary objective of the test will be to demonstrate feasibility of maneuvering the StratoSat™ platforms toward an area of interest, such as an area of initial condition sensitivity for weather forecast, a data sparse region, or a storm track. The target area may be known in advance, or be determined during the flight. Upon reaching the target area or during closest approach to the target, the StratoSat™ platform deploys dropsondes and collects data. The dropsonde release locations and exact timing could be chosen to achieve maximum reduction in forecast error. The effect of targeted observations can be enhanced if real time assimilation of observations into the forecast is possible – the dropsonde release position will then depend on the previous observations.

The Networking Mission test will require at least two StratoSat™ platforms that are launched from the same location. The mission objective will be achieved either by providing observations of the same regions within the target area, but at different times, or by flying the StratoSat™ systems at desired separation distance while observing larger area of the target, or by dispersing the StratoSat™ platforms to two different target regions. The StratoSat™ systems may be launched with an interval of one or several days and follow each other to the target area, or they may be launched simultaneously from the same launch site and then maneuvered to the desired separation distance.

THORPEX Targeting Test Simulations

Figure 9 illustrates a 15-day snapshot of a possible targeting test mission scenario and demonstrates the advantage of trajectory control for 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, if the balloon is south of 45°, the TCS pushes the balloon 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.

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.

The zone drawn in the North Pacific Ocean represents a possible region of high sensitivity for western U.S. weather forecasts. It extends between 25° and 55° north latitude and between 150°E and 150°W longitude. Table 1 gives the number of sonde observations in the region of interest over the 120 days of simulation.

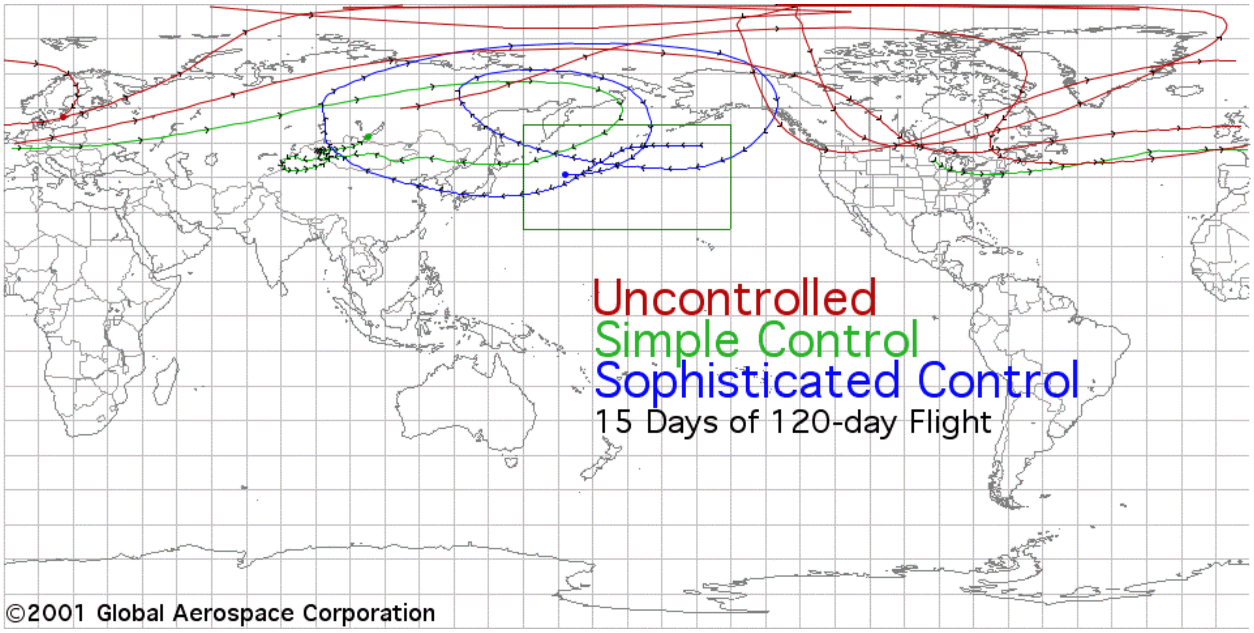

Figure 9 A 15-day Snapshot of an Example THORPEX 120 day Targeting Test

Table 1 Number of Observations "in the box" on Figure 9

Trajectory	**Number of Sonde Drops in High-Sensitivity Region**
Uncontrolled (**Red**)	12
Simple Control (45°) (**Green**)	107
Sophisticated (**Blue**)	175