NASA Institute for Advanced Concepts

# Global Constellation of Stratospheric Scientific Platforms

## Phase II Final Report

### Global Aerospace Corporation

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# Abstract

Under funding from the NASA Institute for Advanced Concepts, Global Aerospace Corporation is developing a revolutionary concept for a global constellation and network of hundreds of stratospheric superpressure balloons which can address major scientific questions relating to NASA's Earth Science Mission by measuring stratospheric gases, collecting data on atmospheric circulation, observing the Earth's surface, and detecting and monitoring environmental hazards. Such a system 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.

In the nearly forty years since the launch of artificial satellites, there has been a shift away from making *in situ* measurements of the global environment to making remote observations from Earth orbiting spacecraft. Today, there may be reason to challenge this remote sensing paradigm. In combination, (a) the advance of electronics, communications and balloon technologies, (b) the difficulty of doing some remote sensing from satellites, and (c) the interest in simultaneous global measurements, argue for a re-evaluation of the current reliance on satellites for many global environmental measurements.

Total system cost for a constellation of very long life stratospheric superpressure balloons is competitive with comparable spacecraft systems due to the inherent high cost of spacecraft and launch vehicles. Developing technology for very long-duration and guided stratospheric balloons will enable an affordable global constellation of formation-flying, stratospheric platforms. The geometry of the global constellation of balloons will be maintained by sophisticated trajectory control algorithms with inter-platform communication facilitated by the emerging global communications infrastructure. Global Aerospace Corporation is developing this concept, exploring additional applications and benefits, and generating first order estimates of the cost of implementing such a revolutionary system.

This Phase II Final Report summarizes the Stratospheric platform constellation (StratCon) concept, discusses the Phase II work in detail, and provides a summary of outreach generated by this effort.

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# 1. Introduction

This is the final report for Phase II of NIAC contract Number 07600-58 for the development of the concept of Global Constellations of Stratospheric Balloons (StratCon).

In this section we describe one concept for global stratospheric constellations, discuss the changing paradigm for Earth science vantage points, summarize the NASA Earth Science Enterprise mission, review the important and relevant technology for global stratospheric constellations, explore the international overflight issues and their implications to global constellations, and describe the importance of this concept to NASA and the World.

## 1.1. Global Constellations of Stratospheric Scientific Platforms

Global Aerospace Corporation is developing a revolutionary concept for a global constellation and network of tens to hundreds of stratospheric superpressure balloons called *StratoSat*™ systems. A network of StratoSats™ can address major scientific questions relating to NASA's *Earth Science Mission*, by globally measuring stratospheric gases, collecting data on atmospheric circulation, observing the Earth's surface, and detecting and monitoring environmental hazards. Figure 1-1 illustrates the StratoSat™ balloon constellation concept.

Each balloon will be designed to operate at an altitude of 35 km for 5 to 10 years in duration. The key stratospheric platform technologies required for an affordable, very long-duration, global balloon constellation are innovative balloon designs, advanced balloon envelope materials and fabrication, lightweight and efficient power generation and energy storage, and balloon trajectory control. Developing technology for very long-duration and guided stratospheric balloons will enable an affordable global constellation of formation-flying, stratospheric platforms. Sophisticated trajectory control algorithms will maintain the structure of the global constellation of balloons with inter-platform communication facilitated by the emerging global communications infrastructure. The technology for such very long duration balloon systems is critically dependant on the current development of NASA's Ultra Long Duration Balloon (ULDB) Project that is expected to demonstrate 100-day flight missions in the near future.

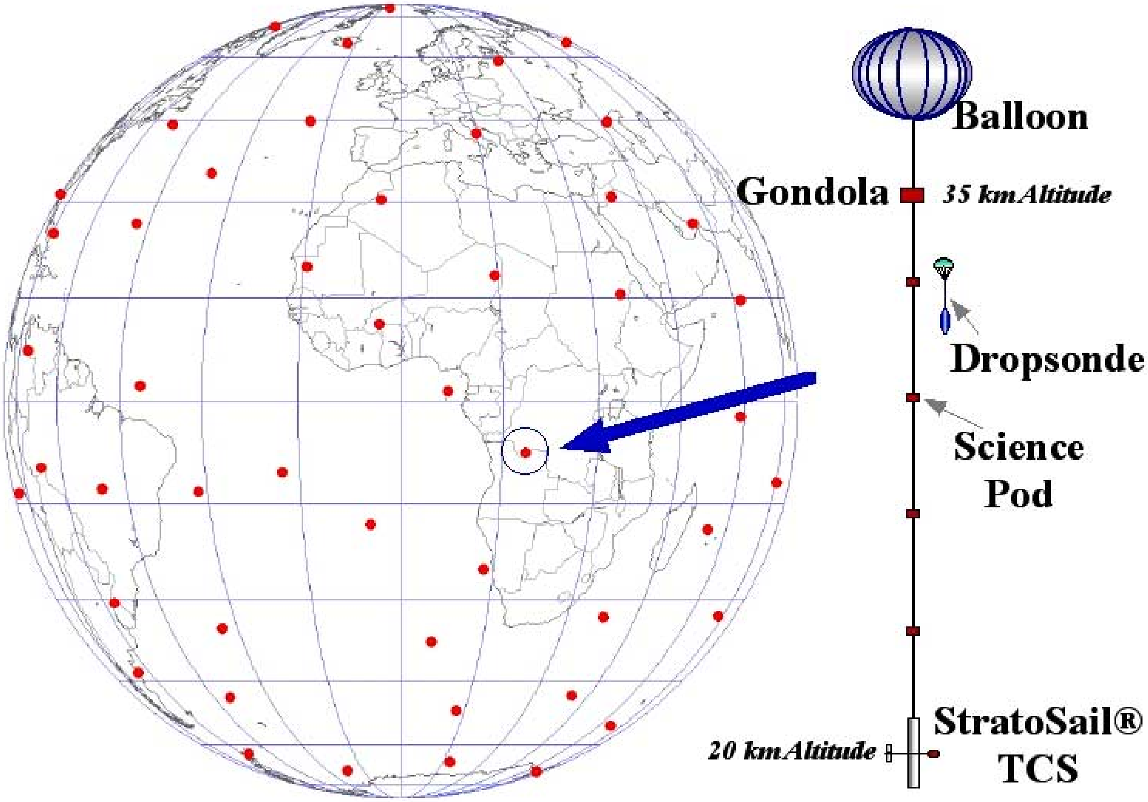


Figure 1-1. Global Constellation of Stratospheric Scientific Platforms

This concept provides an expanded, but complementary, role for a new generation of stratospheric platforms. As with satellites, these platforms will be global in nature and essentially orbit the Earth. However, StratoSat™ systems will fly much lower and slower than satellites, enabling *in situ* measurements not possible from satellites and improving surface and atmospheric remote sensing performance. Such a system provides a wide range of potential benefits including new opportunities for Earth science, global communications, worldwide defense, and monitoring global pollution.

### 1.1.1. Keys to the Concept

The technical and programmatic keys to this new concept are achievable constellation geometry management, significant and cost effective scientific applications, eventual international agreements on overflight, affordable, long-duration balloon systems, balloon trajectory control capability, and a global communications infrastructure.

### 1.1.2. Significance to NASA

The scope of the NASA's *Earth Science Mission* is to develop revolutionary, cost-effective means to enable entirely new investigations that expand our ability to understand the Earth system and the effects of natural and human-induced changes on the global environment. As a revolutionary concept, a global constellation of stratospheric science platforms is expected to create new observational opportunities that will likely cross the traditional bureaucratic boundaries.

A key objective of this mission of NASA is the expansion of scientific knowledge of the Earth system using NASA's unique capabilities from the vantage points of space, aircraft, and *in situ* platforms. NASA has indicated that some observations required for Earth System Science are best made from *in situ* platforms, such as aircraft, balloons, and ground-based instruments. *In situ* observations may be used to correlate space-based sensors or be preferable for addressing phenomena on a local-to-regional-to-global scale.

Derived goals of the NASA's Earth Science Mission that can be addressed from the vantage point of a global constellation of stratospheric scientific platforms include:

- predicting seasonal-to-interannual climate variations,
- identifying natural hazards, processes, and mitigation strategies,
- detecting long-term climate changes, causes, and impacts, and
- understanding the causes of variation in atmospheric ozone concentration and distribution.

In addition to the benefit of creating new observational opportunities, StratoSat™ balloon constellations can have cost and performance benefits to NASA.

## 1.2. A Changing Paradigm

In the satellite era, there has been a shift away from making conventional *in situ* measurements of the global environment to remote sensing from Earth orbiting spacecraft. The reasons for this shift have been global accessibility afforded by satellites; high cost of conventional *in situ* measurement operations, due to workforce (particularly in remote areas) and hardware cost issues; and appropriate national priorities that emphasize the application of high technology space systems as the solution to global science measurements. After forty years, there may be some reason to challenge this remote sensing paradigm with a new *in situ* strategy. In combination, (a) the advance of electronics, communications and balloon technologies, (b) the inherent difficulty of making some remote measurements from satellites, and (c) the interest in simultaneous global measurements, argue for a reevaluation of the current reliance on satellites for many global environmental measurements.

### 1.2.1. Current Earth Observation Vantage Points

Today the Earth is observed from a number of vantage points besides the ground; polar orbiting and geosynchronous Earth orbit (GEO) satellites; research aircraft; balloon-borne radiosondes and their counterparts, aircraft-released dropsondes; and short-duration, high-altitude research balloons. In the sections below we discuss each of the current observation vantage points. In later sections we discuss the advantages of a global constellations of stratospheric platforms.

### *1.2.1.1. Satellites*

Generally, satellites that observe the Earth are in polar, moderate inclination or geosynchronous orbits. Satellites in polar orbits have wide access to latitudes. Such satellites are sometimes in Sun synchronous, polar orbits that provide nearly constant solar illumination, i.e. constant time of day, coverage of the nadir for imaging and spectral instruments. Sometimes a Sun synchronous orbit is selected to optimize the solar illumination throughout the orbit in order to maximize power for instruments like high-power radars. A typical Sun synchronous satellite, such as NASA's SeaWiFS satellite, is at an inclination of about 98°, an altitude of 700 km and descending equator crossings at about 12 Noon. At this orbital altitude the speed is about 7.5 km/s across the surface with a nadir angular rate of 10.7 mrad/s. The high inclination and altitude of these satellites have three adverse implications to satellite remote sensing. In combination, the high inclination and altitude increase natural Earth particle radiation exposure, caused by the Earth's Van Allen radiation belts, to sensitive instruments and sensors. In addition, high altitude orbits increase the requirements on instruments related to surface or limb scanning resolution, which tend to increase the size, mass and complexity of such experiments. Finally, because launch vehicles cannot take advantage of the rotation of the Earth and because they must reach higher altitudes and thus higher energy orbits, the payload mass placed into polar orbits is generally somewhat less than can be placed into lower inclination and altitude orbits.

Several Earth observing satellites have been placed in moderate inclination orbits (28-55° latitude) where they can observe much of the landmass of the Earth or focus on the tropics such as the Tropical Rainfall Measuring Mission (TRMM) at 35° inclination and 350-km altitude. These satellites are usually placed in as low an altitude orbit as possible consistent with orbit decay due to atmospheric drag.

Satellites in geosynchronous orbits have a period of their orbit equal to the period of rotation of the Earth about its axis, about 24 hours. Such orbits are at an altitude of about 35,860 km. As is the usual case these satellites are not inclined to the equatorial plane of the Earth. Observations of the Earth from GEO satellites have typically been restricted to low resolution visible and IR imaging for meteorology purposes. Because these satellites remain stationary above a particular longitude at the equator, they can only observe one third of the Earth at a time. Except for the subsatellite point, the view of any other area on the surface of Earth is at an angle from the vertical. In fact, because of the curvature of the Earth, the limb is 81.3 degrees from the subsatellite point. This means that no latitude beyond 81.3 degrees can be seen with low emission angle (near nadir viewing) from GEO, hence the poles of the Earth are never visible from these orbits. Practically speaking, GEO satellites cannot make useful observations above about 70 degrees latitude because of the oblique viewing conditions. Furthermore, continuous coverage at the equator requires at least 3 satellites evenly spaced around the globe. Satellites in GEO are limited to relatively low-resolution Earth observations either of the surface or of the limbs due to the high altitude. GEO altitude is about 50-times higher than the SeaWiFS's Sun synchronous orbit. High-resolution coverage from GEO is only possible by means of Hubble-class telescopes, which are heavy, expensive and complex. In addition, several satellites are required if relatively low viewing angles are required. Furthermore, such satellites would require large, expensive launch vehicles to be placed into orbit. More distant satellite orbits have been explored, however their practicality is limited by target resolution and coverage issues.

Because of the large investment in simply getting to space, space program managers invest a lot of effort into insuring their spacecraft and instruments will work as required. In general the cost of spacecraft engineering and scientific hardware is very expensive due to the reliability and space environmental requirements. Once in orbit, there are few, if any, opportunities for recalibration or repair: the systems must work properly the first time.

### *1.2.1.2. NASA's Operational High-Altitude Aircraft*

NASA maintains a variety of aircraft and sensor systems dedicated to the support of remote and *in situ* sensing research. For high-altitude research NASA uses two Lockheed ER-2s (S-model U-2) and a WB-57, a high altitude version of the B-57 attack bomber. In addition to the NASA aircraft, the military operates piloted aircraft that fly in the stratosphere. And, commercial ventures are developing piloted aircraft as potential communications platforms. These vehicles operate for relatively short duration (1-12 hours). Atmospheric, land, and ocean processes observations are made by these aircraft for the NASA Earth Science program, as well as for universities and other government agencies.

These aircraft are used as test-beds for advanced sensor design and satellite simulation, as well as to support scientific and operational data collection campaigns. Numerous sensor systems are in use and under development by NASA and other agencies, including atmospheric chemistry experiments, multispectral imaging devices, radar systems, and mapping cameras.

Because these aircraft are manned, the operations cost are relatively high as compared to unmanned systems due to the high level of expertise required of personnel and the high level of safety required to protect pilots.

#### 1.2.1.2.1. NASA's ER-2

NASA operates the ER-2s as readily deployable high-altitude sensor platforms to collect remote sensing and *in situ* data on earth resources, atmospheric chemistry and dynamics, and oceanic processes. In addition, the aircraft also are used for electronic sensor research and development, satellite calibration and satellite data validation.

Typical missions and campaigns performed by the ER-2 include aerial photography, atmospheric experiments, global radiation budget and climate change research, satellite sensor systems development and disaster assessment. High-resolution aerial photography is collected during earth imagery acquisition missions. Multispectral scanner data and photography acquired coincidentally on ER-2 missions provide unique data sets for earth science research. The ER-2 has participated in several major aircraft campaigns to study the decrease in ozone over the Antarctic and Arctic regions. In 1987 an ER-2 was deployed to Chile to conduct flights over the Antarctic. Results from these missions provided the first data implicating man-made chemical compounds, specifically chloroflourocarbons, in the ozone loss over the Antarctic region. Other atmospheric experiments on the ER-2 have been designed to promote the development of improved cloud and radiation parameters for use in climate models. These experiments coordinated satellite, airborne and surface observations to investigate the radiative properties and physical processes of clouds affecting global temperatures. Collecting data with prototype instruments provides scientists the opportunity to develop methodology and algorithms for application to data sets collected with future orbiting systems.

The ER-2 operates at a nominal 20-km altitude. At this altitude the aircraft provides a stable platform for earth imagery acquisition, atmospheric research and electronic sensor development. The aircraft provides an effective horizon of 480 km at altitudes of 20 km. The ER-2 has a range beyond 4800 km; is capable of an 8-hour flight; cruises at 210 m/s; and can operate at altitudes up to 21.3 km if required. Up to 1230 kg of scientific instruments flown aboard the ER-2 can be mounted in various payload areas. On a single flight, the ER-2 can carry over one ton of instruments to altitudes above 19,800 m.

#### 1.2.1.2.2. NASA’s WB-57

The WB-57 is a high altitude version of the B-57 attack bomber built by the Air Force to augment the U–2. Originally built as a high-altitude espionage aircraft for the U.S. Air Force, the WB–57F was designed to carry into the stratosphere photo-reconnaissance and nuclear-sampling payloads too large for the well-known but smaller U-2 spy plane. The WB-57F can perform experiments between 12 and 18 kilometers; has a service ceiling in excess of 22,860 m; cruises at 216 m/s and has a range of 6290 km.

#### 1.2.1.2.3. Proteus

Proteus is the newest manned aircraft to be designed for high altitude, long duration flight. Designed by Burt Rutan, president of Scaled Composites, it incorporates advanced materials and a tandem wing, twin-boom airframe to achieve fuel-efficient station keeping abilities. It is powered by two Williams International FJ44-2E turbofan engines, and it is intended both for piloted and UAV operation. One of its principal missions will be to serve as a telecommunications relay platform and it can be reconfigured for a variety of other purposes, including atmospheric research, reconnaissance/surveillance, ground imaging, and small satellite launch. Still under development, Proteus is designed to cruise at altitudes of more than 20 km for up to 14 hours with a payload in the 900 kg range.

In October 2000 Proteus achieved several altitude records, including sustained horizontal flight of 18,872 m and peak altitude of 17,031 m with a 1000 kg payload. In March 2001 it completed a 36-day science deployment to the Pacific and the North Pole. This mission was considered a success, and it included 125 hours of flying, scientific measurements at altitudes of 16.8 km, and flight duration of up to 11.6 hours. The science payloads were atmospheric sounding instruments employing infrared interferometry and microwave emissions, and these flew in support of the NASA/NOAA/DOD Integrated Program Office (NPOESS) that is developing next-generation Earth observation satellites. Along with the scientific data, the Proteus gathered valuable information about over-the-horizon communications for future unmanned science aircraft under the sponsorship of the Environmental Research Aircraft and Sensor Technology (ERAST) program, led by NASA Dryden Flight Research Center.

#### 1.2.1.2.4. Future UAVs

Unmanned air vehicles (UAVs), because they are not burdened with either a pilot or the resulting highly-redundant (and heavy) safety and support systems, have the potential to fly higher and longer than piloted aircraft. Also, because a pilot's life is not at stake, UAVs can be safely used for missions that would be considered risky for piloted aircraft, such as monitoring of ozone levels over Antarctica (where ejection holds little promise for lengthening survival time). Under programs such as NASA's Environmental Research Aircraft and Sensor Technology (ERAST) program, high altitude, long endurance (HALE) UAVs are being developed as observation platforms for Earth science and meteorological measurements. ERAST includes solar powered aircraft such as Aerovironment's Helios, which has flown above 96,000 feet (the record for non-rocket powered aircraft), as well as consumable fuel aircraft like Predator. NASA Unmanned Aircraft Vehicle (UAV) research continues to pursue long-duration, high–altitude flight goals that enable important Earth science observations. However, at the current time, the realities of UAV performance have yet to meet their promise for Earth science observations. Even if this vehicle class meets its goals, there will still be the issues of high overall cost of operations (life-cycle) and limited payload capability at high altitude.

### *1.2.1.3. Radiosondes and dropsondes*

The role of radiosondes, small balloons carrying operational instruments that take data on ascent until the balloons burst, is important to Earth science measurements, and their use is wide-spread, especially for meteorology. Radiosondes, and their counter part, dropsondes, which are released from aircraft at high altitude, now carry a variety of *in situ* instruments that go beyond the traditional weather balloon measurements of temperature, pressure and humidity. Radiosonde instrumentation can include ozone and other trace gas sensors plus Global Positioning System (GPS) receivers to make precise wind profile measurements. The two key elements that currently limit global radiosonde and dropsonde usage for Earth science and meteorology are the high cost of such measurements in remote areas and the difficulty to achieve very high altitudes, e.g. 20-35 km. Radiosonde measurements can be made to 30 km altitude, however, these are limited due to the cost of the larger balloons required and the handling and launching difficulties, especially in adverse weather conditions.

### *1.2.1.4. Balloons*

Scientific ballooning has played, and will continue to play a significant role in atmospheric science research. Scientific balloons carry research instruments that take data on ascent, float and descent and weigh hundreds to thousands of kilograms. Instruments on these large conventional balloons provided most of the stratospheric data until the advent of space-based instrumentation. They continue to provide calibration and validation data for satellite data sets, as well as high-resolution measurements not achievable by satellite measurements.

#### 1.2.1.4.1. Conventional Zero Pressure Balloons

Zero pressure or so-called open balloons are by far the most common large scientific balloons flown. They consist of very lightweight, fixed-volume envelopes often made from thin polyethylene plastic and usually filled with helium gas for buoyancy. Buoyant gas venting and ballast dropping control altitude, hence their lifetime is limited especially when they thus undergo diurnal cycles which alternately heat and cool the gas, changing buoyancy. Such balloon missions flown at low latitudes (in diurnal conditions) typically last 2-3 days at the most. When these same basic balloons (with smaller payloads and more ballast) are flown at the poles in constant daylight during polar summer, they are called Long-duration Balloons (LDB), and then they can have flight durations of up to 30 days.

For scientists, typical scientific ballooning involves spending a year or more preparing a payload, and 3 weeks at a launch site becoming flight ready and waiting for calm weather enabling a launch opportunity and perhaps a 1-15 day flight. Also, landing often results in damage to the payload. All these together can make conventional scientific ballooning a frustrating operation.

#### 1.2.1.4.2. Future Balloons

NASA is currently developing a new superpressure balloon called Ultra Long Duration Balloon (ULDB). It is a fixed volume balloon with one important difference; the envelope is strong enough to prevent bursting when the balloon reaches its volumetric capacity. Upon reaching this point the pressure inside the balloon envelope is slightly higher than outside and the envelope becomes highly stressed. A ULDB system will rise until the balloon is completely filled where it will then stop ascending, as the envelope is superpressurized. Superpressure balloons fly at a nearly constant altitude where the average density of the floating system equals the density of the air. The ULDB class of stratospheric platforms will provide a major leap forward in return on investment of scientific time and money.

### 1.2.2. Potential Contributions of Stratospheric Constellations

Stratospheric balloon platforms have and will continue to contribute to Earth science research by providing complementary *in situ* and remote sensing measurements to satellites. Because they operate above 99% of the Earth's atmosphere, essentially in a "space" environment, stratospheric balloon platforms are excellent testbeds for new satellite instruments and sensors. In addition, they can complement satellite measurements by providing "ground truth" in regions of the atmosphere of interest to satellite experimenters.

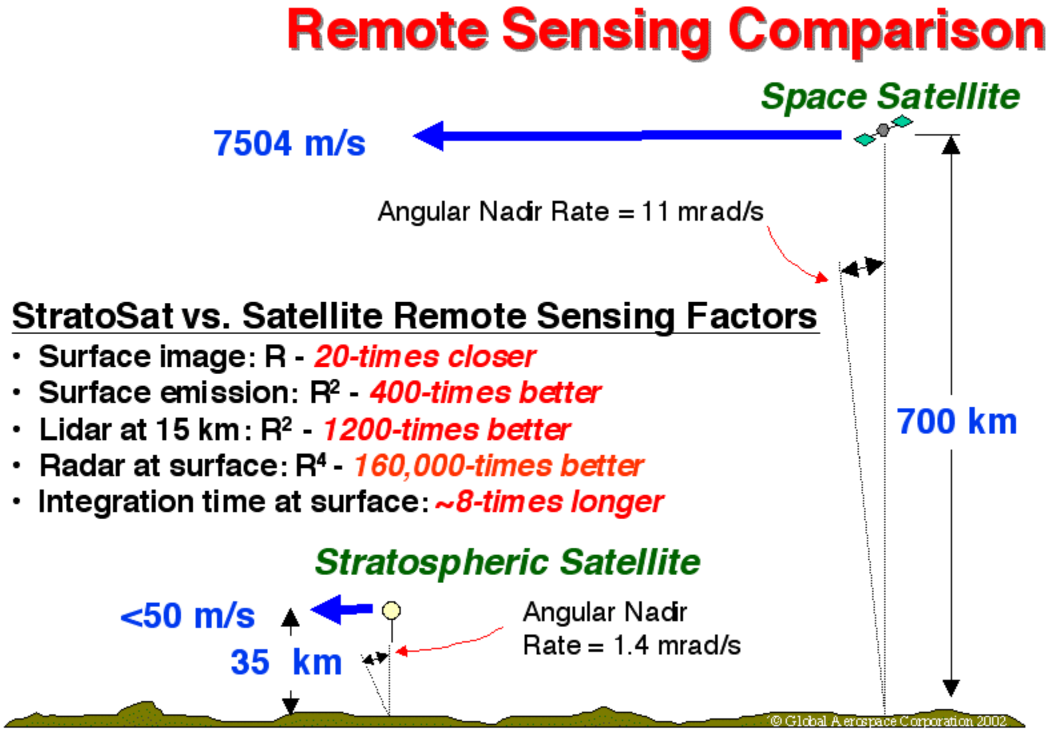
We are proposing an expanded, but complementary role for a new generation of stratospheric platforms based on advanced ULDB technology, called the StratoSat™ System. As with satellites, these platforms will be global in nature and essentially orbit the Earth. As with balloons, StratoSat™ platforms will fly much lower and slower than satellites, which enable *in situ* measurements not possible from satellites, and improves surface and atmospheric remote sensing performance. The following list is an example of Earth science missions for global and regional constellations of stratospheric platforms that address major Earth science issues. Several of these examples are discussed in more detail in Section 3.

A. Global Change Studies
  1. Global Earth Radiation Balance
  2. Monitoring Stratospheric Water
  3. Surface Carbon Sources and Sinks
B. Geomagnetism
  1. Nature of Middle and Lower Crust
  2. Magnetic Signatures of Natural Hazards – Faults
C. Ozone Studies
  1. Mid-latitude Ozone Monitoring
  2. Polar Ozone Loss
D. Weather and Adaptive Sampling
  1. Hurricane Forecasting and Tracking
  2. Tropospheric Winds
  3. Forecasting Weather from Ocean Basins & Remote Areas
E. Hazard Detection and Monitoring

### 1.2.3. Cost and Performance Benefits of Global Balloon Networks

Satellites are expensive because the cost of getting into space is high. This high cost translates into higher reliability due to the high investment in deploying satellites. If a rocket launch costs $50M (rough cost of a Delta II vehicle), the satellite launched will be at least as costly in order to insure that the launch investment is not squandered by premature failures, immature sensors or badly designed spacecraft hardware. While launch vehicles have been getting smaller in order to reduce the per launch costs, the cost per–kilogram-launched has soared for these so-call low-cost launchers. If a network of StratoSat™ platforms could meet or exceed the requirements of a satellite-based Earth observing system for lower cost, this would be an attractive Earth science option. If a StratoSat cost were to be as little as $500k each, a 100 platform constellation would only cost as much as a single Delta II launch to low Earth orbit, not counting the satellite on top. In addition, there is every reason to believe that StratoSat costs will be well below $500k per platform in quantities of 100 or more (See Section 8 of the Phase I Final Report for cost details).

Besides the potential cost benefits of complementary global stratospheric platforms, there are observations that are superior from the StratoSat™ platform vantage point just above most of the atmosphere. The value of active remote sensing measurements (e.g. LIDAR) of rare species in the atmosphere is a function of the r-squared law of the diminution of signal. Assuming the same signal strength at a 15-km altitude atmospheric target, a StratoSat platform at 35-km altitude will see about a 1200-times higher returned signal as would a satellite observing from a 700 km orbit. This improvement in SNR can be used by making the telescope aperture an order of magnitude smaller and/or by reducing the power by an order of magnitude. Furthermore, the integration time is longer from a slowly moving stratospheric platform. One can begin to see that StratoSat constellations are an attractive complement to satellite Earth observation systems. Figure 1-2 illustrates some of the advantages of StratoSat systems as compared to satellites.



**StratoSat vs. Satellite Remote Sensing Factors**

- Surface image: R - *20-times closer*
- Surface emission: $R^2$ - *400-times better*
- Lidar at 15 km: $R^2$ - *1200-times better*
- Radar at surface: $R^4$ - *160,000-times better*
- Integration time at surface: *~8-times longer*

Figure 1-2. StratoSat and Satellite Remote Sensing Comparison

## 1.3. Bringing the World Closer

Because airborne products of industry and transportation diffuse beyond political boundaries, pollution is no longer a regional problem but a world problem. As a world problem, the mitigation of pollution will demand global political solutions. Future global solutions to pollution will require global monitoring and controls in a similar fashion, but on a larger scale, as the U.S. Environmental Protection Agency (EPA) does for this nation. Products of pollution are very difficult to detect from space, especially with sufficient accuracy and spatial resolution, at the present time and for the foreseeable future. A potential role for global stratospheric platforms is the global measurement and monitoring of worldwide pollution and other environmental problems. In addition, StratoSats could be an important component of a monitoring system that will complement satellite instruments currently planned for launched within the next 5 years.

The development of stratospheric constellations will enable new science and Earth observation techniques that themselves will lead to a better world. Global constellations can help to better understand Global Change, the extent to which mankind can influence this change, and what to do about such change. In addition, better forecasting of weather phenomena, especially hurricanes, brought on by improved global circulation models and improved *in situ* data in remote areas as a result of the use of Global Constellations, will help to limit future catastrophic damage and injury because earlier, more accurate predictions will be available.

## 1.4. NASA's Earth Science Enterprise Mission

The mission of NASA's Earth Science Enterprise (ESE) is to develop an understanding of the Earth system and of the changes that are taking place in the system to predict the changes in climate, weather and occurrences of natural hazards. In short, the ESE mission is to answer the following question:

This major question can be subdivided into five more detailed questions:

- How is the Global Earth System Changing?
- What are the Primary causes of the Earth System Variability?
- How does the Earth system respond to natural and human-induced changes?
- What are the consequences of change in the Earth system for human civilization?
- How well can we predict future changes in the Earth system?

Based on the global nature of these questions, it is correctly argued that to study these issues, requires understanding of how the earth works as a system. Some argue that only satellites can provide systematic and continuous monitoring of the earth's atmosphere for a minimum of 15 years to be able to distinguish between anthropogenic and natural changes. However, alternate points of view on this matter exist. The question of the appropriate platform for making these measurements needs to be raised as the long-term strategy begins to be developed. The optimum approach will likely strike a balance between space-based monitoring and *in situ* platforms.

Indeed, according to the ESE Research Strategy:

*"The hallmark of NASA's Earth science program is the synergy between different classes of observations, basic research, modeling, and data analysis, as well as field and laboratory studies. In particular, when engaging in pioneering research about complex scientific issues, the ESE recognizes the need for complementary remote sensing and in situ measurements (p. 24)… NASA's earth science research program … has a robust sub-orbital component, which is focused on improving our understanding of processes needed to understand, interpret, and model remotely sensed observations, as well as to contribute to the calibration and validation of the space-based observations. Innovative combinations of observing instruments and platforms are used in this component of the program. (p. 22). (NASA 2000, Understanding Earth System Change: Earth Science Enterprise Research Strategy for 2000-2010)"*

It is not yet clear how the proper balance is to be determined. For example, satellites monitoring global, ozone mixing ratios, both total column and as a function of altitude, were not the first instruments to identify the existence of an Antarctic ozone hole. The hole was first identified using *in situ* ozone sonde data [Farman and Gardiner, 1987]. After two years of scientific postulating as to the many possible causes of the ozone hole, simultaneous *in situ* ozone and chlorine monoxide measurements on an ER-2 NASA research aircraft, which flew into the hole, provided unambiguous evidence that chlorine, with an increasing anthropogenic source, was catalytically destroying ozone [Anderson *et al.*, 1989]. It is only with this level of scientific analysis that governments can effect policy on a national and worldwide basis to reverse deleterious environmental trends.

## 1.5. Current Relevant Technology and Activities

There are a number of relevant technologies and other activities relating to stratospheric balloon constellations. Some of the more important technologies include the NASA ULDB efforts to develop improved and lighter weight gas envelopes, trajectory simulation and prediction models, and balloon trajectory control systems. Another technology is stratospheric constellation geometry maintenance. In addition, considerable effort is underway in the development of very lightweight, high-energy power systems, which are important for providing power to stratospheric platforms. The National Oceanic and Atmospheric Administration (NOAA) is developing concepts for global balloon-borne weather data collection. In the following sections we review these technologies and activities and identify the aspects that will benefit global stratospheric platforms.

### 1.5.1. ULDB Vehicle

The Ultra Long Duration Balloon (ULDB) Project, managed by the NASA Balloon Projects Office at NASA/GSFC Wallops Flight Facility (WFF), is planning the first ULDB demonstration flight to occur in December 2002/January 2003. The goal of the ULDB program is to fly up to 2000 kg science payloads above >99% of the Earth’s atmosphere for at least 100 days in diurnal conditions, a factor of ~30 times longer than current balloon flights. The ULDB vehicle includes a sophisticated gondola that is integrated with the science payload. This integrated system is referred to as the Ballooncraft.

Recent advances in superpressure balloon designs significantly reduce the required balloon envelope materials strength. One innovative design is called the Euler Elastica or "pumpkin" balloon, which is shaped like an oblate spheroid. A pumpkin-shaped, superpressure balloon has been selected for NASA’s Ultra Long Duration Balloon (ULDB) Project. ULDB balloon systems are designed to carry ~2700-kg suspended masses (including ~2000 kg of science instruments) to 34-km float altitudes. A pumpkin balloon is constructed of several sector-shaped lobed gores. The radius of the lobes is about 1.4 m. This new design, by reducing the radius of curvature of the material, reduces the stress that results from pressurization in the longitudinal direction. In the latitudinal direction, load tendons, made from a super strong fiber (Zylon) , carry the stress instead of the envelope film. The stress on the envelope material for a pumpkin balloon can be reduced by as much a factor of 9 over a spherical balloon stress assuming the same general size, payload and areal density of the film. This means the superpressure balloon envelopes can be fabricated from much lighter materials, which can result in smaller, lighter, less expensive balloons, flying at higher altitudes. Figure 1-3 is a picture from an early test that illustrates the typical pumpkin envelope shape.

Figure 1-3. ULDB Envelope Test Showing Its Characteristic Shape

Under a NASA contract, Raven Industries has developed seaming methods and procedures for the fabrication of ULDB balloon envelopes. These envelopes have been used to develop design concepts and prototype balloons for testing. In support of the ULDB Project, Raven has developed a flexible fabrication process that can accommodate a variety of seaming methods and gore shapes. Systems have been developed that will cut highly accurate gore shapes of practically infinite length. The work leading up to these developments has included the fabrication and burst testing of 3-meter test spheres. The test results indicate that shape, not seam or material strength, is currently the most important consideration for UDLB envelope design.

Assuming high quality fabrication, lifetimes for these balloons are expected to be months to years. Buoyant gas diffusion at the differential pressures and low temperatures found at stratospheric float conditions is estimated to be extremely small. Most gas loss is expected from manufacturing defects. Extrapolations from past experience indicate potential lifetimes in excess of three years without buoyant gas make-up assuming the UV degradation issues can be solved.

The ULDB test program has flown two sub-scale and three full-scale flight tests. The first sub-scale model test resulted in a qualified success due to envelope failure primarily caused by the use of a non-optimal envelope material. The second sub-scale model test (~70,000 $m^3$), used a new polyethylene (PE) film optimized for the pumpkin design. This second flight was a resounding success and flew more than 30 hours experiencing a complete diurnal cycle as planned. Two full-scale flight tests were attempted in Spring 2001 from Alice Springs, Australia but were of limited success due to envelope material and design issues. A subsequent flight test occurred in July 2002 but even though the balloon successfully reached float altitude, the balloon failed due to manufacturing problems that allowed load tendon terminations to become unfastened thus prematurely ending the flight. Current plans call for another full-scale flight test to occur in the December 2002/January 2003 timeframe again from Alice Springs, Australia. This flight test is a prelude to a major space science flight currently scheduled for late 2003.

The current ULDB balloon envelope material (~37 g/m$^2$) though lightweight is still too heavy for the type of balloon envisaged for the global stratospheric balloon concept. Key desirable characteristics of envelope materials for a network of balloons include low modulus of elasticity, higher modulus stiffeners, lighter weight, commercial fabrication technology and UV environment capable.

### 1.5.2. Balloon Trajectory Control System

Global Aerospace has been developing a StratoSail® balloon trajectory control system (TCS) under internal and NASA Small Business Innovative Research (SBIR) funding (Phase I and Phase II). The primary application of the TCS is future ULDB flights. In March of 2002 GAC delivered a mechanical prototype TCS wing assembly system to NASA along with two 15-km long tethers and a winch-down testbed. A StratoSail® TCS has the potential of improving science return, reducing launch and landing operations uncertainty, increasing the probability of payload recovery and avoiding undesirable geopolitical overflight. Figure 1-4 illustrates a view of the TCS in operation. The StratoSail® TCS exploits the difference in wind directions and velocities with altitude in order to passively and continuously generate lateral control forces on a balloon using a tether-deployed aerodynamic surface, a wing or sail, located well below the balloon. The wing generates a lift force that can be controlled to nudge the balloon system in the desired direction. In the case of ULDB missions, the StratoSail® TCS is located 15 kilometers below the balloon at an altitude of 20 km. Because the balloon is surrounded by air that may be ten times thinner than the air at the wing's altitude, the wing can be much smaller than the balloon.

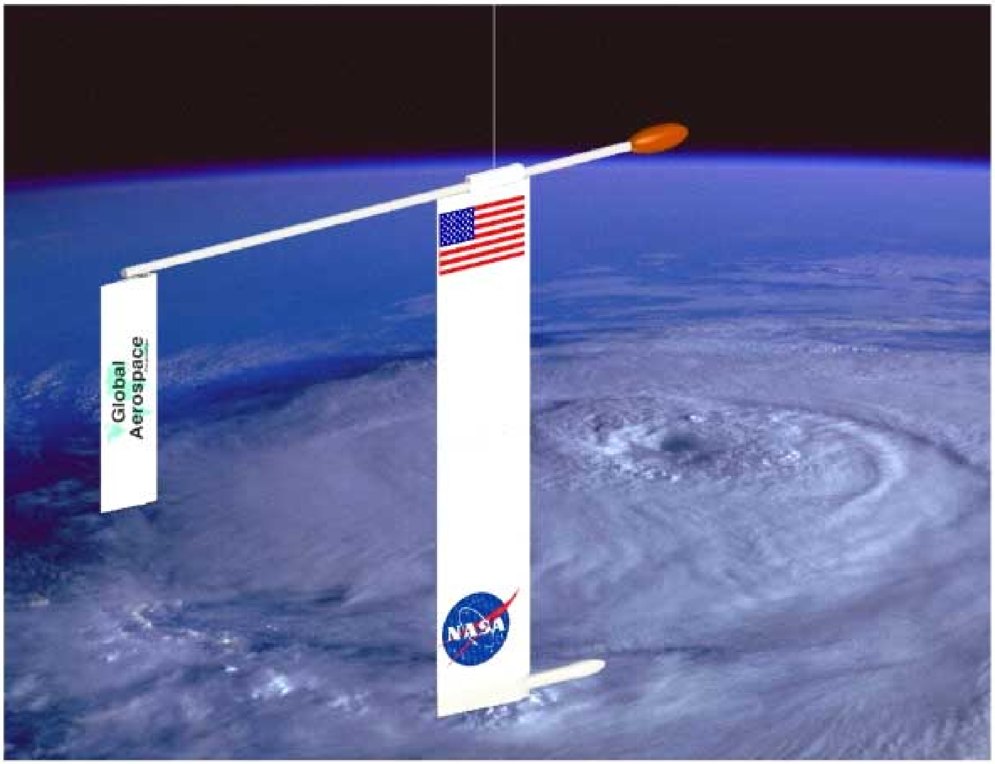


Figure 1-4. StratoSail® Trajectory Control System

Winds at the altitudes of ULDB flights are generally easterly or westerly depending on season and hemisphere, however there is a small, highly variable northward or southward wind drift which can disperse balloons all over the Earth during some seasons. The StratoSail® TCS can be used to offset unwanted drift across the desired flight path. This control strategy requires only a very modest amount of sideways control force. By controlling the latitude of the balloon as it drifts around the world, it is possible to return to the launch site, significantly enhancing the probability of recovering and reusing the scientific instrumentation package. Payload recovery can represent a savings of several million dollars for each sophisticated mission. Trajectory simulation *combined* with a means to control the latitude of the balloon trajectory, will become a powerful new tool to enable NASA balloon flight managers to control the balloon flight path rather than being at the mercy of the winds. Under NIAC funding of this concept GAC has developed a concept for an advanced version of the TCS that will be discussed later.

### 1.5.3. Power Systems

There are several power system options for both generation and energy storage. For a near-term StratoSat™ platform, fixed conventional solar arrays could provide up to about 600 W of power during the day. If increased power is required, 2 kW or more can be supplied from an innovative, modular solar array GAC is developing also under Phase II NASA SBIR funding (~$600k). See http://www.gaerospace.com/projects/Modular_Solar/lightweight_modularSolar.html for a more complete description of this work. The HighPower™ solar array uses gravity to deploy several solar array panels downward from the gondola and employs a GAC patented invention that orients the solar array panels to track the Sun without need for array rotation.

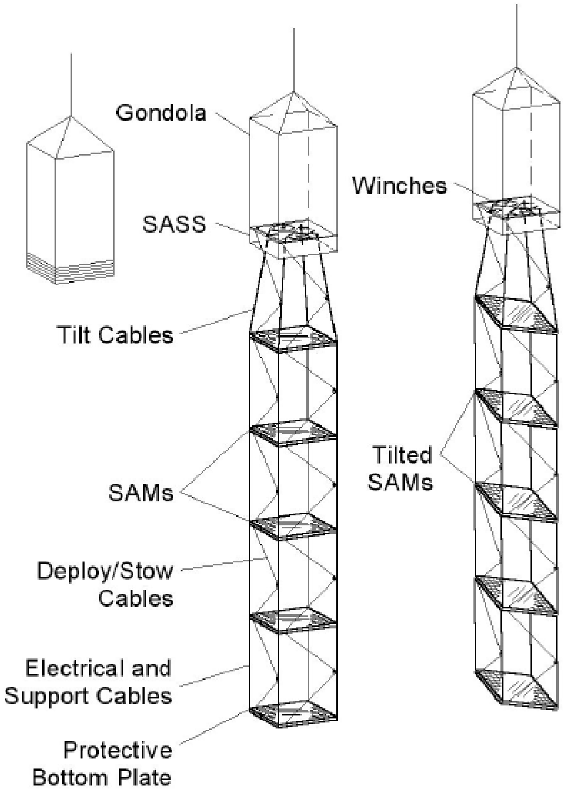


Figure 1-5. HighPower™ solar array design

GAC has also developed, under this NIAC effort, concepts for dual function envelopes that could also function as solar array structure potentially enabling 5-50 kW power levels during the daytime.

Energy storage can be supplied in the near-term by the use of NiMH or lithium-ion polymer batteries that can supply power needs during the night. For very high energy density, NASA has considerable development underway in the area of regenerative fuel cells (RFC) using a water, hydrogen and oxygen cycle. An RFC energy storage system would be preferable due to its high energy density and low mass. These advanced RFCs could provide highly efficient and lightweight energy storage for balloon platforms as well.

### 1.5.4. Trajectory Modeling, Simulation, and Prediction

A key element in the development of the ULDB technology is the ability to simulate and predict the trajectory of the stratospheric balloons both before and during flight. The need for a better trajectory simulation and prediction capability is driven by the long ULDB missions that, by their nature, will have overflight concerns and expensive payloads. Overflight issues will involve international discussions and agreements and require definitive data on balloon path predictability. (There are concerns that some countries may not offer permission to enter their airspace.) In addition, 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. Also, safety issues associated with overflight of populated areas are a concern. High-accuracy, in-flight trajectory simulation capabilities will assist NASA in each of these areas: overflight issues, payload recovery operations, and safety issues.

GAC has supported NASA's balloon program by developing a ULDB Trajectory Simulation and Prediction System (TSPS) WorkStation, the first version of which was delivered to NASA in early 2000. The TSPS is a collection of computer system hardware, computer system software, and integrated balloon-environment trajectory simulation software. The TSPS combines a model of balloon behavior with real-time and historical stratospheric environment data to simulate the trajectory of balloons. Trajectories are displayed on the computer screen on maps, graphs, or in textual data windows. GAC is continuing to develop the TSPS capability using IR&D funding by integrating a vertical balloon performance model into the horizontal simulation.

See http://www.gaerospace.com/projects/ULBDTrajectory/ULDB_traj_sim.html.

### 1.5.5. Stratospheric Constellation Management and *Virtual Stationkeeping*

It would be very convenient to have a free balloon which could remain stationary over a geographic zone (i.e. stationkeeping) in order be able to continuously observe a fixed location. However, balloons at any altitude are subject to the circulation of the atmosphere. Generally, the atmospheric circulation in the stratosphere is zonal in nature; moving from east to west or west to east depending upon season of the year. There is also a highly variable but small component of stratospheric circulation that is meridional in nature, exhibiting a long-term average drift away from the equator toward the poles [Eluszkiewicz, J, et. al., *Residual Circulation in the Stratosphere and Lower Mesosphere as Diagnosed from Microwave Limb Sounder Data*, J. Atmos. Sci. , vol. 53, pp. 217-240, 1996] If a constellation of balloons were to be uniformly spaced over the globe, eventually this average poleward drift would concentrate the balloons in the vicinity of one or the other poles.

Stationkeeping over a solitary point is extremely energy intensive and requires system mass (in the form of propulsion systems) to be carried to constantly fight the winds. The stratospheric constellation concept proposed herein does not fight the predominant zonal flow but instead allows a near-uniform constellation of many balloons to constantly float around the Earth carrying out measurements. The network we are proposing is, in a sense, a virtual stationkeeping balloon platform. When one balloon passes over the horizon and leaves a zone, another enters the zone and replaces it. By continuously nudging a balloon in the latitudinal direction as the balloon repeatedly circles the Earth, the variable meridional and long-term poleward drift can be counteracted, thereby preserving the structure of the constellation. Global Aerospace Corporation is currently developing, under NASA SBIR funding, a system for stratospheric balloon trajectory control [see http://www.gaerospace.com/projects/ULBDStratoSail/ULDB_balloon_trajectory.html]. Such a system, when combined with accurate balloon trajectory simulation and prediction capability, can provide the level of trajectory control required for maintaining a uniform configuration of a balloon constellation.

Another element of constellation management is the near simultaneous control of many hundred balloon trajectories in order to insure a uniform constellation configuration. This requirement is satisfied by near real-time interconnectivity of each balloon with a central constellation control operations facility. Extensive global trajectory simulations would be conducted at this operations center to predict the future behavior of the constellation in the constantly varying stratospheric circulation. Once the predicted behavior of the constellation is known, trajectory control can be applied to each individual balloon. Commands can be sent to each balloon, via a command and control network, to adjust the level of trajectory control in order to maintain constellation configuration.

### 1.5.6. Recovery Systems

Safety of people and property on the ground is a primary requirement of this system concept. A key element of safety is guided payload recovery. IST Aerospace developed the ORION™ Navigation Guidance and Control System (NGCS) for NASA's X-38 program and the French space agency's (CNES) balloon program. The ORION™ system is a version of the Guided Parafoil Airborne Delivery System (GPADS), being developed for the US Department of Defense. The ORION™ system is used to autonomously fly the parafoil to a landing site that has been loaded into the guidance software, turn into the wind, and flare, thus providing a slow speed, low impact landing on land. The French ORION™ system is capable of delivering 350-700-kg payloads to within 100 m of a pre-designated target. The ORION™ system could deliver the StratoSat™ platform payload to a safe landing site (airfield or unpopulated zone) after termination of the flight. To date NASA and the CNES have carried out several flight tests of the ORION™ system. Figure 1-6 shows ORION™ NGCS in operation guiding NASA's X-38 to a safe landing after deployment from an aircraft. Two other systems have been identified that have been or are under development could be of potential interest.

Figure 1-6. The ORION™ NGCS guiding the X-38 to a safe landing

## 1.6. International Overflight Issues

The issues of international overflight of constellations of balloons should not be minimized. Today, permission to fly scientific research platforms, balloons and aircraft, over some nations is difficult to impossible to receive. The overflight issue can be exacerbated if down-looking imaging equipment is carried and/or if scientists from the overflown country are not involved in the mission. Often, intensive international diplomacy is required to allow overflight. The list of countries that can make it difficult to allow overflight includes the more obvious, Libya, Iraq, etc., but also frequently includes China and countries of the former Soviet Union, and surprisingly has included countries like Sweden and Brazil to name a few. The changing international political climate can heavily influence the authorization of overflight.

It is very clear that for global stratospheric balloon constellations to be possible, international agreements are needed to allow such a concept. At this time there is no established definition of the height at which airspace ends and outer space begins. This ambiguity raises the opportunity for future international agreements to address the peaceful scientific uses of the region between airspace and outer space.

Pathways to international overflight include the exercise of the right to free flight in the stratosphere above controlled airspace, capitalize on World Meteorological Organization (WMO) cooperation, expand existing treaties such at the Treaty on Open Skies, or seek new treaties to facilitate free stratospheric flight of science platforms.

# 2. Concept Development Summary

## 2.1. Summary of Phase II Tasks

Phase II of the Global Constellation of Stratospheric Scientific Platforms Development included the following tasks as originally planned and described.

### 2.1.1. Task 1 Earth Science Applications Development

Working with Earth scientists, new science observations and measurements will be developed and expanded for global stratospheric constellations that connect with and are responsive to the NASA Earth Science Mission.

### 2.1.2. Task 2 Proof-of-Concept Science Mission Definition

Working with the Earth science community, a high priority Earth science application will be selected from which a Proof-of-Concept ULDB flight mission will be defined. Mission definition shall include science and system requirements, example payload description, mass and power requirements, mission cost, and potential schedule.

### 2.1.3. Task 3 Global Constellation Geometry Management Development

Global StratoSat™ balloon constellation geometry control strategies and algorithms will be developed and optimized. This task is subdivided into three subtasks: (a) The application of chaos and weak stability boundary (WSB) theories will be investigated to understand the motion and control of single balloons and networks in the stratosphere, (b) Advanced constellation geometry control algorithms will be developed, and (c) Balloon and advanced TCS models will be combined with environmental models and integrated into constellation simulations and analysis.

### 2.1.4. Task 4 Advanced Balloon Design Model Development

Advanced balloon design concepts and balloon cost estimation algorithms will be incorporated into balloon design models. Performance optimization and parametric study capability will be developed for a variety of balloon design parameters (including fabrication cost) as a function of balloon design options, flight requirements and technologies. *This task was eliminated in the first year.*

### 2.1.5. Task 5 Trajectory Control System Model Development

Dynamic and aerodynamic models of TCS operation will be developed that will facilitate the characterization and optimization of the design. Aerodynamic control strategies will be developed that can support the constellation management task.

### 2.1.6. Task 6 Explore New Multi-function Subsystem Concepts

New concepts for multi-function subsystems will be identified and analyzed, including a concept for fuel cell energy storage and buoyancy control and a concept for power generation utilizing the TCS and wind turbines.

### 2.1.7. Task 7 Constellation Systems Costing

GAC will re-evaluate and extend the Phase I system cost understanding as a function of subsystem technology and/or implementation option. The improved cost model developed for the balloon fabrication cost will be incorporated into the new cost estimates. Costs will be compared to satellite systems for carrying out similar tasks.

### 2.1.8. Task 8 Definition of International Airspace Overflight Issues

Carry out research into current balloon overflight issues, international airspace-related treaty status, models for international cooperation and collaboration (WMO) and the potential for new international agreements that could facilitate and/or enable regional and global stratospheric constellations.

### 2.1.9. Task 9 Planning and Reporting

A more detailed Phase II plan will be developed at project initiation. Monthly status reports, a mid-term report and a final report shall be written. We shall participate in and present status reports at the fall NIAC Fellows Conference in Atlanta, GA and at the NIAC Annual Meeting in Washington, D.C. held in 2000 and 2001. GAC will support a site visit by the NIAC Director at the GAC facilities in Altadena, CA, if deemed appropriate by the NIAC Director. Copies of all briefings, presentations or professional society technical papers pertaining to the Phase II study will be provided to NIAC.

## 2.2. Summary of Work Accomplished

This section provides a concise summary of the work accomplished during the Phase II effort. A more detailed description of the work follows in later sections. The progress made is illustrated by this summary of accomplishments:

April 2000

- Began detailed Phase II planning (Task 9),
- Began development of Earth Science Applications (Task 1) in advance of scheduled activities in this area,
- Conducted subcontract negotiations with Princeton University and related discussions with USRA for a subcontract to develop global constellation geometry management concepts (Task 3), and
- Initiated discussions with Department of State on International Overflight issues (Task 8).

May 2000

- Continued detailed Phase II planning (Task 9),
- Continued development of Earth Science Applications (Task 1) with conversations with Harvard University personnel,
- Continued subcontract negotiations with Princeton University and related discussions with USRA for a subcontract to develop global constellation geometry management concepts (Task 3),
- Held discussions with Department of State on International Overflight issues (Task 8), and
- Prepared presentation materials for the NIAC Annual Meeting, 6–7 June 2000 (Task 9).

June 2000

- Continued subcontract negotiations with Princeton University and related discussions with USRA for a subcontract to develop global constellation geometry management concepts (Task 3),
- Developed a “Range Rate Map” concept to assist global constellation geometry management concept development (Task 3), and
- Continued Phase II reporting at NIAC annual meeting (Task 9).

July 2000

- Continued subcontract negotiations with Princeton University and related discussions with USRA for a subcontract to develop global constellation geometry management concepts (Task 3),
- Attended COSPAR 2000 Panels on Earth Science Observations,
- Refined our “Approach Velocity Map” concept to assist global constellation geometry management concept development (Task 3),
- Continued defining multifunction concepts (Task 6),
- Participated in discussions of international overflight issues at COSPAR in Warsaw, Poland (Task 8), and
- Continued Phase II reporting by presenting a paper at COSPAR (Task 9).

August 2000

- Made additional science community contacts with Dr. Judith Curry (University of Colorado), Dr. Syed Ismail (LaRC), Dr. Ross Salawitch (JPL), and Dr. Barney Farmer (JPL-retired) (Task 1),
- Received and evaluated formal subcontract proposal from Princeton University for a subcontract to develop global constellation geometry management concepts (Task 3),
- Began developing advanced global network simulation capabilities (Task 3),

- Continued defining multifunction concepts by preparing for a test flight of an advanced TCS design (Task 6), and
- Continued research into the historical perspective of and pathways to international overflight of stratospheric balloon platforms (Task 8).

September 2000

- Made additional science community contacts with Dr. Jim Anderson (Harvard University) and Dr. Warren Wiscombe (NASA/GSFC) (Task 1),
- Began development of a representative environment for evaluating global constellation geometry control algorithms (Task 3),
- Evaluated global coverage options from 35 km (Task 3),
- Continued development of test plans for multi-function system testing (Task 6), and
- Continued research into the historical perspective of and pathways to international overflight of stratospheric balloon platforms (Task 8).

October 2000

- Made additional science community contacts with Dr. Jim Anderson (Harvard University) (Task 1) and
- Continued development of a representative environment for evaluating global constellation geometry control algorithms (Task 3),

November 2000

- Made additional science community contacts by holding meetings with Dr. Jim Anderson and members of his research group (Harvard University) (Task 1),
- Held discussions with NASA and Harvard University personnel concerning options for proof-of-concept flights (Task 2),
- Continued development of a representative environment for evaluating global constellation geometry control algorithms (Task 3), and
- Finalized subcontract with Princeton University in support of GAC’s development of constellation control methods (Task 3).

December 2000

- Made additional science and programmatic contacts (LaRC, GSFC and NASA/HQs) (Task 1),
- Preparation for January 2001 meetings with scientists at LaRC and GSFC to discuss options for proof-of-concept missions (Task 2),
- Discussions with Harvard personnel and NIAC about proof-of-concept options through NSF (Task 2),
- Continued development of trajectory management algorithms for zone avoidance (Task 3), and

- Begin planning for NIAC site visit (Task 9).

January 2001

- Made additional science and programmatic contacts with UCAR, Simpson Weather Associates, ARL, LaRC, GSFC, and NASA/HQs) (Task 1),
- Meetings with scientists at LaRC and GSFC to discuss options for proof-of-concept missions (Task 2),
- Received interim report from Princeton University regarding progress on constellation control algorithms for constellation geometry management (Task 3),
- Development of trajectory control algorithms for zone avoidance and target overflight (Task 3),
- Presented a paper at the 2001 AMS meeting (Task 9),
- Prepared presentations for the EOS Investigators Working Group and the Space-based LIDAR Working Group meetings in February 2001 (Task 9), and
- Continued preparation for NIAC site visit (Task 9).

February 2001

- Attended and presented papers on global constellation concept at EOS Investigators Working Group (February 1, 2001) and the Space-based LIDAR Working Group (February 9, 2001) meetings (Task 1),
- Prepared Abstract on Global Constellations for ESA Symposium on Rocket and Balloon Programmes (Task 9), and
- Conducted NIAC Site Visit at Global Aerospace Corporate office in Altadena, CA on February 8 (Task 9).

March 2001

- Continued development of hurricane tracking science objective by identifying hurricane contacts at NOAA (Task 1),
- Obtained quantitative picture of hurricane winds for development of an Advanced Trajectory Control System (ATCS) model (Task 1),
- Held discussions with Dave Emmitt (Simpson Weather Associates) concerning hydrology applications for StratCon (Task 1),
- Began developing radiometer calibration system ideas for a demonstration flight (Task 2),
- Began preparations for a meeting at NASA GSFC relating to a possible NRA proposal for Earth Radiation Budget science mission (Task 2),
- Continued development of constellation simulation capabilities, including multi-threaded code optimized for multi-processor computer systems (Task 3),
- Developed requirements for an ATCS computer model (Task 5),

- Developed a flowchart of ATCS model execution (Task 5),
- Executed the modification to the Phase II contract that exercises the option for the second year of funding (Task 9),
- Proposed an adjustment to plan for the second year of Phase II (Task 9),

April 2001

- Developed a presentation package for a possible Demonstration Earth Radiation Budget Experiment (DERBE) proof-of-concept science flight (Task 2),
- Met NASA scientists and a program manager at GSFC regarding a possible DERBE funding options (Task 2),
- Continued developing radiometer calibration system ideas for a demonstration flight (Task 2),
- Developed a new simulation for a proof-of-concept mission that overflies the Great Plains DOE Atmospheric Radiation Measurement (ARM) site while avoiding several no-fly zones (Task 3),
- Updated our StratCon simulations website to include separate pages and new descriptions for key simulations we have performed on the StratCon activity (Task 3),
- Continued development of constellation simulation capabilities, including new presentation capabilities for viewing “footprints” (Task 3),
- Evaluated population density maps of the world with respect to balloon overflight safety and the need for a multi-function guided parafoil descent system for a proof-of-concept science mission (Task 6),
- Received concurrence for an adjustment to the plan for the second year of Phase II (Task 9), and
- Prepared an “abstract of current work” for the Workshop on Radical Agent Concepts (Task 9).

May 2001

- Prepared material for a meeting concerning hydrology applications for StratCon (Task 1),
- Discussed StratCon concept with George Komar, Manager of the Earth Science Technology Office (ESTO) located at GSFC (Task 2),
- Developed a payload concept for a Demonstration Earth Radiation Budget Experiment (DERBE) balloon mission (Task 2),
- Continued development of hurricane overflight constellation management strategies (Task 3),
- Continued development of advanced presentation and analysis capabilities for constellation management (Task 3),
- Attended ESA Balloon and Rocket Conference and presented a paper on StratCon (Task 9),

- Prepared for NIAC annual meeting at ARC (Task 9), and
- Prepared this monthly report (Task 9).

June 2001

- Prepared a new draft of our Earth Science Rationale and Mission Scenarios document that includes several additional science applications (Task 1),
- Reviewed options for stratospheric systems that follow hurricanes (Task 2),
- Prepared a letter to be sent to Mel Shapiro, head of the THORpex program at NOAA (Task 2),
- Developed analysis software to calculate view zones for stratospheric balloons (Task 3),
- Attended ESA balloon and rocket conference and gave a paper on StratCon (Task 9),
- Received acknowledgement that our WRAC submission was received (Task 9),
- Attended the NIAC annual meeting at ARC (Task 9),
- Prepared this monthly report (Task 9),
- Developing a NASA SBIR proposal for a Radiant Flux Measurement platform (Related Activities), and
- Developing a NASA SBIR proposal for a balloon constellation simulation tool (Related Activities).

July 2001

- Joined the Global Disaster Information Network (GDIN) (Task 1),
- Held discussions with Larry Roeder (U.S. Department of State) regarding GDIN applications for StratCon (Task 1),
- Sent a letter to Mel Shapiro, NOAA, who is a member of the THORPEX international science working group (ISWG), discussing options for meeting THORPEX objectives with StratCon technology (Task 2),
- Discussed StratCon technology with Rolf Langland, Naval Research Laboratory, Monterrey, another member of the THORPEX ISWG (Task 2),
- Prepared material for a possible THORPEX proposal of a StratCon demo (Task 2),
- Developed new simulations for communications applications, including coverage zone calculations (Task 3),
- Prepared a detailed model of an advanced trajectory control system for use in constellation simulations (Task 5),
- Received formal invitation to the GSFC Workshop on Radical Agent Concepts (WRAC) (Task 9),
- Received invitation to present a StratCon paper at the GDIN conference in Rome in June 2002 (Task 9), and

- Submitted two abstracts for papers at the Jan 2002 American Meteorological Society (AMS) meeting (Task 9).

August 2001

- Developed a page for inclusion on the Global Disaster Information Network (GDIN) website (Task 1),
- Began communications with Russian researchers regarding potential use of balloons for magnetic field measurements (Task 1),
- Developed THORpex mission options (Task 2),
- Developed simulations of THORpex mission options (Task 3),
- Developed new simulations for Pacific Ocean weather data collection as THORpex (Task 3),
- Developed additional enhancements for our advanced trajectory control system model (Task 5),
- Wrote a paper for the Workshop on Radical Agent Concepts (WRAC) (Task 9), and
- Prepared material for NIAC Director's meeting with NASA Associate Administrators (Task 9).

September 2001

- Reviewed a draft web page on the StratCon concept to be included in the GDIN website (Task 2),
- Submitted StratCon material for THORpex proposal (Task 2),
- Performed new simulations with application to THORpex objectives using advanced trajectory control techniques (Task 3),
- Continued development of new simulation capabilities for multi-objective simulations (Task 3),
- Continued development of advanced atmospheric feature identification techniques (Task 3),
- Investigated options for advanced safety systems for StratoSat™ systems (Task 6),
- Developed preliminary cost estimates for THORPEX campaign (Task 7), and
- Wrote and submitted 2 papers for American Meteorological Society (AMS) Annual Meeting (Task 9).

October 2001

- Identified a NASA Research Announcement (NRA) that might be an option for Earth Science uses of StratCon concepts (Task 1),
- Finalized the GDIN web page on the StratoSat for disaster monitoring (Task 2),

- Contacted NSF personnel affiliated with THORpex to investigate options for THORpex demonstration missions (Task 2),
- Developed and utilized new software that provides prioritization of objectives for controlling global balloon networks (Task 3),
- Developed and performed initial atmospheric feature identification for vortices on real stratospheric data (Task 3),
- Attended the NIAC Fellows Meeting (Task 9),
- Prepared this monthly report (Task 9), and
- Prepared a proposal for a stratospheric balloon roadmap development activity for ESTO (Related Activities).

November 2001

- Met with GSFC GNC personnel to brief them on activities related to StratCon (Task 2),
- Traveled to Washington, DC to brief NASA Code Y on concept (Task 2?),
- Continued discussions with NSF regarding THORpex follow-on activities (Task 2),
- Outlined detailed approach to implementing atmospheric feature identification in constellation simulations (Task 3),
- Updated GAC website to contain additional simulations (Task 9), and
- Signed a contract for NASA Earth Science Technology Office balloon requirements development activity (Related Activities).

December 2001

- Developed new zone description code for atmospheric feature identification (Task 3).

January 2002

- Developed new “hurricane chaser” simulation (Task 3),
- Presented papers at the American Meteorological Society Annual Meeting (Task 9),
- Presented a paper at the GSFC/JPL Workshop on Radical Agent Concepts (WARC) (Task 9), and
- Hosted an Earth Science Technology Office stratospheric balloon ad-hoc science workshop (Related Activities).

February 2002

- Continued development of THORpex proof-of-concept mission related to THORpex (Task 2) and
- Developed new constellation simulation analysis capabilities and applied them to THORpex objectives (Task 3).

March 2002

- Continued development of THORpex proof-of-concept mission by attending the THORpex meeting (Task 2),
- Continued development of simulation and analysis capabilities (Task 3), and
- Prepare for Global Disaster Information Network (GDIN) Conference in Rome, Italy, June 2002 (Related Activity).

April 2002

- Continued development of simulation and analysis capabilities to support disaster simulations (Task 3) and
- Continued preparation for the Global Disaster Information Network (GDIN) Conference in Rome, Italy, June 2002 (Related Activity).

May 2002

- Continued development of mission concepts for global disaster monitoring applications (Task 2),
- Continued development of simulation and analysis capabilities to support disaster simulations (Task 3) and
- Continued preparation for the Global Disaster Information Network (GDIN) Conference in Rome, Italy, June 2002 (Task 9).

June 2002

- Made contact with NOAA personnel potentially interested in StratCon concepts (Task 1),
- Developed a simulation and statistics for GDIN objectives (Task 3),
- Presented a paper at the GDIN annual meeting in Rome, Italy (Task 9), and
- Participated in the industry working group at the GDIN annual meeting (Task 9).

July 2002

- Developed a very long duration (987 day) simulation of uncontrolled balloons (Task 3),
- GAC published a press release that was published by "Beyond2000.com," and "The Engineer" magazine (Task 9),
- Prepared Impact of StratCon report (Task 9),
- Invitation received and accepted for briefing to NRO September 15, 2002 (Task 9),

August 2002

- Began final report (Task 9), and
- Began preparations of briefing to NRO September 25, 2002 (Task 9).

September 2002

- Briefed Technology Seminar at NRO on September 25, 2002 (Task 9).

### 2.2.1. Task 1 Earth Science Applications Development

We have continued working with Earth scientists during Phase II. A number of meetings have occurred between GAC and Earth scientists toward the development of new applications for constellations of stratospheric science platforms. High priority Earth science applications have now been identified and include Earth radiation balance (ERB), atmospheric chemistry, geomagnetism, adaptive sampling for weather prediction research, tropospheric winds, hurricane tracking and monitoring, hazard detection and disaster management.

#### *2.2.1.1. Earth Radiation Balance (ERB)*

Constellations of stratospheric balloons can provide unique opportunity to measure ERB at the top-of-atmosphere (TOA, ~35 km). A radiometer-carrying platform would be able to provide direct measurements of radiative fluxes that satellites cannot measure (satellites measure radiances, and then convert them into fluxes using some assumptions). In addition, measurements of diurnal variations and high resolution spatial structure of the flux fields, and targeted observations of fluxes related to various short and long lived atmospheric phenomena would become possible. StratoSat platforms can also carry additional instrumentation, such as meteorological dropsondes, multi-band spectral instruments, cloud radars, LIDARs and such, to fully characterize the underlying atmosphere to enable validation atmospheric models.

#### *2.2.1.2. Atmospheric Chemistry*

*In situ* platforms are necessary to validate the satellite measurements of the atmospheric constituents within the stratosphere and upper troposphere over long timescales and to provide high-resolution vertical profiling. Many of the satellite stratospheric observations are controversial and require *in situ* validation. Constellations of stratospheric balloons positioned in the tropics and midlatitudes could monitor changes in stratospheric water, ozone and other relevant constituents with a suite of *in situ* instruments positioned on the gondola or/and on the tether. Long flight durations would allow to observe changes in stratospheric structure within at least one season. Polar constellations would monitor ozone destruction, while a global constellation can search for surface sources and sinks of carbon or monitor compliance with emission treaties.

#### *2.2.1.3. Geomagnetism*

Stratospheric measurements of the Earth’s magnetic field gradient allow separation of the internal and external components of the field and to study the crustal magnetic anomalies in a very unique way. A constellation of StratoSat™ platforms can carry several scalar (or vector) magnetometers positioned over several kilometers along the tether below the gondola. These measurements would provide measurements of magnetic field with intermediate spatial frequencies that would complement the satellite and surface surveys. In addition, balloon measurements would provide measurements in places that are hard to access with conventional means.

#### *2.2.1.4. Tropospheric Winds*

A LIDAR positioned on a stratospheric balloon platform would be much closer to the surface and underlying atmosphere, than the space based LIDAR. This would make the stratospheric LIDAR smaller, less power consuming and less expensive. Multiple LIDARs on a constellation of StratoSat™ platforms could enable, for the first time, truly global measurements of troposphere winds.

#### *2.2.1.5. Adaptive Sampling for Weather Prediction*

Constellations of StratoSat™ platforms carrying meteorological instruments and hundreds of light dropsondes can be positioned in the Northern Hemisphere and perform targeted observations of weather systems in the data sparse regions, such as North Pacific and North Atlantic. Such measurements could significantly improve the forecasting capabilities.

#### *2.2.1.6. Hurricane Tracking and Monitoring*

In a similar way as in Adaptive Sampling for Weather Prediction, a smaller linear constellation can monitor tropical regions for occurrences of hurricanes and then follow them, making measurements of “steering winds” around the hurricanes. Such measurements can significantly improve the forecasting of the hurricane tracks and landfall time and location, which in turn can save lives and resources.

#### *2.2.1.7. Hazard Detection and Disaster Management*

Global constellation of StratoSat™ platforms carrying high-resolution cameras, radars and other instruments can monitor the whole globe for occurrences of natural disasters. The StratoSat™ platforms would provide the means to quickly obtain mapping of the disaster area, performs atmospheric sampling of the hazard site, assess damage, provide emergency communication link, or monitor compliance with international treaties.

### 2.2.2. Task 2 Proof-of-Concept Science Mission Definition

As summarized above, there have been considerable discussions with scientists and program managers on Earth science applications of stratospheric platforms. In these discussions GAC has raised the possibility of a proof-of-concept (POC) mission and has solicited ideas that may be developed further. Several low-cost POC missions have been discussed including a Hurricane Intercept, Earth Radiation Balance, Satellite Radiometry and Wind LIDAR Missions. Objectives and strawman payloads of these missions have been suggested.

#### *2.2.2.1. Demonstration Earth Radiation Balance Experiment (DERBE)*

Dr. Warren Wiscombe, at GSFC, first suggested this mission. GAC has developed a concept for a possible Demonstration Earth Radiation Budget Experiment (DERBE). GAC briefed Don Anderson, Code YS Manager of the Radiation Sciences Program**,** Warren Wiscombe (GSFC scientist), and Martial Haeffelin (formerly of Virginia Tech) on this concept in April 2001. The DERBE mission consists of one balloon, a simple gondola and prototype Earth Radiation Budget instrumentation. The system would orbit the Earth at 35-km altitude periodically over flying important atmospheric radiation monitoring sites, e.g. the Oklahoma Atmospheric Radiation Measurement (ARM) site and other targets of opportunity. This concept is discussed further in Section 4.

#### *2.2.2.2. Hurricane Intercept Mission (HIM)*

The hurricane intercept mission (HIM) arose because it was recognized by scientists that stratospheric balloon platforms may be able to make high resolution diurnal observations that are not possible from any other platform. These measurements can include winds, sea-surface state, precipitation maps, and detailed temperature profiles in the vicinity and within the hurricane. Such measurements could significantly improve forecasts of hurricane intensity and ground track. One demonstration concept consists of a linear network of several balloons distributed around the world at similar latitudes moving in the pervasive zonal flow. When a hurricane target is identified, these balloons would adjust their latitude, by the use of TCS systems, to ensure hurricane overflight. This concept is discussed further in Section 4.

#### *2.2.2.3. Complementary Radiometry Mission (SRM)*

In November 2000, GAC evaluated options for complementary radiometry missions, where balloons in a sparse constellation would complement measurements made by orbiting satellites. The instigation for this mission concept came from the Harvard University Atmospheric Research Program (HUARP) at Harvard. Balloons would be targeted to arrive at a geographic location at the precise time of satellite overflight in order to get coincident measurements. Coincident measurements would be possible below the satellite on a global scale. This concept is discussed further in Section 4.

#### *2.2.2.4. Wind LIDAR Mission*

A Wind LIDAR proof-of-concept mission was proposed to determine the potential for calibration and validation of satellite LIDAR data. In 2001 plans were being formed for possible data buys of satellite wind LIDAR data. A sparse network of balloons providing high-resolution measurements was seen as a means of validating the commercial satellite data. This concept is discussed further in Section 4.

#### *2.2.2.5. THORpex*

A proof-of-concept mission was proposed as a possible part of the proposed THORpex program. A single balloon system combined with simple gondola and first generation TCS would be targeted to a high weather sensitive region in the N. Pacific in order to deploy conventional dropsondes. This POC mission could demonstrate the value of a global network of StratoSat™ Platforms for improving weather forecasting.

### 2.2.3. Task 3 Global Constellation Geometry Management Development

During Phase II of this activity, we spent considerable time on constellation geometry management, because it is essential for demonstrating the feasibility of the StratCon concept. We evaluated the percentage of the Earth's surface that could be observed by a constellation of balloons at various altitudes. We performed analyses of the rates at which balloons approach each other under typical wind conditions and plotted the results on contour maps that we called "Approach Velocity Maps." We also studied typical wind differences between 35 km and 20 km. Graphs of this data assisted us in understanding theoretical performance capabilities from StratoSail® Trajectory Control Systems.

During Phase I of this activity, we developed simulations of uniformly distributed balloon constellations. These simulations showed the initial feasibility of using bounded and underactuated control systems to maintain desired constellation geometry. In Phase II, we have extended and enhanced those simulation capabilities to evaluate new constellation geometries related to several new science scenarios. These new simulations indicate that with the trajectory control authority provided by a StratoSail® TCS, we can achieve many interesting science objectives. And, through a Princeton University subcontract, we developed a new framework for constellation geometry management that utilizes concepts from behavior of natural groups (flocks, schools, and pods) and Weak Stability Boundary theory.

A number of balloon, network and constellation simulations have been developed including (1) global constellations of 100 to 400 balloon platforms for a variety of science goals, (2) single and dual linear networks ("string-of-pearls") for hurricane tracking and for fix point monitoring, hemispherical networks for weather, climate and communications applications, (3) single balloon overflight of surface targets for ERB demonstration missions, and (4) adaptive balloon-borne sampling using simple and sophisticated control (feature recognition).

Recognizing that the constellation controlled framework developed in collaboration with Princeton can be improved by recognizing atmospheric features, such as large-scale vortices, we developed an algorithm that recognizes the vortical structures in the wind field data.

### 2.2.4. Task 4 Advanced Balloon Design Model Development

This task was eliminated in the first year due to the problems encountered by the NASA balloon program in their development of the ULDB system. Since the ULDB system was to form the basis for the design of the StratoSat™ Platform it was decided to defer this work until more progress had been made in long duration flights of the ULDB.

### 2.2.5. Task 5 Trajectory Control System Model Development

In Phase II, GAC developed models for the operation an advanced TCS. We also developed a new model of trajectory control system behavior that was used in the constellation simulations through the second year of Phase II. This new model brought our TCS and constellation evolution models to an enhanced level of fidelity. We incorporated the following realistic StratoSail® TCS characteristics into constellation modeling:

- $\Delta V$ control authority for a StratoSail® TCS is a function of the magnitude and direction of the relative wind between the balloon and wing altitudes and
- $\Delta V$ control for a StratoSail® TCS is limited to only those directions achievable by the TCS (roughly, about 25 % of a full control circle).

The results of the various models are presented later in this report.

### 2.2.6. Task 6 Explore New Multi-function Subsystem Concepts

In Phase II, we began developing concepts for generating power during StratoSat nighttime operation. The concept being studied involves the use of the StratoSail® Trajectory Control System combined with a wind turbine to provide 200–1000 W of power during periods of darkness. This concept looks promising and may have a lot of potential.

In addition, we made a preliminary evaluation of global population density maps with regard to overflight safety. For a demonstration mission and for future constellations of StratoSats™, it may be necessary to fly a precision-guided parafoil payload recovery system. Such systems, in development by the French balloon program, provide both slow payload descent and precision targeting of payload landing sites on the ground. The parafoil systems could be used, for example, to bring a payload down in an open field (airport, for instance) in an otherwise heavily populated city.

### 2.2.7. Task 7 Constellation Systems Costing

In Phase II we refined and developed costs for a constellation of StratoSat™ Platforms carrying out adaptive dropsonde operations and we compared these costs with an alternate approach called the driftsonde concept. The driftsonde concept has several small disposable radiation-controlled (Racoons) balloons launching from the perimeter of ocean basins. These balloons float over the oceans deploying dropsondes every 6 hours. These estimates showed that for a large StratoSat™ Platform network that operated over more than one ocean basin, the cost per dropsonde profile was significantly less than the driftsonde concept. The following table summaries the costs of a hemispherical network associated with dropsonde releases and data collection. This costs estimate assumes that the StratoSat™ platform network investment is justified and amortized for other applications.

Table 2-1. Driftsonde versus StratoSat™ Platform Adaptive Sampling

| **Assumptions** | | **Costs** |
|---|---|---|
| Number of StratoSat™ platforms in network | 383 | |
| Liffe cycle cost per unit of network, $ | 390,000 | |
| Campaign duration, days | 90 | |
| Number of dropsondes released from each balloon | 1,000 | |
| Data return cost, $/5kb | 1 | |
| Drop duration. Min | 35 | |
| Life cycle, years | 10 | |
| **Dropsondes** | | |
| ***Maximum Capacity*** | | |
| Maximum number of dropsondes | 383,000 | |
| Estimated cost per micro-dropsonde, $ | 25 | |
| **Total cost of dropsondes, $** | | **$9,575,000** |
| ***Required Capacity*** | | |
| Number of dropsondes in zone every 6 hours | 40 | |
| Number of dropsondes required per year for campaign | 14,400 | |
| Total number of dropsondes required in 10 years | 144,000 | |
| Estimated cost of dropsonde, $ | 25 | |
| **Total cost of dropsondes, $** | | **$3,600,000** |
| **Data** | | |
| Number of measurements | 8 | |
| Bits/measurement | 8 | |
| Measurements per second | 1 | |
| Measurement duration, s | 2,100 | |
| Data per dropsonde, bits | 134,400 | |
| Cost of data return per dropsonde, $ | 26.88 | |
| **Total cost for maximum number of dropsondes, $** | | **$10,295,040** |
| **Total cost for required number of dropsondes, $** | | **$3,870,720** |
| **Total required campaign cost, $** | | **$7,470,720** |
| **Total maximum campaign cost, $** | | **$19,870,040** |
| **Average cost per profile, $** | | **$51.88** |

### 2.2.8. Task 8 Definition of International Airspace Overflight Issues

Considerable effort on this task occurred in Phase II including the review of the literature on Airspace Law and the similarities and differences with the Law of the Seas and Space Law. The record of case law was reviewed and the relevance to global constellations of balloons understood. Discussions were carried out with appropriate officials of the US Department of State, the US Defense Threat Reduction Agency (DTRA), and the World Meteorological Organization (WMO). Pathways to the international overflight of stratospheric scientific balloons were identified. In July at the COSPAR 2000 Mr. Nock was asked to chair a subcommittee of the Panel on Scientific Ballooning (PSB) to draft a resolution on overflight of scientific balloons. This proposed resolution, accepted by COSPAR as Internal Decision 1/2000, called for a Task Group to be formed to examine the technical aspects of overflight of scientific balloons. In October 2002 this Task Group met at the COSPAR 2002 meeting to begin discussions on the future of overflight for scientific balloons.

### 2.2.9. Task 9 Planning and Reporting

In Phase II we published 28 monthly reports, wrote 9 papers and gave many presentations for several conferences including: COSPAR in 2000 and 2002, the 2001 ESA Symposium on European Rocket and Balloon Programmes, the 2001 and 2002 American Meteorological Society (AMS) Meetings, the Earth Observation Systems (EOS) Investigators Working Group (IWG), the 2002 Workshop on Radical Agent Concepts, and the Working Group on Space-Based Wind Lidar. In addition we made over 19 presentations and briefings on the NIAC effort to science groups, to NASA Program and Science Managers, and to NASA and academic scientists.

## 2.3. StratoSat™ Subsystem Design Summary

The following sections summarize the ultimate StratoSat™ subsystem function and preliminary design. As Phase II progressed we realized that there is really a wide spectrum of platform sizes (and costs) possible. The system described here is probably at the low end of payload capability. The system described was developed assuming that in the next 10-20 years there will be significant reductions in subsystem and instrument mass. In the meantime, less technologically mature and considerably larger and costlier systems can be flown and still meet many of the requirements of the applications we have developed.

The technology horizon for estimating masses of subsystems and components is 2010. Advanced design technology is incorporated if there was a clear path to achieving technology goals. If there was no clear path to revolutionary advances in StratoSat™ subsystem technology, future significant cost reductions were assumed. Mass estimates assume contingency mass, which can range from 1%, which is the error in making a mass measurement, to as large as 100% if the component design and/or technology is not mature. The mass estimate of the StratoSat system capable of a 35-km float altitude is summarized in the following table.

Table 2-2. StratoSat Mass Summary

| Subsystem | Mass, kg |
|---|---|
| Balloon | 252.0 |
| Helium | 87.4 |
| Power | 26.4 |
| Telecommunications | 4.9 |
| Mechanical | 30.1 |
| Guidance and Control | 1.2 |
| Robotic Controller | 0.5 |
| Trajectory Control | 80.7 |
| Science | 55.7 |
| Science Reserve | 21.5 |
| Total | 560.4 |

### 2.3.1. Balloon

The balloon subsystem provides the buoyancy for the StratoSat. The balloon subsystem consists of an envelope or shell, to contain the buoyant gas and provide mechanical payload support, end fittings to secure the envelope to itself and to a suspended payload, termination hardware to release gas and deploy aerodecelerators, a flight train to connect the balloon envelope to the payload, monitoring sensors, and (if needed) buoyant gas relief and leakage replenishment hardware. A detailed balloon subsystem mass list is shown in Table 2-3. The balloon shell of the baseline balloon subsystem consists of the following components: lobed gores, tendons, inflation tube, reefing sleeve, and termination hardware. The shell is comprised of 140 gores or sectors of 15-g/m$^2$ areal density film similar to the co-extruded composite being tested for the ULDB Project, only thinner and possibly stronger. The film material would be protected from UV damage either with UV inhibitors within the film or a thin coating or paint on the outside. Each gore would be about 1.34 m wide and about 77 meters long, and attached to its neighbor by means of a heat-sealed seam. The entire shell gore film mass is about 132 kg. Along the seams would be an attachment system for the Zylon cord load tendon. Either the Zylon load tendon or its attachment system needs to protect the tendon against UV and light damage. 140 load tendons of 24,000 Denier (mass in g of 9000 m of fiber) Zylon are needed along with their attachment sleeves and UV protection requiring about 53 kg of mass. Each tendon is about 77 m long and masses about 205 g/tendon not counting attachment and UV protection sleeves.

Table 2-3. Balloon Subsystem Mass Summary

| Component | Mass, kg |
|---|---|
| Shell | 132 |
| Load Tendons/Sleeve/Attachment | 53 |
| Fittings | 40 |
| Inflation Tube | 5 |
| Destruct Device | 1 |
| Reefing Sleeve | 5 |
| Buoyancy Control and Monitoring | 15 |
| Flight Train | 1 |
| Total Mass | 252 |

A 5-kg inflation tube, which is affixed to the envelope, allows the inflation to begin at the top of the balloon even though the balloon is reefed (the balloon is reefed to minimize aerodynamic forces on the balloon during the launch operations). The 4.5-kg reefing sleeve, which is integrated into one of the gore seams, keeps the envelope area minimized as it is being inflated. The balloon’s reefing sleeve essentially serves the same function of the reefing straps on the square-rigged sailing ships. Finally, there is the termination hardware or rip line that opens a small panel in the top of the balloon upon the receipt of a destruct command. This destruct rip line is about 1 kg of mass. An alternative termination concept could include a planned deflation, through valves at the top of the balloon, to achieve a desired low descent rate at the surface after the gondola has been cut away.

### 2.3.2. Power

The power subsystem consists of power generation (solar array), power management and distribution, and energy storage components. In the design of the StratoSat system it is highly desirable to integrate the functions of the power subsystem into the balloon system to take advantage of the large area available and to reduce overall system mass. A key challenge to this approach is to have an envelope design that deals with the structural loads resulting from the thermal heating that will be caused by the solar cells on the balloon envelope.

The functional block diagram of the StratoSat Power Subsystem is shown in Figure 2-1. The solar array provides power at about 100 VDC to the power system. This voltage has been selected to reduce solar array wiring mass. The battery is connected directly to the 28 VDC power bus. Battery charge control is provided by the Charge Controller, which, for lithium-ion polymer, provides an active shunt regulator across each battery cell. This provides overcharge protection in the case of cell imbalance. Additionally, a control signal to the Power Controller adjusts the SSR to provide the correct bus voltage level during charge. At night, the bus voltage is supported by the battery and follows the battery discharge curve. The power from the unregulated 28 VDC bus is distributed to the loads through solid-state switches that also provide overload protection. The switches are monitored and controlled by the central computer. Power conversion can be supplied in the power subsystem as shown in the block diagram, or can be contained within the loads.

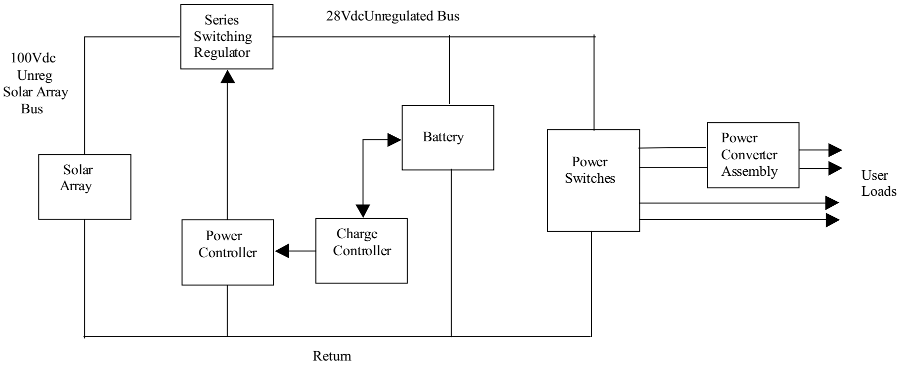


Figure 2-1. StratoSat Power Subsystem Functional Block Diagram

For the purposes of the reference design we have assumed the integration of thin-film, 10% efficient, a–Si solar array into the balloon envelope either as load tapes or within the center of the balloon gores. The total area of array required is only 90 $m^2$ with a 4.94 kW power requirement. Assuming 100 $g/m^2$ solar array or 549 W/kg (10% efficiency) the solar array mass is 9 kg.

The batteries for StratoSat have been assumed to be lithium-ion polymer at an energy density of 200 Wh/kg. For the mission example calculated, the nighttime load is 100 W and a battery depth of discharge of 75% was used. This results in a battery mass of 10.7 kg, and a required capacity of 74 Ah. It is planned that the battery cells be integrated into the top of the gondola structure or other location. The analysis for this location has not been completed at this time. The battery thermal requirements are fairly broad with the only concerns being loss of performance below 0°C, and a maximum temperature above 60°C.

### 2.3.3. Telecommunications

The telecommunications subsystem includes all the means by which the StratoSat communicates with the operations, each other, satellites, aviation authorities, and recovery operations. The telecommunications subsystem consists of a variety of radio transmitters and receivers, signal conditioning and decoding hardware, antennas and radar reflective components. Figure 2-2 illustrates a simplified functional block diagram of the entire telecommunications subsystem. The high rate radio subsystem connects the balloon payload to broadband satellite data services. Uplink, balloon-to-satellite, data rate is 2 Mb/s. Downlink data rate is 2 Mb/s. The terminal hardware takes care of the satellite protocols, data packetizing and error coding to achieve an end-to-end bit error rate of $10^{-10}$. The system also provides automated antenna tracking of the Teledesic spacecraft. Because the spacecraft may not be in geostationary orbits their apparent positions in the sky may change and therefore require the user terminal antenna to track them. Typical broadband communications hardware will employ two antennas, one to track the current spacecraft used for communications and the second to begin tracking the next spacecraft that will be used for communications. Hand-over between spacecraft is performed automatically.

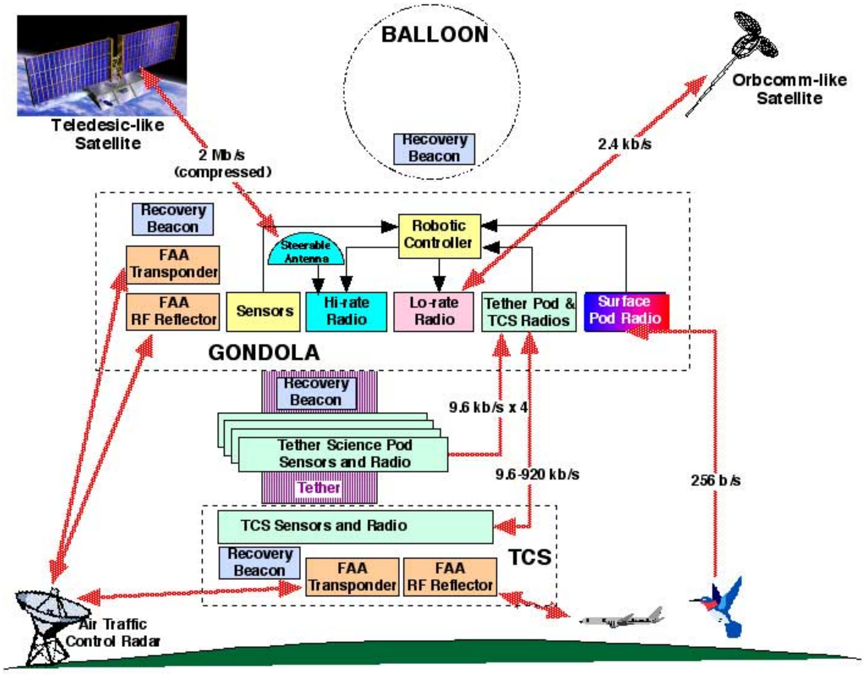


Figure 2-2. StratoSat Telecommunications Functional Block Diagram

The low rate data link uses hardware compatible with a satellite messaging service (Iridium and Orbcomm are two examples). The Orbcomm system is now comprised of 35 satellites that provide worldwide, low-rate, messaging services to small, hand-held, portable or mobile communicators. At 2400 b/s uplink and 4800 b/s downlink rate. The data handling capacity of the Orbcomm service is limited. At the present time Magellan Corp and Panasonic produce OEM communicators that include programmable control, analog and digital interfaces and GPS location, movement and timing functions. The Magellan OEM communicator card has a mass of only 84 g and its dimensions are 10 x 8.4 x 1.5 cm. The card has on-board storage to buffer messages up to 32 kbytes. Larger messages can be accommodated via external data storage mechanisms.

### 2.3.4. Mechanical

The mechanical subsystem provides the mechanical support, thermal control, subsystem interconnectivity, and mechanical device hardware. The mechanical subsystem consists of gondola support structure, mechanical interface to flight train and trajectory control tether, thermal insulation, heater and radiator components, electrical and data bus cabling, and mechanical devices for cutting and/or releasing cables or tethers or for deploying components including science instruments.

The gondola main support structure is a single vertically oriented honeycomb panel. The upper end is attached to the balloon tether. The lower end supports the TWA. The vertical arrangement of the panel efficiently transfers the predominantly vertical loads. Avionics boxes and other components are mounted to both surfaces of the panel. The ends of the panels include brackets to mount the large tubes enclosing the downward looking telescope-like optical instruments. An under-dense foam box covered with multi-layer insulation is attached to the mounting plate and provides thermal resistance between the avionics and the cold exterior. At night, the heat balance is such that the power dissipated in the instrumentation maintains an acceptable operating temperature. During the day, with additional heat input from the sun, a radiator surface is exposed to permit heat to escape to space. This is shown in the figure as a louvered radiator, similar to those used on spacecraft. Alternatively, a more effective design would be a simple insulation-covered door, which can be opened when the temperature inside climbs above a preset value. As the temperature falls again, the door is closed. This arrangement has better insulating properties when the door is fully closed than the louver arrangement. A disadvantage of the door is that a motor is required to open and close it. For spacecraft, the louver assembly operates without power, using bimetallic strips, which keeps weight even lower, but does degrade insulating properties when closed compared with the door used here. For the current application, the trade-off favors the motorized door with better insulation.

A winch system is mounted at the bottom end of the gondola. Since the winch components are not sensitive to low temperatures, they are mounted outside the thermal enclosure. This permits the thermal enclosure to be smaller, reducing the heat lost through its surfaces. This, in turn, reduces the thermal control power required.

Figure 2-3 is a computer drawing of the StratoSat gondola along with the TCS hardware including the TCS Wing Assembly.

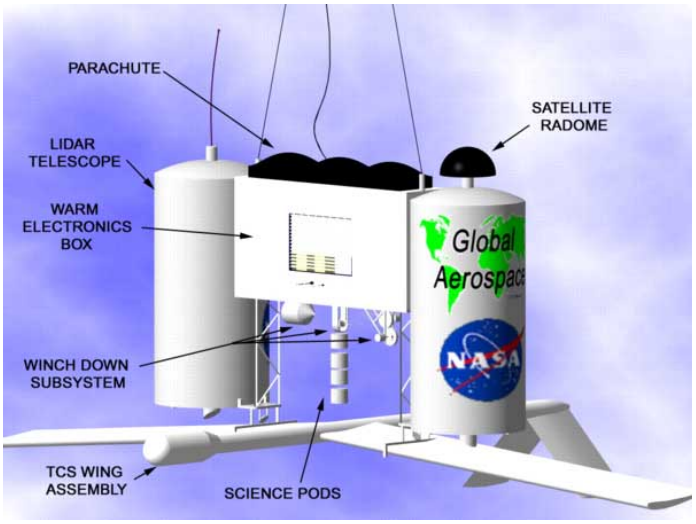


Figure 2-3. StratoSat Gondola and Trajectory Control Systems

### 2.3.5. Guidance and Control

The guidance and control subsystem provides onboard navigation and orientation knowledge information, and it provides subsystem and science articulation functions. The guidance and control subsystem consists of ambient atmospheric, celestial, acceleration, rotation rate and GPS sensors for determining the state of the StratoSat and the environment in which it is floating. The G&C subsystem includes a wind speed sensor, a rate gyro, an accelerometer and tilt sensor, a GPS units for position and orientation, atmospheric pressure sensor and a temperature sensor.

### 2.3.6. Robotic Controller

The robotic controller performs many if not all on-board computational functions. It initiates autonomous activities of the StratoSat™ Platform that could be related to scientific data gathering, communications, and navigation and guidance functions. The robotics controller accepts and stores ground commands from the Operations Control Center. In addition, the robotic controller acts as one node of a global computer network in relaying data to and from ground stations and other StratoSats (if cross-links are eventually implemented). The robotic controller assesses StratoSat™ Platform state (health, position, speed and direction, and orientation) and makes state-driven decisions, such as commanding the trajectory control subsystem. A microprocessor system was selected over a micro-controller option in order to enable the use of commercial, state-of-the-art computational performance and to enable a wide choice of sophisticated operating systems.

### 2.3.7. Trajectory Control

The trajectory control subsystem (TCS) produces the force to move the balloon platform in a desired direction. Suspending an aerodynamic surface, or wing, several kilometers below the balloon, generates this force and taking advantage of the high relative winds between widely separated altitudes. In addition, the TCS provides a scientific platform at the level of the suspended wing and at places all along the tether between the wing and the balloon.

The first generation TCS used a single wing suspended vertically. The design was based on the assumption that the lift force would be much less than weight of the TCS. Since then, we have discovered that the wing can be made lighter and sometimes the aerodynamic forces can be higher than we initially expected. In these conditions, the wing can swing to the side and move up into less dense air. This limits the maximum trajectory control performance available. In order to take advantage of the stronger winds at lower altitudes, we modified the design and developed an advanced dual wing TCS design (resembling an upside down glider). This advanced TCS requires roll control in addition to controlling the angle of attack of the wing. In the modeling performed here, we assume the performance capabilities of this advanced TCS to provide higher levels of trajectory control than achievable with the first generation TCS.

Figure 2-4 illustrates the advanced TCS system. The lift vector has a downward component that acts in concert with the weight of the system to hold the TWA down in denser air. An optimization scheme was developed to determine the roll angle required to provide the maximum horizontal component of the lift force. This optimization includes the reduction of relative wind as the wing operates at different altitudes as well as the reduction in density. For very light winds, the optimization yields a roll angle of 90°, equivalent to the first generation TWA. This is a check that the optimization approach is working correctly.

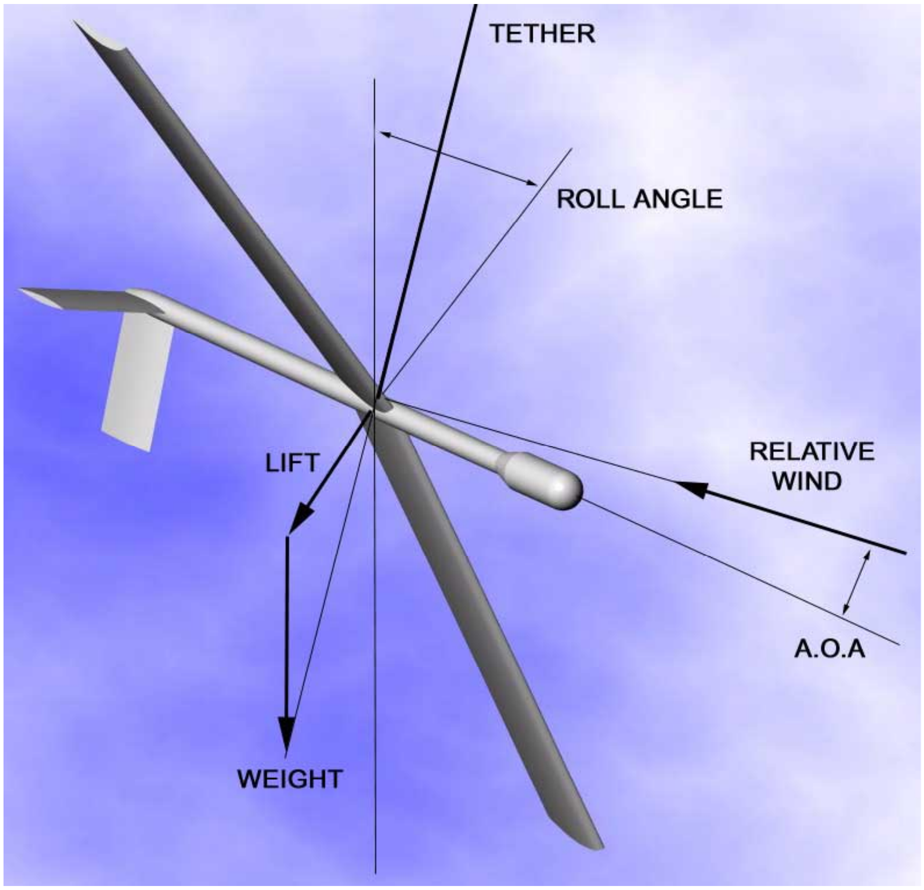


Figure 2-4. Advanced Trajectory Control System (ATCS).

The entire trajectory control system (TCS) consists of the TCS Wing Assembly (TWA), the TCS Interface Package (TIP) the tether, a winch system, and interface electronics and radios. The

TWA has a wingspan of 8m and a chord of 1m. The V-tail includes ruddervators (combination rudder and elevator). These control surfaces operate differentially to provide yaw control and together to provide pitch control. Ailerons on the wings provide roll control. A device equivalent to the artificial horizon in a normal aircraft is required for the system to determine its roll angle and control it appropriately depending on the dynamic pressure as measured, for example, using a pitot-static tube.

### 2.3.8. Termination

The termination subsystem provides the means to reliably and safely terminate the mission of a StratoSat™ Platform under a variety of conditions. Three termination modes are defined which deal with the various termination conditions expected. The first mode is ***emergency*** termination that occurs within milliseconds of sudden balloon envelope catastrophic failure. Second is ***nominal*** termination that occurs within hours or days of a non-catastrophic, but debilitating subsystem failure. Finally, ***rapid*** termination that occurs within minutes or hours of a major on-board power failure that jeopardizes the safety of the flight. Components of the termination subsystem include sensors, redundant radios and computers, cable and tether cutters, parachutes or parafoils, and recovery beacons.

### 2.3.9. Science

Science experiments and instruments are located at three places, namely, the gondola, along the tether to the TCS, on the TCS and within small packages dropped from the gondola to the surface. An example payload was selected for the purpose of driving the StratoSat™ system design. The payload described below addresses the science objective of understanding water vapor and global circulation in the tropics (see the Phase I Final Report, Section 3.2.1). This payload would also provide a continuous picture of water vapor entering the stratosphere. It would address issues involving our understanding of how much water enters the stratosphere on an annual basis and provide a basis for our understanding trends or variability in stratospheric water which have been observed by satellites and sonde data. Science experiments at the gondola will take advantage of the 30-35 km altitude for their measurements. In general, though not necessarily on the same platform, these experiments could include high-resolution, steerable visible and IR cameras, radiometers, *in situ* atmospheric chemistry and water vapor sensors, laser sounding instruments, GPS receivers, and limb scanning IR and microwave instruments.

At the gondola:

- Ozone LIDAR (measures ozone profiles to ground)
- Water vapor LIDAR (measures water vapor profiles down into mid troposphere)
- Water vapor and ozone infrared absorption instruments
- Cavity ringdown-laser absorption spectroscopy for $CO_2$
- Temperature

Science instruments placed on the tether will by their nature be very lightweight, self-contained, independent and have a low cross-section in order to minimize aerodynamic drag. In addition such instruments will likely be multiple sensors placed at intervals along the tether to take advantage of altitude difference. Some candidate instruments include ambient atmospheric measurements (U, T, P), wind sensors, *in situ* chemical and water vapor sensors, and retroreflectors for IR absorption instruments. Along the tether (2, 4, and 6 and 10 kilometers above the StratoSail® TCS):

- Water vapor and ozone infrared absorption instruments
- Temperature

Instruments installed at the TCS will take advantage of a relatively stable and independent platform located 15 km beneath the balloon. Potential science instruments placed on the TCS include ambient atmospheric measurements, *in situ* chemical and water vapor sensors, radiometers, and even lightweight visible and IR cameras. At the StratoSail® TCS (at ~20 km altitude):

- Microwave temperature profiler at bottom of the tether (measures temperature to about 6 km below the instrument).
- Water vapor and ozone infrared absorption instruments
- Temperature

Sensors typically flown on ground-launched, disposable radiosondes (U, T, P, and winds) are good candidates for dropsondes. In addition, more sophisticated measurements of interest are ozone and other atmospheric chemistry sensors. Dropsondes designed for long-duration network missions will be very small (25-50 g) in order to carry enough copies to drop them periodically over desired target areas. The implication for dropsonde sensors is that they too must be very small. For the particular example science payload discussed here, dropsondes are not carried.

## 2.3.10. Operations System Description

The constellation system includes at least three operations elements, namely an Operations Center, a Launch Facility, and a Weather Forecast Center. Figure 2-5 shows the operations system schematic.

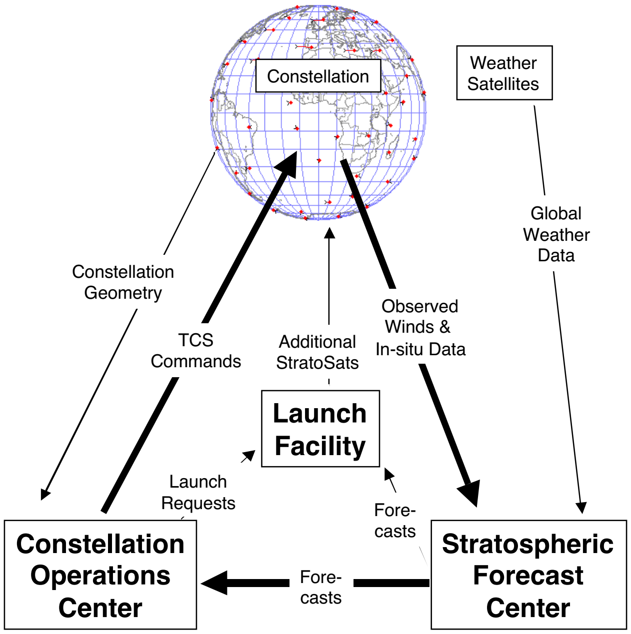


Figure 2-5. Operations System Schematic.

# 3. Earth Science Applications Development

Typically, concepts for revolutionary ideas are years ahead of applications (e.g. the Internet and GPS). Hence, in Phase II we accelerated this process by developing potential future applications in parallel with the concept. An aspect of the proposed work is the continued examination of potential applications and benefits of a global constellation of stratospheric Earth science platforms. We have worked with a variety of Earth scientists to define applications for a global network of stratospheric science platforms. In addition, a proof-of-concept mission is seen as a logical first step to any global constellation development.

The purpose of the applications development effort is to illustrate how balloon-borne *in situ* instrumentation on advanced global stratospheric balloon constellations can be used to help answer some of the key questions we face regarding global change. In our report on Earth Science Rationale and Mission Scenarios, http://www.gaerospace.com/projects/StratoCon/pdf_docs/NIACesrms.pdf we indicated that developing both the technologies for implementation of this approach as well as utilizing *in situ* balloon-borne instrumentation is consistent with the recent recommendations of a large body of atmospheric scientists.

We have studied only selected mission scenarios that have objectives of answering scientific questions that are part of NASA's mission. These mission concepts describe measurements from regional and global constellations of very long duration balloon-borne scientific stratospheric platforms. These example concepts have been developed based on our current understanding of science priorities and the extrapolations of technological developments in measurement capabilities. We have expanded on the Phase I work both in depth and breadth across the Earth science community.

## 3.1. Earth Science Interactions in Phase II

We have worked with a number of Earth scientists and Earth observation program managers throughout Phase II. The following discussion summarizes these discussions, meetings, and contacts.

### 3.1.1. Applications Development 2000

In May 2000, GAC had discussions with the Department of State, Advanced Space and Technology Office regarding the application of stratospheric constellations to the monitoring of future environmental agreements.

At the NIAC Annual Meeting in June 2000 at NASA GSFC the Director of GSFC, Al Diaz, expressed interest and support in the development of Earth science applications for stratospheric balloon technology. He also indicated interest in supporting a proposed proof-of-concept mission. After the NIAC meeting, GAC had discussions with NASA/GSFC scientists regarding Earth science constellation applications, possible next steps and potential further contacts at NASA HQs and at Universities.

In August 2000, GAC contacted several scientists who might have had interest in the Global Constellation of Stratospheric Balloons concept. Dr. Judith Curry, Colorado University, indicated an interest in dropsonde capability in oceanic regions where StratoSats™ would operate in a "targeted observations" mode. In this mode, StratoSats™ TCS could be commanded to move to locations that numerical models say are regions of greatest error for a specific forecast.

Also in August we also spoke to an atmospheric scientist, Barney Farmer (JPL-retired), who suggest discussions with several people at JPL including Ross Salawitch and others interested in the transport of atmospheric gases between the troposphere and the stratosphere. Dr. Salawitch was interested in the measurement of the abundance of key isotopes of oxygen, carbon and hydrogen in both regions of the atmosphere as they are contained in $CO_2$ and $H_2O$ molecules, i.e. HDO, $H_2{}^{18}O$, ${}^{13}CO_2$. Constellations of long-life, trajectory-controlled balloons could make a significant contribution to the understanding of the dynamics in the atmosphere, particularly in the tropics, if *in situ* remote sensing measurements are feasible. *In situ* methods involve deploying tunable diode lasers (TDL) at altitudes of interest. Remote sensing of these gases from high altitude balloons may be feasible by use of LIDARs.

GAC also spoke in August to Dr. Syed Ismail at NASA LaRC of the LIDAR group there about the use of LIDAR instruments on balloon platforms. Dr Ismail was interested in studying the feasibility of making trace gas measurements, like isotopic ratios) with balloon-borne LIDARs. In its current evolution from ground systems to space free flyers, the NASA LIDAR program is missing a platform between the ER-2 aircraft and the Space Shuttle. Balloons could be an excellent, cost-effective transition platform for LIDARs to space. In addition, long-life balloons may be a preferred platform for some measurements due to the million-times increase in tropospheric sensing SNR due to their low altitude and low operations costs.

In September 2000, GAC initiated discussions with Dr. Jim Anderson who leads the Harvard University Atmospheric Research Program (HUARP) that conducted the “Reel-Down” experiments in the 1980s. They also made the first definitive measurements of ozone depletion in the Antarctic. Dr. Anderson has expressed possible interest in the use of a regional StratoSat™ balloon network for new experiments in the tropics. These discussions resulted in two meetings at Harvard in November to discuss future applications of StratoSat™ Platforms and possible proof-of-concept missions.

Also in September GAC had fruitful discussions with Dr. Warren Wiscombe (NASA/GSFC) regarding the use of StratoSat™ balloon constellations for Earth Radiation Balance (ERB) experiments. Dr. Wiscombe identified potential advantages of using constellations of StratoSats™ for ERB experiments. Dr. Wiscombe connected GAC to Don Anderson, the new head of the Radiation Science Program at NASA Headquarters.

During October 2000, GAC continued discussions with Jim Anderson, director of HUARP, to discuss Global Aerospace Corporation’s ideas on constellations of stratospheric balloons for Earth Science. Dr. Anderson discussed Harvard’s particular interest in radiometry measurements in the tropics that could complement satellite measurements in the same region. A small constellation of balloons would provide an unprecedented opportunity to understand Earth’s IR radiation. A second area of interest for Harvard is stratospheric ozone measurements in the lower stratosphere. Again, a small constellation of balloons would provide new opportunities for measuring atmospheric trace gasses. Anderson said this concept could significantly enhance our understanding of the stratosphere for "five cents on the dollar."

A follow-up meeting between HUARP and GAC personnel occurred November 2000. At the November HUARP meetings, we discussed Harvard's interest in the StratCon concept and the potential applications of the concept to Harvard's stratospheric research interests. Broad areas of Harvard's interest include collaborative satellite radiometry coupled with the use of LIDAR and stratospheric chemistry. GAC covered several topics at the meeting, including: Harvard's mission requirements, mission options and preliminary evaluation of mission options, funding context options, and potential mission scenarios. GAC also discussed the technology developments that lead up to potential future stratospheric constellations and summarized the timeline for these developments. At the conclusion of the meeting, we discussed options for baseline mission scenarios in terms of science objectives, location (if a regional constellation is desired), launch site, balloon vehicle, and system configuration. GAC also discussed several cost elements, including the balloon, a winch system, gondola, science, structure, and science payloads.

At the November 2000 NIAC meeting, GAC met with Dr. Warren Wiscombe (GSFC), Dr. Peter Hildebrand (GSFC), Dr. Mark Abbot (OSU), and Dr. Martin Mlynczak (LaRC) to discuss the potential science applications of the StratCon concept. Dr. Wiscombe was very interested in the potential for doing global Earth Radiation Budget (ERB) measurements from constellations of balloons. In addition, Dr. Wiscombe suggested that LIDAR wind measurements in the troposphere would be very exciting and a "killer app" for a global balloon system since the range to the troposphere is so much shorter from a balloon than a satellite and hence the signal to noise is significantly higher assuming the same LIDAR system. There is also considerable recent NASA interest in doing LIDAR wind measurements. Dr. Hildebrand was interested in the potential for microwave measurements from balloon because of the decreased range to the surface as compared to satellites. Dr. Mlynczak is interested in the fine-scale radiation balance of the planet and was interested in the application of balloons for providing vertical profiles of radiation fluxes in order to understand where and why radiation is absorbed and radiated in the atmosphere. Meetings were planned in January at GSFC and LaRC to follow up on the ideas that were explored.

### 3.1.2. Applications Development 2001

January was a very rich period for science and program manager contacts by GAC under this NIAC effort as evidenced by the following table.

Table 3-1. January 2001 Science Contacts.

| Scientist | Location/Company | Interest |
|---|---|---|
| Martial Haeffelin | LaRC/Virginia Tech | Balloon ERB measurements |
| Marty Mlynczak | LaRC | Balloon ERB measurements |
| Syed Ismail | LaRC | Atmospheric Chemistry Lidar |
| Russell DeYoung | LaRC | Atmospheric Chemistry Lidar |
| Bill Grant | LaRC | Atmospheric Chemistry Lidar |
| Warren Wiscombe | GSFC | Balloon ERB measurements, Wind Lidar |
| Bruce Gentry | GSFC | Wind Lidar |
| Geary Schwemmer | GSFC | Wind Lidar |
| Dave Miller | GSFC | Wind Lidar |
| Randolph Ware | UCAR | GPS atmospheric measurements |
| Christian Rocken | UCAR | GPS atmospheric measurements |
| Attila Komjathy | University of Colorado at Boulder | GPS ocean reflection measurements |
| Valery Zavorotny | NOAA | GPS ocean reflection measurements |
| Cinzia Zuffada | JPL | GPS ocean reflection measurements |
| Dave Emmitt | Simpson Weather Associates | Wind Lidar |
| James Cogan | Army Research Laboratory | Wind Lidar |
| Robert Dolce | Kipp & Zonen | Atmospheric radiation measurement instruments |

Discussions at the 2000 NIAC Workshop with Dr. Mark Abbot lead to an invitation to present a paper on our concept at the EOS Investigators Workshop in late January 2001 in Ft. Lauderdale, FL.

Discussions at the NIAC meeting also led to January 2001 discussions at NASA GSFC (Warren Wiscombe) and LaRC (Martial Haeffelin and Marty Mlynczak) on the contribution of balloon constellations to Earth Radiation Balance research, discussions with LaRC (Syed Ismail, Russell DeYoung and Bill Grant) on the use of LIDAR on stratospheric balloons for observing tropospheric chemistry, and discussions at GSFC (Bruce Gentry and Geary Schwemmer) on the potential for Wind LIDAR measurements from stratospheric balloons. At LaRC GAC discussed Earth Radiation Balance (ERB) and LIDAR atmospheric chemistry measurements on stratospheric constellations. At LaRC GAC began with an invited seminar to atmospheric scientists on the NIAC global stratospheric constellation concept which had been arranged by Dr. Mlynczak. After the seminar there was considerable discussion regarding the advantages and disadvantages of balloon-borne radiometers for directly measuring the broadband flux. Attending the seminar was Martial Haeffelin (LaRC and Virginia Tech) who discussed his radiation flux experiment on the ULDB Ballooncraft test flight, flown in spring 2001.

At GSFC GAC met with Dr. Warren Wiscombe to discuss Wiscombe's ideas on the use of global balloon networks for making direct ERB measurements (he had included a chart on his ideas at the NIAC Workshop in November). Wiscombe discussed the advantages of using global balloons for ERB measurements as compared to the use of satellite systems (see below).

**ADVANTAGES OF STRATOSATS TO ERB***

- Flux Measured Directly
- Flux Measured at 35 km (Commonly Accepted TOA to Which ERBE/CERES Products Are Extrapolated); No Extrapolation From 800 Km Down
- No Diurnal Bias; All Times of Day Are Sampled
- No Sun Angle Bias (Past Orbits Have Sampled at Same Su Angle Every Day, Except ERBS)
- By Virtue of Rapid Time Sampling and Slowness of Movement of Platforms Real Dynamics of ERB Can Measured and Studied; Never Before Possible

* Warren Wiscombe, NASA/GSFC

Figure 3-1. Advantages of StratoSats to ERB

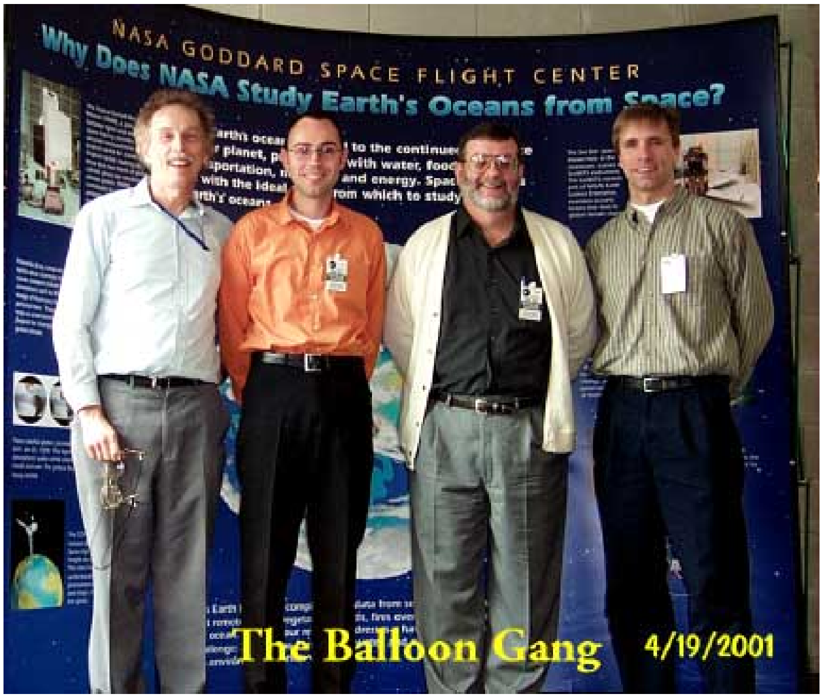


Figure 3-2. Earth Radiation Budget Meeting.

At the same visit to GSFC, GAC met with several Wind LIDAR researchers, including Bruce Gentry, Geary Schwemmer and Dave Miller, where we gave a briefing on the NIAC stratospheric constellation concept. Dr. Gentry was very interested in the concept, however he was concerned in general about the future of Wind LIDAR research because of the consideration of a Wind LIDAR data purchase option. Gentry felt a balloon-borne LIDAR could have a data validation role to play in a data-buy scheme. Gentry also mentioned that a balloon network could have an interesting role to play in hurricane tracking and research since satellites have very limited diurnal coverage, whereas a balloon network could observe the area in and around a hurricane continuously. The hurricane concept was raised as an exciting new application. We also discussed the differences between a satellite LIDAR as opposed to a balloon system. The specific example of the proposed Zephyr Space Shuttle experiment was compared with a possible future StratoSat™ system. A strawman payload definition was generated. Dr. Geary Schwemmer displayed his holographic optical element (HOE) within a ground-based Wind LIDAR instrument. The HOE enables scanning of both the Laser and the reflected signal with simple rotation of the HOE instead of rotating the entire telescope in azimuth along a cone. This approach may have significant benefits to both satellite and balloon-borne instruments.

In mid-January 2001 GAC presented a paper on global balloon constellations at the American Meteorological Society (AMS) meeting. At the AMS meeting, we made contact with researchers who (a) use occultation of GPS signals to measure atmospheric parameters and (b) use reflected GPS signals off the ocean surface to measure sea surface temperature and sea surface winds. The baseline design for StratoSat systems includes GPS systems to locate the balloon. So, performing these experiments would incur very little additional mass and cost. In addition, we met researchers who perform Observing System Simulation Experiments (OSSEs) which estimate the potential future impact of new atmospheric measurements on weather forecast accuracy. We continued the dialog in the hope that StratCon characteristics could be included for some possible future simulations.

In early February 2001 (after the NIAC Site Visit) GAC gave a paper on global balloon constellations to the Workshop on Space-Based LIDAR Winds. Considerable interest was generated in the concept including the potential for a new constellation application for high resolution river monitoring which GAC followed up in May 2001 by developing a presentation material for the *HydraSat* Hydrology Working Group meeting in Greenbelt, MD. GAC personnel were not able to attend this meeting, but Dave Emmitt from Simpson Weather Associates presented some StratCon information from Global Aerospace Corporation at the meeting.

After the AMS presentation by GAC, Randolph Ware, Director of the GPS Science and Technology Program at the University Corporation for Atmospheric Research (UCAR), approached GAC to discuss the use of GPS signals to obtain useful atmospheric information. There are two potential ways to use GPS signals to determine atmospheric parameters from a balloon platform: occultation and surface reflection. After the AMS meeting, GAC made several additional contacts in the GPS atmospheric science community that are listed in the table above.

In March of 2001, we made progress on a hurricane tracking application and initiated development of a new hydrology science. Regarding hurricanes, we identified some hurricane scientists/meteorologists at NOAA who are responsible for hurricane warnings. They are interested in reducing the over-warning ratio, the length of coastline placed under hurricane warnings to the length experiencing hurricane conditions, from approximately 3:1 to 2:1. A constellation of stratospheric balloons could provide data that would help reduce over-warning.

In addition, we obtained some data that provides a quantitative spatial picture of hurricane winds as a function of altitude and distance from the eye. The data will be useful for developing trajectory control system concepts that may be able to track hurricanes. We also began exploring a new science option for stratospheric constellations of balloons, namely global hydrology. It is important for climate researchers to understand continental water runoff when analyzing the global water budget and predicting how that budget will be affected by global climate change. NASA is developing instrumentation concepts and ideas for measurement of quantities such as river and lake water level, river and lake spatial dimensions, and river discharge that will assist researchers in analyzing the global water budget. Satellite systems have been proposed for such measurements, but limited time over target is a potential limiting factor for their usefulness. In contrast to satellites, a network of balloons could provide high-accuracy measurements with sufficient time over target. For climate change research, rivers larger than 250 m in width would need to be studied with a revisit frequency of 1 visit/week.

In June 2001 we prepared a letter to Mel Shapiro at NOAA. He is one of the authors of a proposal for The Hemispheric Observing System Research and Predictability Experiment (THORpex) that endeavors "to test the hypothesis that 2 to 10-day numerical forecasts of high-impact weather events can be significantly improved by adding high-quality observations in critical areas of the extra-tropical oceanic storm-tracks and other data-sparse remote areas, and that cost-effective new *in situ* observing systems can be developed to provide these required observations." Our letter discussed the StratCon concept and indicates that it could provide significant data for THORpex. THORpex is a large experiment that will determine, both numerically and experimentally, the effectiveness of "adaptive sampling," i.e. tuning the worldwide observing system to obtain weather forecast improvements by collecting relatively few high-impact measurements in data-sparse regions. Shapiro is a prominent member of the THORpex International Science Working Group (ISWG). Dr. Shapiro and other members of the ISWG prepared a THORPEX proposal to two World Meteorological Organization (WMO) working groups: the World Weather Research Program (WWRP) and the Working Group on Numerical Experiments (WGNE). The proposal was submitted in October 2001. If approved, the WMO will indicate to member countries that THORpex activities should commence. Funding for THORpex comes from WMO member countries and agencies: it is the task of the THORpex proposers to obtain funding for the activities, because the WMO does not distribute funding itself. In the U.S., NOAA, NASA, ONR, and NSF are being cultivated as potential sources of funding by U.S. members of the THORpex ISWG. The letter sent to Shapiro generated some interest and led to continuing discussions with Dr. Rolf Langland of the Naval Research Laboratory, Monterey, another member of the THORpex ISWG. The ideas being developed by GAC in the NIAC StratCon activity could play an important role in meeting the THORpex objectives. A successful StratoSat™ platform demonstration mission in the context of THORpex could steer THORpex towards accepting constellations of StratoSat™ platforms as one of the "cost-effective, new observing systems." We prepared material for Langland that was included in the THORpex proposal.

In July 2001 we began development of global disaster monitoring applications for StratCon. GAC joined the Global Disaster Information Network (GDIN). Information about GDIN can be found at http://www.gdin.org. The GDIN is a UN-endorsed body that endeavors to "get the right information, to the right people, on time in order to make the right decision, so as to help mitigate and effectively respond to the toll of natural and man-made disasters." We held discussions with Larry Roeder, U.S. Department of State, the GDIN policy advisor for natural disasters and emergency information, regarding the use of StratoSat™ systems for global disaster monitoring. We have been asked to prepare a web page highlighting the StratCon concept and how it could be used for GDIN. In addition, we were asked to submit a paper on the StratoSat™ platform concept for the GDIN 2002 conference held in June 2002 in Rome, Italy. Mr. Roeder was interested on a possible pilot project. In August 2001 we continued our work on developing StratCon concepts to meet the objectives of the Global Disaster Information Network (GDIN). We prepared a report showing how StratCon concepts could be used to meet GDIN objectives. The report has been submitted to GDIN for inclusion in their website.

In August 2001 we also began communications with Russian researchers regarding the potential use of balloons for Earth magnetic field measurements. We replied to expression of interest from Dr. Valery Fomichev, the Deputy Director of IZMIRAN (Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of Russian Academy of Science). IZMIRAN has extensive experience in utilization of stratospheric balloons for measurements of Earth's magnetic field. A number of experiments were performed in 1993 utilizing the gradientmeter developed at IZMIRAN. We discussed with Dr. Fomichev potential integration of the StratoSail® TCS onto the existing experimental setup and utilizing the trajectory control possibilities for three-dimensional mapping of the magnetic field anomalies. Such maps may provide valuable insight into the fault structure of the continental crust and potentially assist in earthquake prediction. Dr. Fomichev shared with us technical information pertaining to the design of the IZMIRANs experiments and agreed that trajectory control is very important for three-dimensional mapping of the magnetic field. These discussions eventually led to a visit in June 2002 by Dr. Yuri Tsvetkov to the US to attend an Earth Science Working Group meeting on science requirements for stratospheric platforms.

In September 2001, GAC submitted StratCon material to Dr. Langland for the THORpex proposal to the WMO World Weather Research Program (WWRP), Scientific Steering Committee (SSC) and the Working Group on Numerical Experimentation (WGNE). The submission can be found in Appendix 4. The THORpex proposal has been submitted to these committees and will be reviewed in Geneva, Switzerland and Offenbach, Germany, respectively, at the end of October 2001. Information on StratCon is included as one of several options for in-situ observing systems.

In November 2001, GAC visited NASA HQ to have discussions with Code Y personnel regarding global constellations of balloon platforms for Earth science. GAC met with and briefed Mr. Ed Sheffner and Alex Tuyahov, both of whom support the NASA Earth Science Applications Office. The purpose of the Applications Office is to facilitate applications of NASA Earth science, technology development and data to a broader use.

### 3.1.3. Applications Development 2002

In February 2002, GAC talked with Dr. Frank Marks of NOAA Hurricane Research Division about applications of stratospheric balloon constellations to hurricane tracking. GAC met Dr. Marks at the January 2002 American Meteorological Society (AMS) meeting. Dr. Marks suggested that one of the useful applications for such a constellation, apart from scientific observations of the hurricanes, might be to provide a real time data link from a hurricane observing aircraft to the ground station. GAC also contacted Dr. Sim Aberson, a research meteorologist at NOAA/AOML Hurricane Research Division, who is closely involved in dropsonde observations of hurricanes. Dr. Aberson indicated his interest in the StratCon concept and agreed to further discussions.

In June 2002, GAC attended the Global Disaster Information Network (GDIN) annual meeting in Rome, Italy. GAC's attendance at this meeting is part of our ongoing efforts to define applications for the StratCon concept. At the GDIN annual meeting in Rome in June 2002, GAC presented constellation simulations that introduced global Stratospheric Satellites as a means of providing communications and remote sensing data for disasters in remote areas of the world. Mr. Baker, of GAC, was also asked to be the rapporteur for the GDIN Industry Working Group at the Rome meeting. At the meeting, Mr. Baker contacted several other industry and government personnel to discuss using stratospheric balloons for global disaster monitoring.

Also in June GAC briefed the National Polar-orbiting Operational Environmental Satellite System (NPOESS) science management. NPOESS is a joint NASA/NOAA/DOD program to "provide the U.S. with an enduring capability to globally measure atmospheric, land, and oceanic environmental parameters. The system will provide timely and accurate weather and environmental data to weather forecasters, military commanders, civilian leaders, and the scientific community." Interest was expressed in StratoSat™ Platforms as potential elements of a calibration/validation program for the system, and as a possible testbed for NPOESS sensor development.

Table 3-2 and Table 3-3 below summarize potential contributions of StratoSat™ platforms to NPOESS. Table 3-2 lists the sensors that would be carried by NPOESS satellites and their brief descriptions in the first four rows of the table. The products that would be provided by NPOESS are listed in the leftmost column of the table. The cells marked by * indicate that the sensor in the column would contribute the product in this row. The cells colored by yellow indicate potential contribution by StratoSat™ platforms. The cells also contain a short description of the potential contribution. As can be seen in Table 3-2, StratoSat™ platforms can potentially contribute to all sensors and products, except for the ionospheric measurements.

Table 3-3 is similar to the Table 3-2, except it lists "payloads similar to existing instruments" and "shared data" that would be a part of NPOESS. As before, StratoSat™ platforms can potentially benefit all payloads and datasets, but one.

Finally, in September 2002, we presented the Stratospheric Satellite concept at the National Reconnaissance Office technology seminar (see Appendix 1 for the briefing).

Table 3-2. Potential Contributions of StratoSat™ Systems to NPOESS (1)

| **NPOESS Product** | | **Sensors under development** | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **Sensor Name** | **VIIRS — Visible/Infrared Imager/Radiometer Suite** | **CMIS — Conical Microwave Imager/Sounder** | **CrIS — Crosstrack Infrared Sounder** | **GPSOS Global Positioning System Occultation Sensor** | **OMPS — Ozone Mapping and Profiler Suite** | **SESS — Space Environment Sensor Suite** | **ATMS — Advanced Technology Microwave Sounder** |
| | **Sensor Summary** | Collects visible and infrared radiometric data of the Earth's atmosphere, ocean, and land surfaces. Data types include atmospheric, clouds, Earth radiation budget, land/water and sea surface temperature, ocean color, and low light imagery. | Clouds, sea winds, hurricanes, rainfall. Collects global microwave radiometry and sounding data to produce microwave imagery and other meteorological and oceanographic data. | Atmospheric moisture, temperature, pressure. Measures Earth's radiation to determine the vertical distribution of temperature, moisture, and pressure in the atmosphere. | Measures the refraction of radiowave signals from the GPS and Russia's Global Navigation Satellite System (GLONASS) to characterize the ionosphere. | Collects data to permit the calculation of the vertical and horizontal distribution of ozone in the Earth's atmosphere | Magnetic fields, electron, aurora. Neutral and charged particles, electron and magnetic fields, and optical signatures of aurora. | In conjunction with CrIS, global observations of temperature and moisture profiles at high temporal resolution (~ daily). (currently under development by NASA) |
| | **Resolution & Coverage** | 0.3-14 micron spectral range; 400 to 800 m resolution. | 15 to 50 km horizontal resolution, 2 km vertical resolution; vertical coverage from surface to 100 mb | 3.5 to 16 microns spectral range; 15 km horizontal and 2 km vertical resolutions. | | 50 to 250 km horizontal and 5 km vertical resolutions, coverage from 0 to 60 km | | 23-183 GHz |
| **Ocean Wind Vectors** | | | * higher spatial resolution measurements from lower altitude | | | | | |
| **Atmospheric Profiles** | | | * Validation of atm. profiles with dropsondes, 20 m vertical resolution, profiles above 100 mb | * Validation of atm. profiles with dropsondes, 20 m vertical resolution. | | | | * Validation of derived atm. profiles with dropsondes |
| **Ocean Color & Sea Surface Temperatures** | | * Higher resolution imagery and higher sensitivity (SNR) from lower altitude | * higher resolution imagery & meas. from lower altitudes | | | | | |
| **Land Measurements** | | * Higher resolution imagery and higher sensitivity (SNR) from lower altitude | * higher resolution imagery & meas. from lower altitudes | | | | | |
| **Improved Ozone Monitoring** | | | | | | * High vertical resolution profile validation with (developing) dropsondes below 35 km | | |
| **Aerosols** | | * Higher resolution imagery and higher sensitivity (SNR) from lower altitude | | | | | | |
| **Ionosphere** | | | | | * | | | |
| **Distress signal relay** | | | | | | | | |
| **ERB** | | | | | | | | |

| | |
|---|---|
| * | Sensor Contributes to NPOESS Product |
| 🟨 | StratoSat Platform Contributes to NPOESS Product |

Table 3-3. Potential Contributions of StratoSat™ Systems to NPOESS (2)

| **NPOESS Product** | | **Payloads similar to existing instruments** | | **Shared data from other agencies** | |
|---|---|---|---|---|---|
| | **Sensor Name** | **SARSAT — Search and Rescue Satellite Aided Tracking** | **TSIS — Total Solar Irradiance Sensor** | **ASCAT — Advanced Scatterometer** | **CERES — Clouds and the Earth's Radiant Energy System** |
| | **Sensor Summary** | The SARSAT system uses NOAA satellites in low-Earth and geostationary orbits to detect and locate aviators, mariners, and land-based users in distress. | TSIS is a total solar irradiance monitor plus a 0.2-2 micron solar spectral irradiance monitor. This is being developed by NASA | Being flown on METOP—ocean measurements (surface stress and surface wind), sea ice coverage | **On ERBS**—Earth Radiation Budget Satellite (1984) |
| | **Resolution & Coverage** | | | 50 km resolution | |
| **Ocean Wind Vectors** | | | | * higher resolution from lower altitude (?) | |
| **Atmospheric Profiles** | | | | | |
| **Ocean Color & Sea Surface Temperatures** | | | | | |
| **Land Measurements** | | | | | |
| **Improved Ozone Monitoring** | | | | | |
| **Aerosols** | | | | | |
| **Ionosphere** | | | | | |
| **Distress signal relay** | | * signal amplification & relay | | | |
| **ERB** | | | * | | * More accurate "ground" truth flux measurements from TOA with Active Cavity Radiometer, calibration and validation |

## 3.2. Earth Science Applications

We have developed a number of concepts for applications for constellations of StratoSat™ platforms in collaboration with scientific community. These applications cover measurements of Earth Radiation Balance (ERB), monitoring of ozone and water in tropics and midlatitudes, geomagnetic measurements, measurements of tropospheric winds with LIDARs, adaptive sampling for weather prediction, hurricane tracking, global hazard monitoring and disaster management. We describe each application in more detail below.

### 3.2.1. Earth Radiation Balance (ERB)

The Earth's climate system is driven by the distribution of incoming energy from the sun and the outgoing energy escaping to space. The earth radiation balance (ERB) is constantly changing due to natural and anthropogenic changes on regional and global scales, such as clouds, jet contrails, the surface, and the atmosphere. The measurement of the solar radiant flux reflected from and the terrestrial radiant flux emitted by the earth-atmosphere system is an integral part of NASA's Earth Science Enterprise program. A new set of Earth radiation balance data is now being provided by the NASA CERES (Clouds and the Earth's Radiant Energy System) instrument on the Tropical Rainfall Measuring Mission (TRMM), by the Terra satellite mission that began in March 2000 and is expected to continue through 2007, and also by the newly launched Aqua satellite. Figure 3-3 shows an example of data being returned by Terra CERES instrument. The image shows monthly averaged thermal (LW) radiation emitted to space from Earth's surface and atmosphere (left sphere) and sunlight (SW radiation) reflected back to space by the ocean, land, aerosols, and clouds (right sphere) for the month of April, 2001. The LW flux varies from about 100 W/m$^2$ (light-blue) to 350 W/m$^2$ (yellow). SW flux varies from 0 W/m$^2$ (blue) to about 400 W/m$^2$ (light-green) (Data courtesy Bruce Wielicki and Takmeng Wong, and the CERES Science Team at NASA Langley Research Center; Images courtesy Tom Bridgman, NASA GSFC Scientific Visualization Studio).

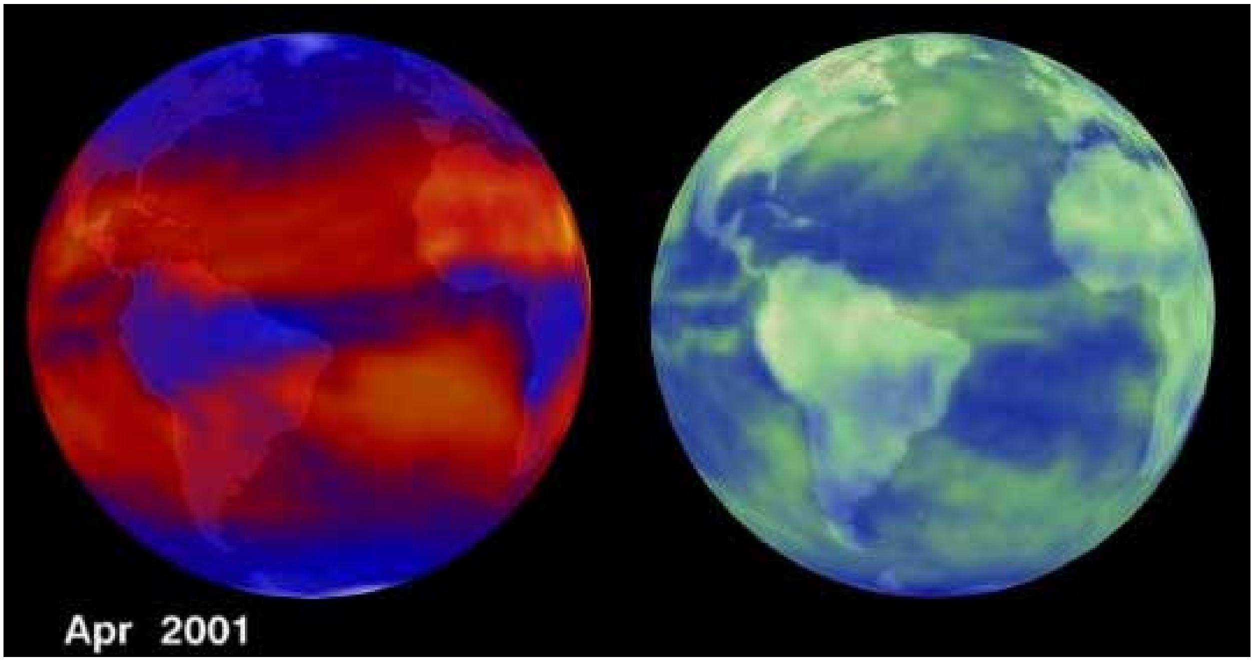


Figure 3-3 LW and SW fluxes measured by CERES.

The ERB measurements on these missions assist the development and testing of our ability to predict long-term climate variability, seasonal-to-interannual changes on the local-to-global scales, and the effects of natural disasters such as major floods, biomass burning, and volcanic eruptions.

A weakness of all space-based radiometric instruments is that they are calibrated in terms of the radiance ($W/m^2/sr$). The radiance data returned from space must then be converted from radiance at orbital altitude to flux ($W/m^2$) at the TOA. This is accomplished using the earth-satellite geometry along with angular directionality models (ADMs) to account for the directionality of thermal radiation emitted and sunlight reflected from the earth-atmosphere system. Integration of the net flux (incoming minus outgoing) over the area of an imaginary sphere defined by the TOA then yields the earth radiant energy budget (W). Integration of the net flux over a spherical sector of this imaginary sphere yields the regional earth radiant energy budget. In most ERB satellite missions such as CERES, the radiance-to-flux conversion process is the principal source of uncertainty in instantaneous fluxes estimated from radiance measurements. It introduces a 4-percent averaged uncertainty in the flux estimation (instantaneous error can be up to 100%).

An advantageous location from which to measure the ERB is the TOA, where in-situ measurements can be utilized directly. StratoSat™ platforms offer the possibility of positioning a flux-measuring instrument at the TOA, thereby measuring the desired flux directly and so obviating the need for ADMs and their attendant uncertainty. StratoSat™ platforms can be used to validate satellite measurements or to do independent observations.

Direct flux measurements from a StratoSat™ platform will be a very valuable validation dataset for satellite ERB measurements, because they eliminate all the assumptions needed in remote sensing. Since the calibration uncertainty of the satellite instrumentation itself is better than 1 percent, we expect the direct measurements can provide more accurate flux products if we move those instruments to 35 km. The non-science cost of the low-cost StratoSat™ platforms could be much lower than that of satellite missions.

For a StratoSat™ platform at 35 km, the spatial resolution of the flux measurement is on the order of 700 km. Satellite data produced by ADM have a spatial resolution of about 100 km. 100-day long StratoSat™ platform mission would provide opportunity to validate flux products generated using ADMs for CERES. More important, 100-day operations offer an opportunity to study seasonal variations.

In addition, fluxes measured from a constellation of StratoSat™ platforms do not have diurnal bias because all times of day are sampled. They also do not have sun-angle bias. Slow-moving StratoSat™ platforms (approximately 1-percent as fast as satellites) can observe the dynamics of terrestrial and solar radiation. From sunrise to sunset, a StratoSat™ platform could capture the diurnal variations of the TOA fluxes over particular area. A constellation of StratoSat™ platforms would be able to monitor dynamic changes in LW and SW fluxes over the entire globe. This would provide unprecedented data to study short time scale phenomena in a continuous and global observation context.

One can start with a single StratoSat™ platform to test the whole system. The horizontal coverage of these measurements would be of the order of 1000 by 1000 km, with the resolution of 50 to 100 km. The horizontal resolution is the distance between the successive measurements. It may be equal to the dimensions of the radiometer footprint. The flight duration could be 10 days. This application would be very useful for supporting satellite validation.

One then could move to regional coverage, with a small constellation (3-5 StratoSat™ platforms) participating in a field mission to provide the TOA fluxes for radiation closure measurement or satellite retrieval validation purposes. Regional coverage by StratoSat™ platforms can also be used to trace the severe weather system, such as thunderstorm and squall. The horizontal resolution would be of the order of 100 to 200 km with the flight duration from 6 month to a year. This would become a most useful tool to assist some field programs such as the joint Atmospheric Radiation Measurement (ARM) supported by the Department of Energy and several other agencies including NASA.

Eventually one would hope to have a large constellation to measure the ERB globally. The measurement resolution would be of the order of 200 to 500 km with the flight duration from 5 to 10 years.

The measurements would be adaptive, meaning that the platforms would be directed and repositioned to observe specific phenomena or regions. Angular distribution and spectral flux measurements, vertical atmospheric profiles and surface properties measurements could be done simultaneously with the total flux measurements. Atmospheric and surface properties could be done over longer – synoptic – timescales, than the flux measurements, because they are not expected to very significantly over short timescales.

This application would address several questions outlined in the ESE mission statement, namely:

- What trends in … solar radiation are driving global climate?
- What are the effects of clouds … on earth's climate?
- How do stratospheric trace constituents respond to change in climate … ?
- How are variations in local weather … related to global climate variation?
- How well can transient climate variations be understood and predicted?
- How well can long-term climate trends be assessed or predicted?

The multitude of measurements and payloads that can be carried by StratoSat™ platforms in the context of the ERB observations are described below.

#### *3.2.1.1. Radiation flux at TOA*

The flux measurements could be done with the active cavity radiometer (ACR) that would provide wide field-of-view broadband flux measurements, scanning spectral radiometer for angular and spectral distribution and a broadband radiometer (scanning or an array of instruments) for angular distribution of broadband radiance. The spectral instrument is needed (as well as broadband instruments) to balance the radiation budget spectrally, rather than just broadband. The advantage of the ACR instrument is in that it is potentially absolute and very stable instrument not requiring calibration in flight.

### 3.2.1.2. Vertical atmospheric profiles of P, T, h, $O_3$, u and v

Knowledge of the atmospheric profiles of pressure (P), temperature (T), humidity (h), ozone ($O_3$) and winds (u and v), obtained simultaneously with the flux measurements would allow to link these parameters to the changes in the ERB and to test the ERB models. The wind measurements are not directly related to the ERB measurements, but could be used to deduce the stability and movement of the platform. The currently existing network of meteorological radiosondes is spatially inhomogeneous and exists primarily over North American and Eurasian continents. The StratoSat™ platforms would carry many lightweight meteorological dropsondes for vertical profiling of the atmosphere. The dropsondes would be similar to GPS dropwindsondes developed at NCAR/NOAA (Figure 3-4). Current dropwindsondes cannot measure ozone, but work is currently being done at NCAR Atmospheric Technology Division (ATD) to include the ozone measurements. Each one currently weighs about 0.4 kg.

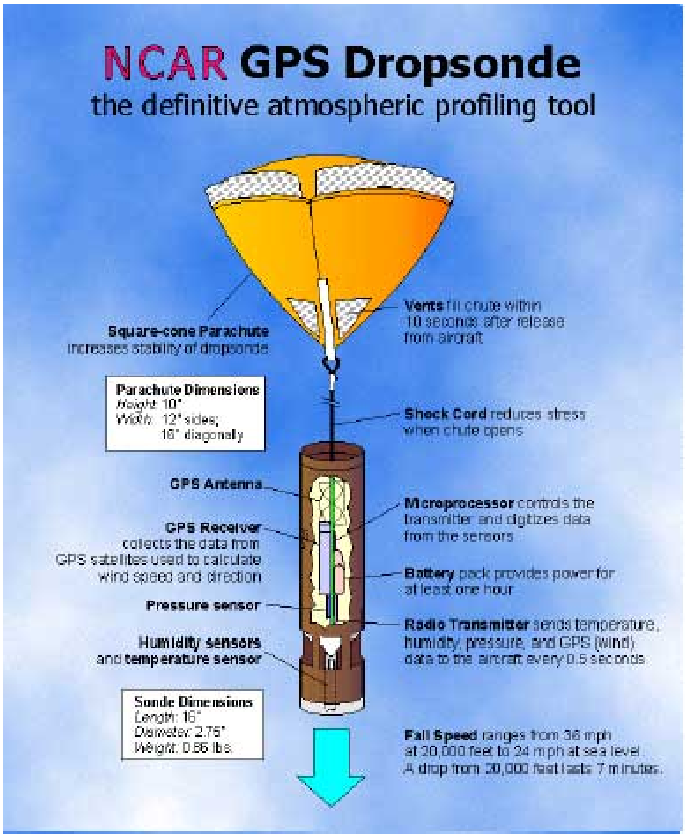


Figure 3-4 NCAR/NOAA GPS dropsonde

### 3.2.1.3. Vertical atmospheric profiles of aerosols and cloud properties

Clouds and aerosols affect ERB by absorbing and/or reflecting the radiation. Simultaneous determination of cloud top and base heights, optical depth, cloud extinction, ice habit, asymmetry factor at more than one wavelength, liquid water content and particle mean effective radius with the flux measurements are needed to test the ERB models and to understand the changes and trends in the ERB. These measurements could be done with cloud radar or an *in situ* dropsonde or profiling drone. Instruments measuring number densities of cloud particles and precipitation particles do exist as separate probes mounted on the meteorological aircraft. There are currently no dropsondes dedicated to such measurements.

These measurements could be supported with the filtered two-color imager for cloud scene/type identification.

### 3.2.1.4. Vertical Profiles of Flux Divergence

Observations of the vertical profiles of flux divergences would also be beneficial for ERB observations. These measurements could be done with a radiation dropsonde. Possible issues with the flux divergence dropsonde measurements include relationship between the dropsonde speed and radiometer response, and levering.

### 3.2.1.5. High-resolution $O_2$, $H_2O$ and $CO_2$ Spectrometry

High–resolution observations of the oxygen A-band, water vapor band (940 nm) and $CO_2$ band (8-9 µm) can provide climatological statistics about cloud fields. The knowledge of the cloud fields is valuable in interpreting the scene from which the flux is measured and for climatology.

Figure 3-5 below shows the schematics of the ERB measurements of the StratoSat™ platform with ACR and cloud LIDAR payloads. The ACR is positioned at the gondola, at the altitude of TOA, while the LIDAR can be positioned at the gondola or at the altitude of the end of the tether, 15 km below the gondola, to increase signal-to-noise ratio. Deployment of a LIDAR at the end of a long tether may present problems with energy transfer from a battery at the gondola.

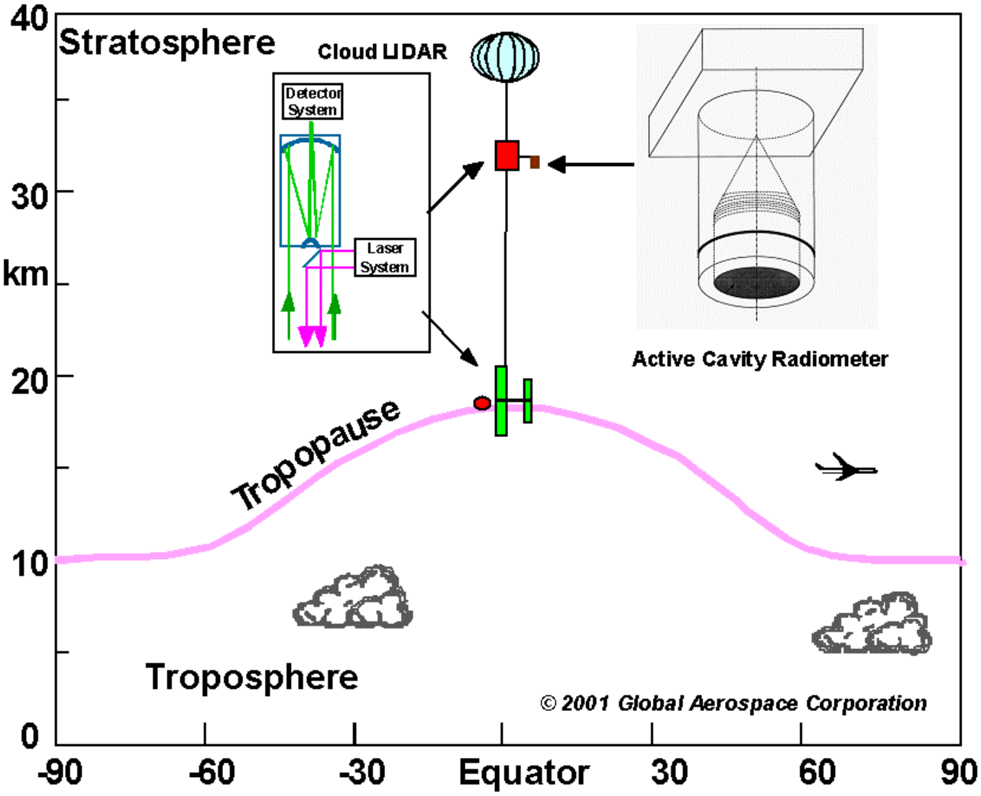


Figure 3-5 Example StratoSat™ platform ERB payload featuring ACR and cloud LIDAR

### 3.2.2. Atmospheric Chemistry

#### *3.2.2.1. Monitoring water vapor budget in stratosphere*

This application addresses the following questions from the ESE mission statement:

- How are global precipitation, evaporation, and the cycling of water changing?
- What trends in atmospheric constituents … are driving global climate?
- How do stratospheric trace constituents respond to change in climate and atmospheric composition?

Key climatological questions are related to the region of the tropical atmosphere between 14 and 20 km, around the tropopause. This region is important climatologically because it is the source region for the bulk of the air that is transported from the troposphere into the lower stratosphere. It is also the region where the mixing ratio of water vapor entering the stratosphere is determined. Water vapor is the most important greenhouse gas in the atmosphere and its stratospheric mixing ratio can have a significant effect on the Earth’s climate. The increase of water in the stratosphere can also lead to larger ozone holes that persist for longer times. Thus, it is important to know what processes control the transport of water in the tropopause region.

*In situ* measurements are needed in this region to resolve the small vertical structure of the changes that are occurring that cannot be resolved with the satellite observations. Above 20 km the gradients of water vapor with altitude, latitude, and longitude are small enough so that the satellite-borne instruments are able to provide the required observations. However, the satellite instruments detect seasonal signatures in water vapor content that extends to higher altitudes than the *in situ* measurements. Thus, one may argue that *in situ* measurements are needed not only in the 14 to 20 km region, but also all the way up to 30 to 35 km.

Whether water vapor of the stratosphere is increasing or not is a controversial question. There are unresolved issues with the accuracy of the existing measurements and their long-term trends. Instrument intercomparisons detailed in Chapter 2 of the December 2000 SPARC (Stratospheric Processes and their Role in Climate) Assessment of Upper Tropospheric and Stratospheric Water Vapor show 20-30% differences between instruments that remain unresolved. Figure 2.69 in chapter 2 of that document illustrates that trend determinations can depend both on the instrument used as well as the time period chosen. Also, water vapor measurements made with the instrument that most convincingly shows an increasing trend in water vapor (the Frost Point Hygrometer) exhibits differences of up to 30% when compared with other *in situ* instruments.

To monitor stratospheric water vapor one has to simultaneously measure methane and molecular hydrogen too, because they affect the water content through oxidation. Molecular hydrogen, however, is typically present at concentrations of 0.5 parts per million with little variability. Thus, the stratospheric payload focused on the stratospheric water vapor budget would simultaneously measure water, methane, pressure and temperature.

If the changes in water vapor content are indeed occurring, the related question is what causes them? If the changes in water vapor concentration are inconsistent with methane changes alone, one would have to look for an alternative explanation. The simplest hypothesis is that the temperature of the tropical tropopause controls the stratospheric water content. The dehydration occurs when air rising in the upper tropical troposphere passes through a temperature minimum, typically called the cold-point tropopause. Ice particles would form, grow and condense out leaving a water vapor mixing ratio determined by the vapor pressure of water at that temperature. The changes in stratospheric water would thus track changes in the temperature of the tropical tropopause.

While there is some published evidence that stratospheric water vapor is consistent with cold-point tropical tropopause temperatures, these temperatures have been decreasing while stratospheric water vapor is reportedly increasing. It is not clear that a single measurement cannot answer the question of what controls the water content of the stratosphere. A set of complex measurements will need to be performed in the upper troposphere (below the tropopause) and lower stratosphere to determine the processes that dehydrate the air entering the stratosphere. In addition to the monitoring measurements, one would measure $CO_2$, CO, isotopic water (HOD and $H_2O^{18}$) to trace thermodynamic history of the air parcel, and vertical velocities. The measurements would need to be made continuously over an extended region, because of the different mechanisms that could be responsible for the dehydration. Today's aircraft cannot provide continuous measurements, thus one would look for constellations of StratoSat™ platforms to perform these measurements. Figure 3-6 schematically illustrates the proposed application.

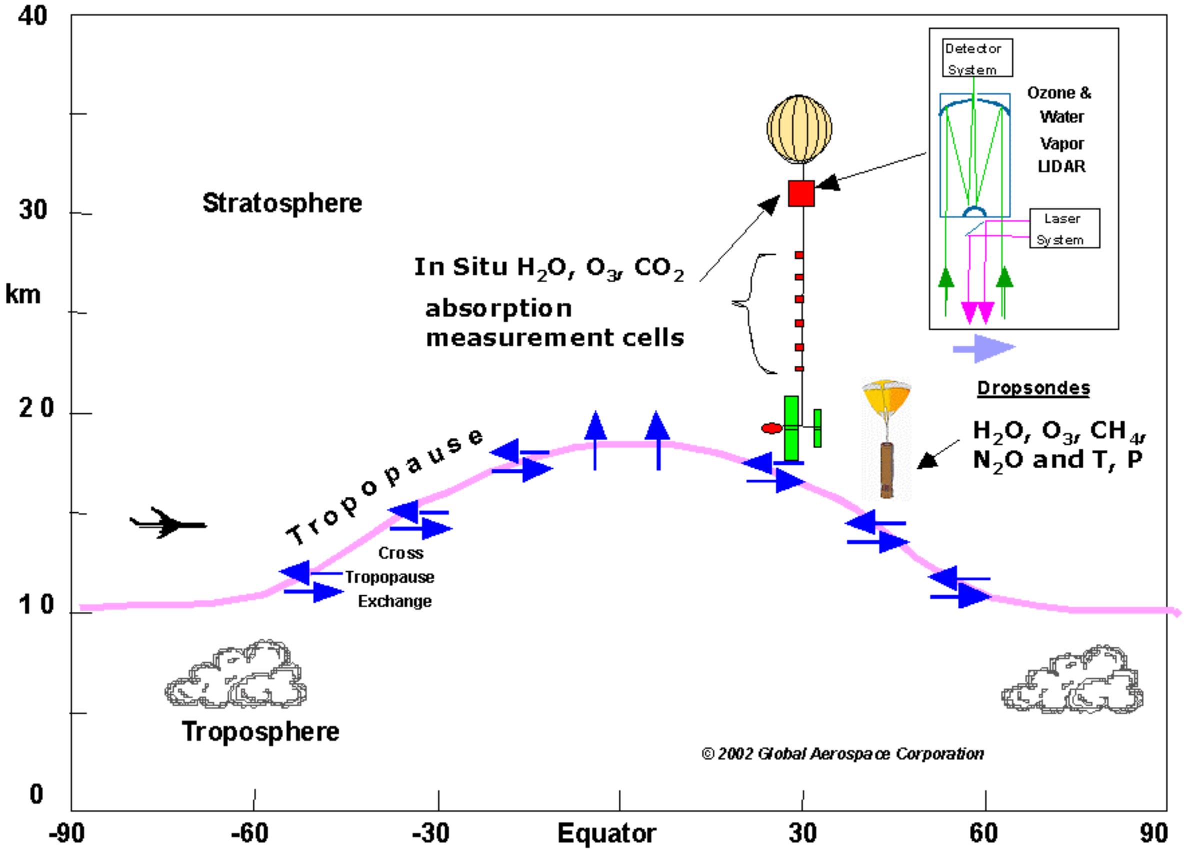


Figure 3-6. Schematic of the stratospheric ozone and water monitoring StratoSat™ platform application

The constellation would cover the tropical and region and mid-latitudes. The poles do not need to be covered. The platforms would be concentrated in the tropical region (between 15° N and 15° S) – 20 to 30 platforms, with about 5 platforms in mid-latitudes. The number of platforms should be sufficient to study different atmospheric flow regimes (jets, monsoons, etc.). The measurements would cover the regions from 14 to 20 km (to see the seasonal cycle) and from 20 to 35 km (for the annual cycle of water) with the vertical resolution of 100 m or better (ideally - continuously). The required flight duration sufficient to obtain a "snapshot" of a season or to observe a transitional season (spring/summer) is about 90 days. During this time the simultaneous observations of the relevant species and parameters must be made once a day. These measurements could be made in conjunction with the ozone measurements (see below).

Water and methane could be measured *in situ* via multipass IR absorption. Two instruments would be needed – one for water, the other one – for methane. $CO_2$ can be measured with a similar instrument, except for calibration gases. The *in situ* absorption instruments can be positioned along the tether in the region of the interest to provide the data on vertical distribution of $H_2O$, $O_3$ and $CO_2$. Advanced dropsondes (not available today) could be employed to measure vertical profiles of $H_2O$, $O_3$, $CH_4$, $N_2O$ concentrations and meteorological variables – pressure and temperature.

### *3.2.2.2. Monitoring trends in stratospheric ozone*

This application addresses the following questions from the ESE mission statement:

- How is stratospheric ozone changing, as the abundance of ozone-destroying chemicals decreases and new substitutes increases?
- What trends in atmospheric constituents … are driving global climate?
- How do stratospheric trace constituents respond to change in climate and atmospheric composition?

Ozone in the lower northern mid-latitude stratosphere has been decreasing by about 1%/year for the last 10 years. The question is whether this is due to *in situ* destruction by chlorine chemistry or is it a dynamics effect. To test the dynamics hypothesis one would need a constellation of stratospheric platforms covering an extended area of the atmosphere, because the ozone is brought into lower mid-latitude stratosphere from different regions, the upper stratosphere, the lower tropical stratosphere, and the upper tropical troposphere. To monitor ozone and to relate ozone changes to a change in atmospheric transport requires a simultaneous measurement of $CO_2$, which gives not only the average stratospheric age of the air but also information on the component of the air mass that recently came from the tropics. By adding the ozone instrument to the payload described in Section 3.2.2.1 one can "kill two birds with one stone" – to monitor both the water and the ozone. The ozone would be measured by an *in situ* absorption instrument. The ozone-monitoring constellation would have 20 to 25 StratoSat™ platforms in northern mid-latitudes (between 35° an 50° N). The number of platforms should be sufficient to capture the structure of the circulation affecting the ozone. The observations would need to be more frequent than once per day, the exact number being constrained by consumables, energy, etc. Figure 3-6 schematically illustrates the proposed payload.

### *3.2.2.3. High-resolution, high-accuracy monitoring of surface sources/sinks of $CO_2$ and other greenhouse gases*

This application addresses the following questions from the ESE mission statement:

- What trends in atmospheric constituents … are driving global climate?
- How do ecosystems respond to and affect … the carbon cycle?
- How well can cycling of carbon through the earth system be modeled … ?

One of the strongest drivers of the warming trends in the Earth atmosphere seems to be $CO_2$ that has been steadily increasing in the atmosphere since the industrial revolution. Because of this it is important to know the budget of the $CO_2$ in the atmosphere. To calculate the budget of the $CO_2$ one has to account for various sources of the $CO_2$, such as biomass burning, and sinks, such as plants, oceans, etc. Based on currently available data, the budget does not come out right – it is inconsistent with the observed increase of the $CO_2$ in the atmosphere. The same is true for the budgets of the other greenhouse gases. Thus, global monitoring of the $CO_2$ (and other greenhouse gases) fluxes is needed to establish the budget. The monitoring assumes remote high-resolution observation of the sources on the ground to identify the so-called "hot spots" of $CO_2$ emission or absorption. The problem with the satellite measurements is that observations from space measure the total atmospheric $CO_2$ column, while the perturbations at the surface are very small. The global total concentration of the $CO_2$ in the atmosphere varies by about 5% seasonally and between the northern and the southern hemispheres. Observations need to be made at greater detail, greater precision and with higher spatial resolution at places that are really active to pick up much smaller sources and sinks in the background.

StratoSat™ platforms offer an unprecedented opportunity for long term monitoring of concentrations of atmospheric species and $CO_2$ in particular with LIDARs. LIDARs are hard to use for this purpose from space, because even at Low Earth Orbits (LEO) the LIDARs require large telescopes and powerful lasers. At 35 km the signal is 100 times stronger than at 350 km (typical LEO orbit) or 400 times stronger than at 700 km (sun synchronous orbit) and LIDARs may not need telescopes or a powerful laser.

Another advantage of the use of the StratoSat™ platforms is the increased time of observation of localized regions that would allow seeing the daily dynamics of the source/sink. Polar LEO satellites are only able to observe a given point on the surface twice a day. Constellations of several hundred StratoSat™ platforms can provide a more or less uniform coverage comparable to coverage from a polar satellite. The cost of multiple expensive instruments (LIDARs) may make this option impractical. On the other hand, global coverage is not required. There is already some understanding of where the important spots are. For example, no coverage is required over Arctic (although it may be possible), because the $CO_2$ fluxes are usually linked to biological activity.

The suggested application is also applicable for monitoring greenhouse emission treaty obligations. Initially, the payload will contain instruments to measure $CO_2$. Observations of other greenhouses gases are dependent on the development of smaller sensors. The instruments would measure concentrations below the boundary layer or the total column abundance. Topography may need to be measured simultaneously with the other measurements, to provide context for the total column abundance. The number of species that can be measured from a single platform would be determined by power constraints. A separate LIDAR or passive instrument would be needed for every species. A passive instrument, such as interferometer, spectrometer, reflected sunlight radiometers or similar, can be used to measure concentrations of greenhouse gases and specifically $CO_2$.

#### *3.2.2.4. Polar Ozone Loss*

This application addresses the following questions from the ESE mission statement:

- How is stratospheric ozone changing, as the abundance of ozone-destroying chemicals decreases and new substitutes increases?
- What trends in atmospheric constituents … are driving global climate?
- How do stratospheric trace constituents respond to change in climate and atmospheric composition?

It also responds to Recommendation Three of the Pathways report, *Elucidating the links among radiation, dynamics, chemistry, and climate, as well as* Recommendation Four advocating that *Earth observations must more aggressively employ technical innovation.*

Data has shown that the potential for polar ozone depletion depends on the length of time the vortex holds together and how long the temperatures in the vortex remain cold enough for polar stratospheric clouds to form. Ozone depletion has been observed in the poles but quantification is difficult. Air in the vortex is continually descending and being mixed with air external to the vortex. Quantifying ozone loss requires the ability to calculate the fraction of air mixed into the vortex and what is the character of that air.

A NASA sponsored mission: SOLVE, utilizing balloon and aircraft instrumentation was designed to study the formation and breakup of the vortex. This type of mission required extensive planning and relies on the ability to time the formation and breakup of the vortex. Conventional balloon-borne payloads with instruments capable of measuring the structure of the atmosphere around and in the vortex can only realistically provide measurements twice during a winter to spring period and aircraft have a limited number of missions into the vortex. Additionally, the aircraft can only reach about 20 km thus accessing only the bottom of the vortex. Two StratoSat™ platform payloads with proven instrumentation are proposed here.

One, an *in situ* high accuracy, high precision, sub-kilometer altitude resolution payload containing the following instruments:

- JPL ALIAS II ($N_2O$, $CH_4$)
- NASA ARC Argus ($N_2O$, $CH_4$)
- Harvard University Carbon Dioxide ($CO_2$)
- NOAA CMDL LACE (sulfur hexafluoride ($SF_6$), and fluorocarbons CFC-11, CFC-12, CFC-113)
- JPL Ozone ($O_3$, P, and T)

- NOAA CMDL Water vapor ($H_2O$, P, and T)

All these instruments take data on descent, and some on ascent, thus providing 1 to 2 high-resolution profiles per launch.

Two, a remote sensing payload containing the following instruments:

- JPL Mark IV solar infrared absorption provides 2 km altitude resolution and measures $H_2O$, $CH_4$, $N_2O$, CFC-11, CFC-12, $SF_6$, $O_3$, $CO_2$, CO, NO, $NO_2$, $HNO_3$, HCl, HF, $CF_4$.
- JPL Submillimeterwave Limb Sounder (SLS) measures thermal emission profiles from stratospheric ClO, HCl, $N_2O$, $CF_2CL_2$ (CFC-12), and $O_3$.

StratoSat™ platform payloads similar to those flown during the NASA SOLVE mission in the Arctic in 1999-2000 and capable of maintaining their position throughout the fall winter and spring would provide critical information during years with or without significant ozone depletion. The remote sensing payload with an FTIR making absorption measurements in the limb-scanning mode at the gondola would provide detailed information about vortex formation and breakup, transport across the boundary, and mixing of descending vortex air with mid-latitude air from below. In addition to the FTIR, an SLS would be flown. This instrument would specifically be used to measure reactive species responsible for ozone loss. These include chlorine monoxide (ClO), bromine monoxide (BrO), and key radicals responsible for ozone destruction. Currently, the actual measurements of the ClO and BrO profiles are quite infrequent (less than 1 balloon lunch per year) and the flights are short (about 3-10 hours) providing only a couple of profiles. An ultra-long flight (100 days) on a StratoSat™ platform would provide hundreds of profiles and deliver an extensive picture of the evolution of the structure of these reactive species. The *in situ* payload would be used for high accuracy, high precision, sub-kilometer altitude resolution measurements of ozone loss, denitrification, dehydration, and the presence of polar stratospheric clouds. Together the two payloads would provide the means of quantitatively analyzing ozone destruction in the entire vortex.

Figure 3-7 illustrates the combination of payloads in and near the Arctic vortex. The remote sensing payload is as described containing the FTIR and SLS instruments at the gondola. The *in situ* payload contains instruments on the tether, positioned specifically at intervals where maximum ozone loss is expected to occur. That payload will contain two instrument suites. One, a tracer suite, will measure ozone, $H_2O$, $CH_4$, $N_2O$, $CO_2$, pressure and temperature. This will provide detailed information on the transport of air in a region. The other, measuring HCl, and particles will be used to provide information on the detailed calculation of ozone loss. This payload could be used to follow an air mass to do two exciting experiments, one to monitor ozone destruction, the other to follow the formation of polar stratospheric clouds. Such a mission concept can be accomplished with a constellation of 10-20 StratoSat™ platforms each operating in a region from 60° to the pole.

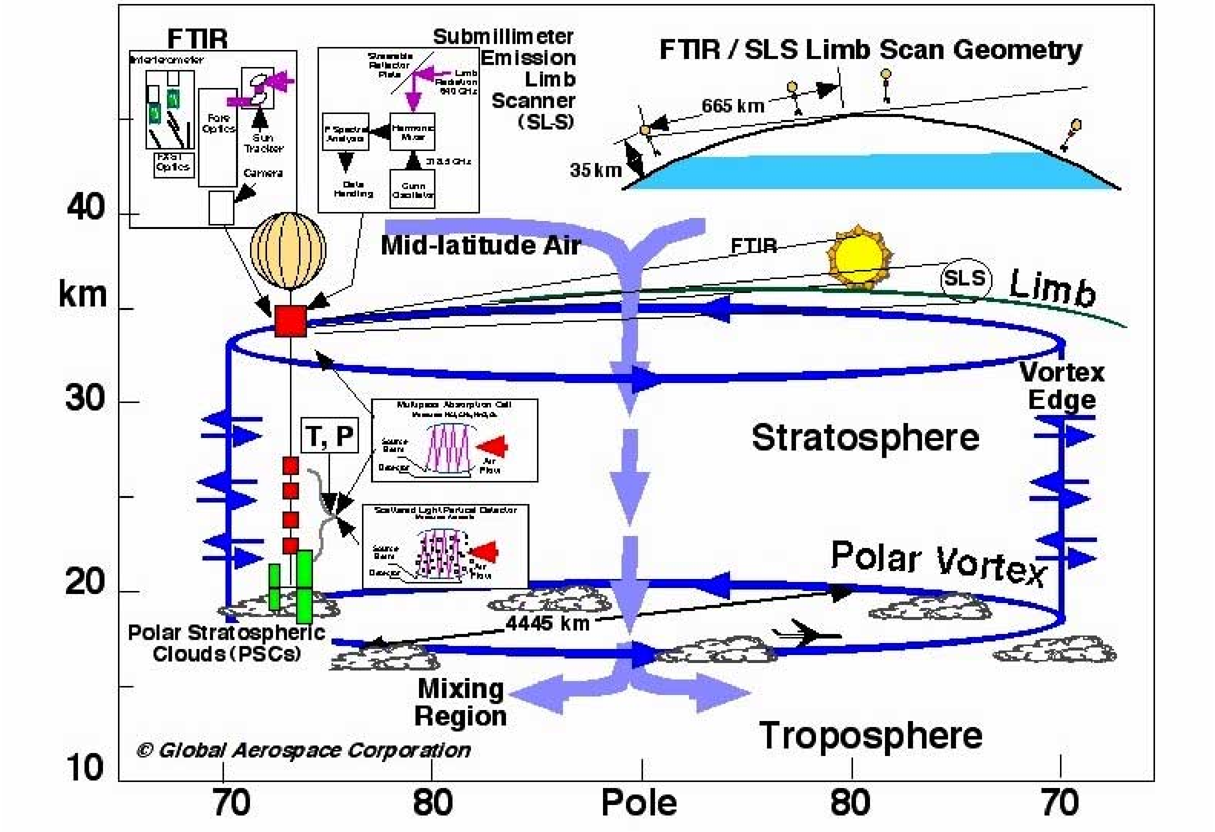


Figure 3-7. Schematic illustration of the polar ozone loss application

### 3.2.3. Geomagnetism

This application would address the following question from the ESE mission statement: What are the motions of the earth and the earth's interior, and what information can be inferred about earth's internal processes?

Based on seismic data the Earth's interior is partitioned into a core, mantle and crust (see cutaway view of the Earth on Figure 3-8, picturing the crust, mantle, liquid outer core, and solid inner core). The crust is the outermost part of the solid Earth and is approximately 30 km thick. The structure of the crust needs to be studied to understand the geological processes (like plate tectonics) that shape the surface of the Earth.

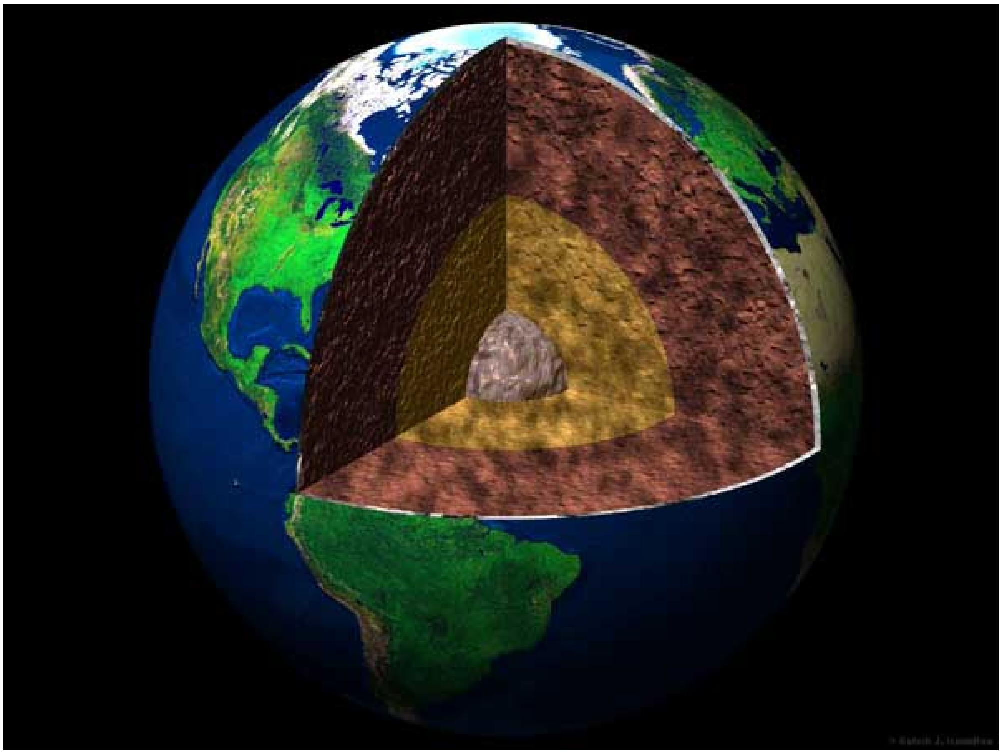


Figure 3-8 Cutaway view of the Earth (image copyright Calvin J. Hamilton, http://www.solarviews.com).

One of the ways to study the crustal structure is by measuring the Earth’s magnetic field. Structure, depth to magnetic source, location of source, magnetization directions, and conductivity distribution could be deduced from these measurements. Measuring the Earth’s magnetic field from StratoSat™ platforms offer several advantages over surface, aircraft, and satellite measurements.

Even though surface measurements are made around the world by magnetic observatories, they only cover a small fraction of the Earth’s surface. Systematic observations are lacking over oceans, Antarctica, Africa, South America, Siberia and other places. Aircraft observations lack sufficient range, cannot provide global coverage and are relatively expensive. Measurements from oceanic vessels are slow and expensive. Satellite measurements are affected by ionospheric and magnetospheric disturbances and require very high instrument sensitivity due to the weak field at orbital altitudes (the decrease of magnetic field with distance is inversely proportional to the cube of the distance). The high orbital speed of the satellites also reduces the resolution of the measurements. Long duration StratoSat™ platforms would be able to make systematic measurements over hard to reach places over long periods of time.

Measurements from stratospheric heights would also allow the addition of intermediate wavelength information to the existing surface and satellite surveys. Because the stratospheric altitudes (30-35 km) are comparable to the thickness of the crust (30 km) the whole depth of the crust can be “seen” from these altitudes. While it is beneficial to be closer to the magnetic source (i.e., closer to the surface), “patching” together the surface and satellite surveys calls for higher stratospheric altitudes.

In addition, some magnetic field observations are only possible from stratospheric altitudes. For example, vertical gradient measurements of the magnetic field from the stratospheric altitudes are currently the most reliable method of separating the external and internal components of the Earth's magnetic field and for measuring crustal magnetic anomalies.

Systematic observations are required globally to distinguish magnetic field variations over various spatial and temporal scales, and to separate the effects of the components of the magnetic field. Gradient measurements require simultaneous measurements with 2 km vertical or horizontal resolution to infer magnetization and conductivity distributions. Vertical gradient measurements seem to be more valuable, because the spectrum of such measurements is the same as the spectrum of the field. Vertical gradient measurement can measure magnetic signal from a very deep source, which cannot be done with a horizontal gradient measurement. Gradient measurements are accomplished by simultaneously making measurements by spatially separated instruments. Depending on a platform capability, this may require one or more platforms.

The instrument "footprint" on the surface for magnetic field measurements is of the order of the instrument altitude. To provide complete coverage for a stratospheric survey the platform ground tracks would need to be separated by no more than 35 km to provide overlap between surface instrument footprints. Figure 3-9 illustrates the concept of Earth's magnetic field gradient measurements.

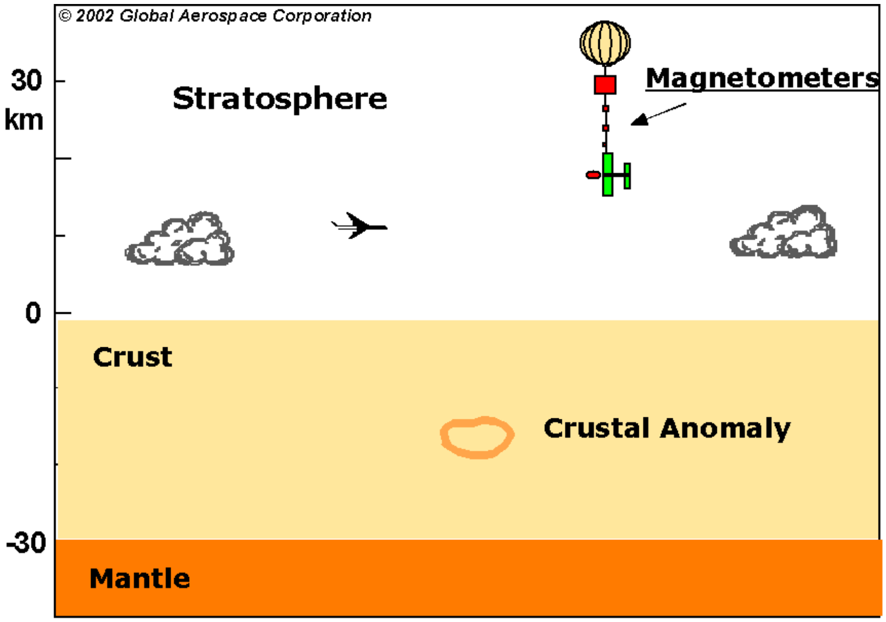


Figure 3-9. Schematic view of the StratoSat™ platform gradient magnetic field measurement

Scalar (proton) and vector (flux gate) magnetometers can be employed for magnetic field surveys. The scalar instrument measures the total value of the magnetic field at a particular point in space. It does not give information about the direction of the magnetic field vector, which fully characterizes the magnetic field. The scalar magnetometer is sufficient for a magnetization distribution survey. The instrument is a light (1 to 2 kg) and relatively cheap instrument with a very light power draw (1 W).

Another approach may employ a vector instrument. Such an instrument would be required for conductivity distribution survey. A vector magnetometer with associated star camera is a relatively expensive instrument package and needs to be recovered after flight termination. It is relatively heavy (5-10 kg) and draws 2 to 3 W of power. Vector measurements have very stringent requirements on the instrument (and platform) attitude knowledge: the attitude must be known to better than 3 arc seconds. The instrument would be calibrated on the ground before the flight.

A third type of magnetometer may be implemented in the future. It is the self-calibrating scalar-vector helium magnetometer currently being developed by the NASA Instrument Incubator Program (IIP).

### 3.2.4. Tropospheric Winds

Several researchers at GSFC are interested in the possibility of measuring tropospheric winds using LIDAR on a balloon platform in the stratosphere. Some researchers are concerned in general about the future of Wind LIDAR research because of the consideration of a Wind LIDAR data purchase option. Several university/industrial teams have suggested they could implement such a system today without further technology development by NASA. Even if wind LIDAR data-buy options are exercised, a balloon-borne LIDAR could have an important data validation role to play.

Some differences between a satellite and balloon LIDAR have been examined. Since the StratoSat™ platform operates lower, there is a gain in SNR that can be translated to lower operating power and/or higher sensitivity and/or reduced telescope aperture and thus size. For the same focal length, the footprint of the LIDAR is smaller, meaning there is higher spatial resolution possible. For a fully optimized experiment one expects to achieve significant improvements in spatial (2-4 km) and vertical resolution (100-200 m) and wind speed accuracy (<1 m/s). Since a global network of StratoSat™ platforms will operate at a wide variety of local times, good diurnal coverage is expected as contrasted with a Sun synchronous satellite that only observes two times of day.

### 3.2.5. Adaptive Sampling for Weather Prediction Research

This application addresses the following question from the ESE mission statement: How can weather forecast duration and reliability be improved by new space-based observation?

Constellations of StratoSat™ platforms can provide an unprecedented opportunity to observe and forecast weather on a global scale. Currently, *in situ* weather measurements are made twice a day at various locations, concentrated primarily over Europe and North America. Large regions remain unsampled, which affects accuracy of the forecast. Numerical analysis suggests that increasing sampling inside the data poor regions (such as North Pacific) can significantly improve short term (3-5 days) and long term (10 days) forecast over CONUS. Constellations of StratoSat™ platforms carrying multiple lightweight meteorological sondes (see Figure 3-4) can gather weather data over hard to access regions or over developing weather systems and thus improve the forecasting capabilities.

**T**he **H**emispheric **O**bserving-system **R**esearch and ***p***redictability ***ex***periment (THOR*pex*) (http://www.mmm.ucar.edu/uswrp/thorpex/THORpex_wmo.pdf) proposes to verify the hypothesis that targeted observations in selected areas can significantly improve weather forecast. Figure 3-10 illustrates a 15-day snapshot of a possible THOR*pex* targeting test mission scenario for a StratoSat™ platform and demonstrates the advantage of trajectory control for targeted observations.

The goal of the simulation shown on Figure 3-10 is to direct the StratoSat™ platform to overfly the data sparse region in the North Pacific denoted by a green box. It is assumed that while inside the target region the StratoSat™ platform deploys meteorological dropsondes every 4 hours. Three trajectories are shown for comparison: of the uncontrolled balloon, of the StratoSat™ platform controlled by a simple control algorithm and of the StratoSat™ platform controlled by a sophisticated control algorithm.

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.

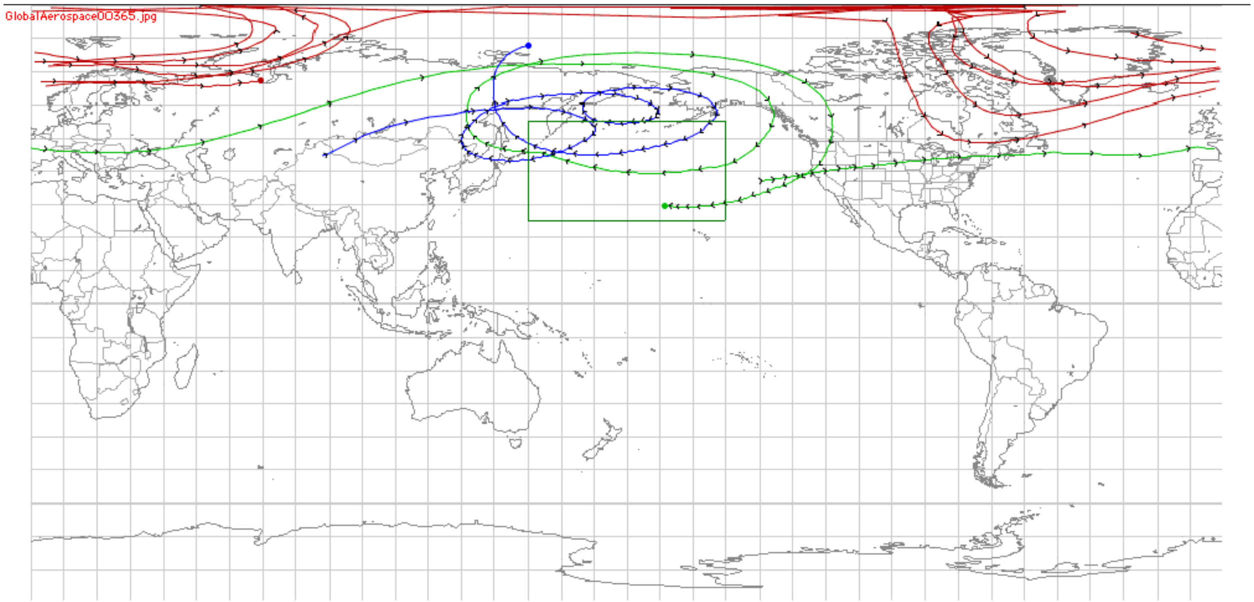


Figure 3-10. A 15-day Snapshot of an Example THORPEX 120 day Targeting Test

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 3-10 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 3-4 gives the number of sonde observations in the region of interest over the 120 days of simulation.

Table 3-4. Number of Observations "in the box" on

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

It can be seen from the Table 3-4 that trajectory control increases the amount of observations in the data sparse region by an order of magnitude. A constellation of StratoSat™ platforms would thus allow long-term presence and meteorological data gathering over data sparse regions.

### 3.2.6. Hurricane Tracking and Monitoring

This application and its payload for hurricane tracking addresses Imperative 2 of the *Atmospheric Sciences entering the 21st century: to* "Develop new observation capabilities for resolving critical variables on time and space scales relevant to forecasts of significant atmospheric phenomena." Its application to providing high-resolution global atmospheric data additionally addresses the Pathways Report recommendation regarding characterizing climate change.

This application also addresses the following question of the ESE mission statement:

- How can weather forecast duration and reliability be improved by new space-based observations, data assimilation, and modeling?

Disruption of life and devastation of property typically occur along the path of a hurricane. The prediction of the paths of hurricanes has improved over the last 30 years, due to the availability of satellite data and fast computers. Even so, 72 hours before landfall the predictions are still in error on the average of by 200 miles. [W. K. Stevens, New York Times, October 4, 1998]. In addition, when a hurricane is forecast to hit a coast on a near normal trajectory, up to 300 miles of coast are placed under a hurricane warning, which is about 4 times the zone that will actually be seriously affected. One financial impact of hurricane warning is the cost of evacuation of coastal areas. Estimates of the cost of evacuation of the Gulf Coast, not counting disruption of commercial activities, is $200 K per mile evacuated [Hurricane Familiarization Booklet, NOAA PA 91001, April 1993]. Depending on the economic sectors along a stretch of coast, the full cost has been estimated between $1-50 M per mile evacuated [C. Adams, The Economic Cost of Hurricane Evacuations, 1st USWRP Science Symposium, March 1999].

Assuming the low estimate for evacuation cost, if the predictions could be improved by only 50% reducing the coast evacuation to 150 miles, a savings would occur of about $150 M for just one hurricane landfall! In Phase I we estimated the cost of emplacement of a 100-balloon network at only $39 M. The economics indicate that it may be useful to examine further the cost and benefits of a regional balloon constellation that is focused on improving hurricane tracking and prediction.

Property damage might be unavoidable, but avoiding disruption and the saving of lives can be the result of more accurate prediction of a hurricane track and its size. There are three complementary areas that need to be addressed in improving hurricane forecasting:

- Accurate high resolution atmospheric pressure, temperature, and wind data
- Ocean temperatures in the vicinity of the hurricane; and
- The physics in the models that use this data for forecasting the track and growth of the hurricane.

The winds in the vicinity of the hurricane are important for predicting where the hurricane is going. The winds outside the hurricane are important for estimation of intensity of the hurricane. Both wind measurements are needed. Currently, satellites provide low-resolution atmospheric data, buoys provide surface wind, pressure, air and ocean temperature, and manned aircraft fly into the storm to supplement the wind, pressure and temperature data around the storm. While this network of information has continued to improve hurricane forecasting, more high quality, high resolution *in situ* data is needed.

A constellation of platforms could be used to address this problem. Stationed in the Atlantic (and Pacific) they could carry dropsondes to measure wind, temperature and pressure in he vicinity of the hurricane. This added information would provide significant data increase input into the models. With a projected sonde mass in ten years of 25 to 50 grams, each balloon payload could have more than 1000 sondes for this experiment that provides profiles from balloon altitude to the surface. In addition to the dropsondes, a Precipitation Radar may be an important instrument on such a payload due to its ability to provide additional data on storm intensity. The possible candidate instruments for a hurricane-focused regional constellation may include:

- Meteorological Dropsondes
- High Resolution Wind LIDAR
- GPS Reflection Sea-state
- Precipitation Radar
- Low Resolution Imager

Figure 3-11 illustrates the number of StratoSat™ platforms required to have a particular over flight frequency. This chart assumed a stationary target.

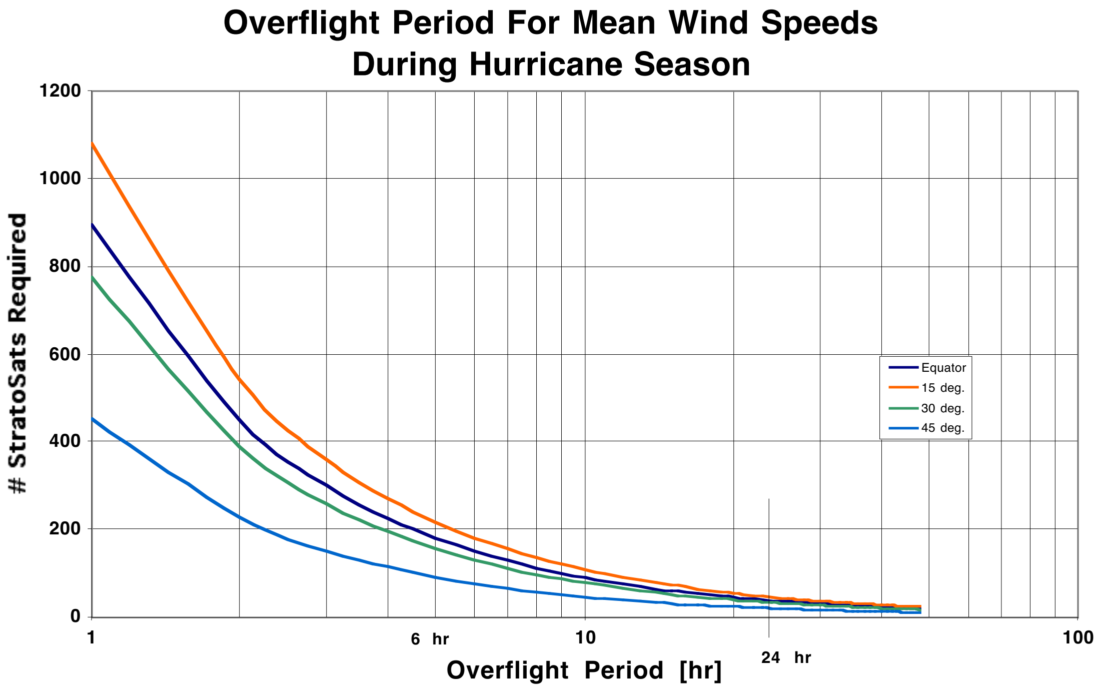


Figure 3-11. Hurricane Overflight Periods

Figure 3-12 illustrates the hurricane intercept application. A string-like constellation of StratoSat™ platforms (indicated by red dots with "tails", representing 24-hour trajectories) intercept a hurricane (a large circle just above the equator) in equatorial Atlantic.

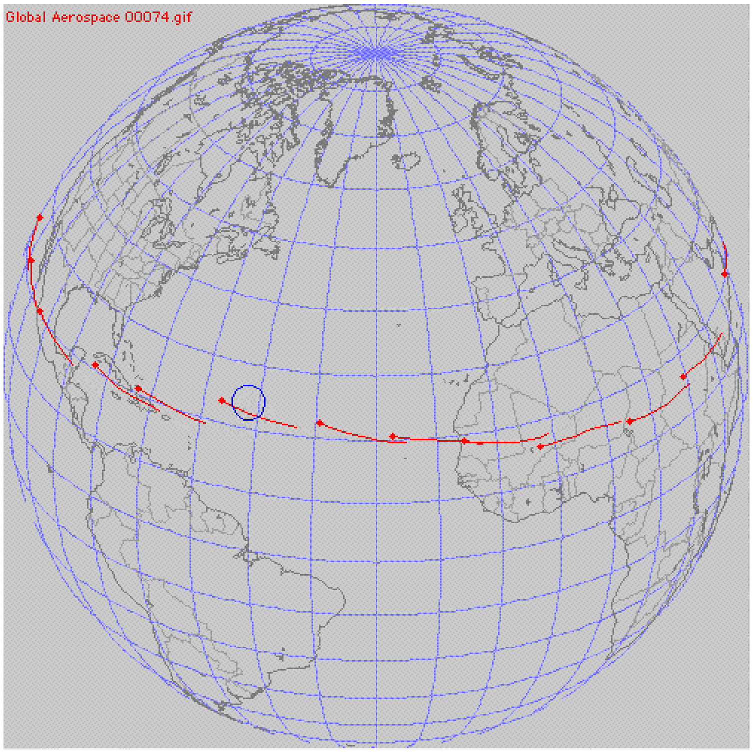


Figure 3-12. Hurricane Intercept Network

Because this constellation of platforms could be useful for weather forecasting as well as hurricane tracking, there should be temperature, pressure, and horizontal wind measurements on the tether, at approximately 3 km intervals. These data could be used for input into assimilated weather forecasting models. Over the last few decades improvements in weather forecasting have been limited more by computing capability than by the lack of physical data. We have reached the stage that the bottleneck for improving weather forecasting is higher resolution data. Satellite data sets have helped to fill in regions where radiosondes are lacking. However, *in situ* measurements will provide climatology data far more accurate than that given by a satellite-based system. Additionally, this network will supplement the global radiosonde network, which has very limited coverage in remote areas.

### 3.2.7. Hazard Detection and Disaster Management

Constellations of StratoSat™ platforms can provide disaster information in time to make the right decisions by globally observing the Earth's surface and detecting and monitoring environmental hazards. Such a constellation can be deployed globally as a part of the Global Disaster Information Network (GDIN, http://www.gdin.org/). The payload may consist of a high-resolution camera for surface imaging, infrared sensitive instruments for mapping the fires or lava flows, spectrometric instruments to detect hazardous gases in the troposphere, communication equipment that can serve as a temporary communication relay link in a disaster stricken area, and such.

A dense constellation of StratoSat™ platforms would allow for a constant “virtual” presence over large areas of the Earth, so that in the event of a disaster a StratoSat™ platform could start to provide images of the disaster site and other information well before any other observing platform can be delivered to the site. As one StratoSat™ platform leaves the observation area carried by the winds, the other one (or several) would enter the area to continue the observations, providing uninterrupted “virtual” presence over the site. The StratoSat™ platform can provide imaging with a higher resolution that can be available from satellites and, more importantly, would be constantly “virtually” present over the disaster site. In addition, the StratoSat™ platforms could provide an emergency communication relay over an area with destroyed communication infrastructure and thus support the emergency relief efforts.

Figure 3-13 below is a snapshot from a simulation of a constellation of the StratoSat™ platforms for disaster monitoring. The constellation consists of 100 StratoSat™ platforms at 35 km initially randomly distributed between ±20° latitude. This latitudinal corridor was chosen because it covers many remotely populated areas that would be difficult to access in the case of a disaster. Presumably, a disaster site in North America or Europe would be more accessible by aircraft and other means due to proximity to developed countries.

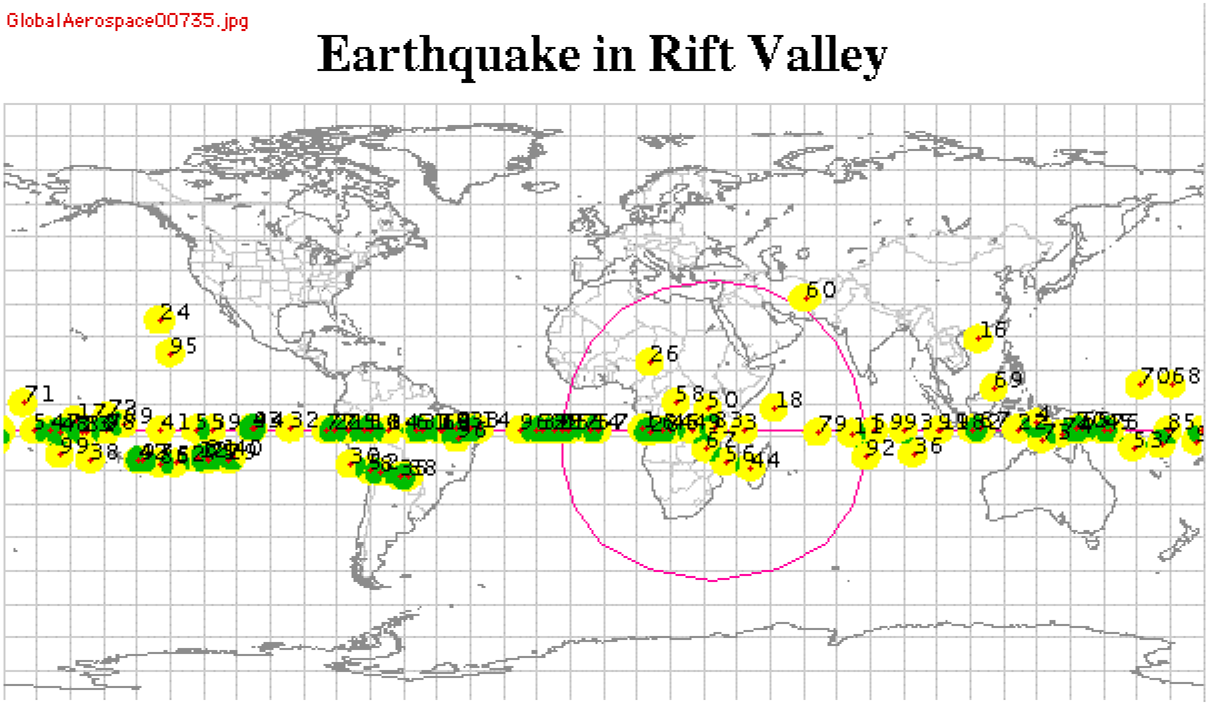


Figure 3-13. Snapshot of the GDIN constellation simulation

The simulation continues for 365 days. It is assumed the StratoSat™ platforms are equipped with the advanced StratoSail® TCS. During this time four disasters occur at four different locations and different moments in time. Figure 3-13 corresponds to an earthquake in the Rift Valley in Eastern Africa. The StratoSat™ platforms are directed towards the site of the disaster once within the “influence zone” (marked by a red circle around the disaster site on Figure 3-13). StratoSat™ platforms outside the “influence zone” are directed to maintain the latitude of the disaster site. Figure 3-13 shows the constellations shortly after the start of the disaster. The StratoSat™ platforms can be seen rearranging into a linear constellation to maintain the latitude of the disaster site (8°S). StratoSat™ platforms within the “influence zone” can be seen floating towards the disaster site. Several StratoSat™ platforms can observe the disaster site.

This simulation indicates that a constellation of 100 StratoSat™ platforms would be able to provide continuous coverage over a disaster site within the ±20° latitude corridor. The access times, i.e. the time between the start of the disaster and the arrival of the first StratoSat™ platform over the site, are of the order of several hours.

# 4. Proof-of-Concept Mission Development

## 4.1. Introduction

A proof-of-concept (POC) mission is the key to the development of global and regional stratospheric constellation concepts. A POC mission does not necessarily have to be a multi-platform mission; although the science to be demonstrated may require more than one platform. A POC mission is intended to show and demonstrate the value of the science that can be conducted on a constellation of platforms, not to demonstrate the technology for the basic systems. An exception to this is where technology needs to be demonstrated if it is being used in a new way, e.g. trajectory control for hurricane intercepts. In general, we propose that such a POC mission is carried out using ULDB technology, which is being tested now. This approach ensures that reliable systems will be available in the near-term and that significant mass margins will be carried. A POC mission is envisioned as a low-cost mission (a few $M) that would be conducted by NASA Code Y as a demonstration mission outside of the usual Announcement of Opportunity (AO) process. The timeframe for this mission is driven by the need to complete the development of all appropriate ULDB flight systems (balloon, TCS, and power) and the need to prepare the science instruments. The earliest date for such a POC mission is estimated to be 2004 or 2005 depending on funding.

In this section we list various mission options, discuss mission requirements of three options.

## 4.2. Proof-of-Concept Mission Options

Several mission options exist for a POC mission, and these are listed below:

a) Hurricane Intercept
b) Global Circulation in the Tropics
c) Earth Radiation Balance
d) High Resolution Tropical Rainfall
e) Satellite Wind Lidar Validation
f) Satellite Radiometry Calibration and Validation
g) Arctic Vortex Ozone

It is possible that several of the demonstration objectives could be carried out on a single mission if financial, payload mass and power resources permitted. Since the full-scale ULDB system has a capability of carrying over 1500 kg of science payload the major constraint will likely be financial in nature. After interaction with the Harvard University, GAC developed three options of particular interest to the Harvard University Atmospheric Research Program (HUARP). After working closely with NASA GSFC, GAC studied Earth Radiation Balance and Satellite Wind Lidar Validation mission concepts. As a result of high interest in the potential for a linear network to better predict hurricane landfall, GAC developed a POC for a hurricane intercept mission.

## 4.3. Harvard Concept Options, Requirements and Analysis

While preparing for discussions with the HUARP at Harvard University in November 2000 regarding possible POC missions, GAC examined three of these options in more detail. The following table shows preliminary requirements for those missions. The *Trop/Strat Transport* column corresponds to a proof-of-concept mission as part of the Global Circulation in the Tropics science theme. The *Radiometry* column corresponds to a complementary satellite radiometry calibration/validation proof-of-concept mission. And the *Ozone Depletion* column corresponds to an arctic vortex ozone proof-of-concept mission as described in the Earth Science Mission Scenarios and Rationale Document (See http://www.gaerospace.com/projects/StratoCon/global_constellation.html). For two of these concepts, it is desirable to obtain continuous vertical profiles of atmospheric parameters, so a vertical translation system (reel-down and reel-up) is considered. Note that several cells in the table are blank indicating that some requirements are unknown at this time.

Table 4-1. Mission Requirements for Several Proof-of-Concept Missions

| | **Trop/Strat Transport** | **Radiometry** | **Ozone Depletion** |
|---|---|---|---|
| Location | **Tropics** | **Tropics** | **Arctic Vortex** |
| Flight Duration | **100 days** | **100 days** | **100 days** |
| Hours of Sunlight Per Day | | | |
| Season | | | **Summer** |
| Gondola Science Altitude | **22 km** | **30 km** | **26 km** |
| Gondola Science Mass | **50 kg** | **100 kg** | **50 kg** |
| Upper Reeled Science Altitude | **22 km** | **Use science pods:** | **26 km** |
| Lower Reeled Science Altitude | **14 km** | **one per km** | **20 km** |
| Reeled Science Mass | **100 kg** | n/a | **100 kg** |
| Ascent Rate | **2 m/s** | n/a | **2 m/s** |
| Descent Rate | **3 m/s** | n/a | **3 m/s** |
| Vertical Translation Duty Cycle | **3 cycles/24 hours** | n/a | **3 cycles/24 hours** |
| Daytime Vertical Translation Duty Cycle | **2 cycles/day** | n/a | **3 cycles/day** |
| Nighttime Vertical Translation Duty Cycle | **1 cycle/night** | n/a | **0 cycles/night** |
| Avg. Gondola Science Payload Power | | **500 W** | |
| Peak Gondola Science Payload Power | | **600 W** | |
| Avg. Reeled Science Payload Power | **200 W** | n/a | **200 W** |
| Peak Reeled Science Payload Power | **275 W** | n/a | |

GAC simulated trajectories of balloons in relationship to satellite ground tracks for complementary radiometry missions, where balloons in a constellation and orbiting satellites would carry similar instruments. Figure 4-1 shows a single balloon trajectory (red) and satellite ground track (blue) and indicates that there are several opportunities for complementary measurements each day.

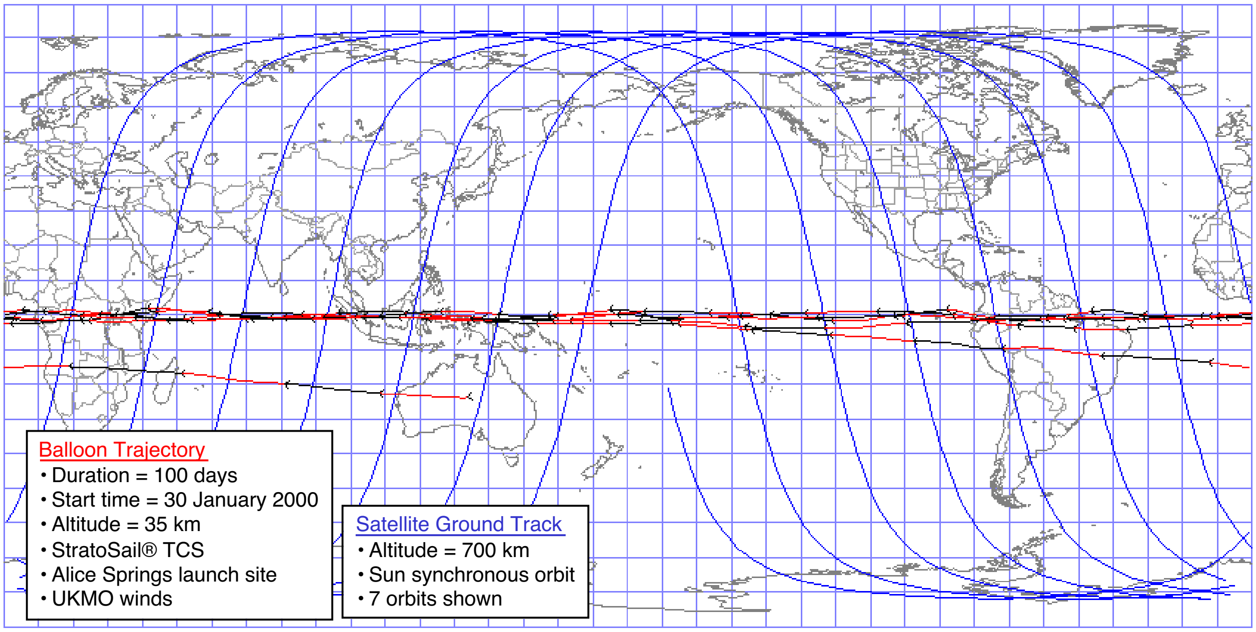


Figure 4-1. Balloon Trajectory and Satellite Ground Track Comparison.

### 4.3.1. Balloon Options

During this study, we developed preliminary StratoSat balloon options. From Table 4-1, we note that the highest required altitude is 30 km. The NASA scientific balloon program's ULDB test balloon (June 2000) floated at 28.3 km. That altitude meets the requirement for two of the three proof-of-concept missions and nearly meets the requirement for the Radiometry proof-of-concept mission. Conversations with NASA balloon program personnel verified that the test flight balloon could be a low-cost starting point for a lower-altitude proof-of-concept mission. The following table shows a comparison between the test flight balloon and the full-scale UDLB design as of January 2001 and tested in March 2001.

Table 4-2. Balloon System Options

| | **ULDB Test Flight (June 2000)** | **ULDB Full Scale Balloon (January 2001)** |
|---|---|---|
| **Design Altitude** | **28.3 km** | **34.1 km** |
| **Total Suspended Payload Capability** | **777 kg** | **2045 kg** |
| **Payload Capability at 26 km** | **1,387 kg** | **12,907 kg** |
| **Volume** | **68,554 m3** | **520,464 m3** |
| **Surface area** | **9,218 m2** | **35,607 m2** |
| **Height** | **35 m** | **81 m** |
| **Diameter** | **58.5 m** | **115 m** |
| **Dry Mass** | **637 kg** | **2461 kg** |
| **He Mass** | **226 kg** | **700 kg** |

There exists a family of ULDB-type balloon designs between the test flight design point and the full-scale ULDB system design point. In addition, these two balloon designs have different suspended mass capabilities at different altitudes. The following graph shows these relationships. The graph indicates that significant suspended mass capability is available from the test flight balloon design at altitudes of interest for these proof-of-concept missions. This analysis does not take into account the structural requirements on the balloon for the additional payload weight at lower altitudes.

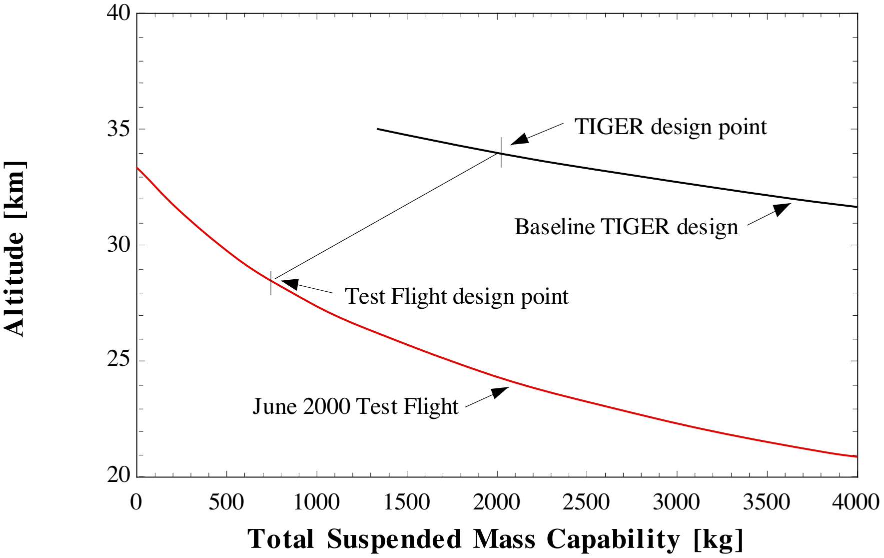


Figure 4-2. Suspended Mass Capabilities for ULDB-type Balloons.

### 4.3.2. Mission Design Model

To analyze the trades between mass and power for engineering and science, we developed a preliminary mission design model. The following sections describe the model assumptions and mass summary.

#### *4.3.2.1. Assumptions*

The mission design model includes several assumptions about the flight subsystems. This section provides details of those assumptions. These are the baseline assumptions that were made for the study. During the study we varied several key assumptions while holding the others constant to evaluate the sensitivity of the balloon design to those assumptions.

*Science Mass*

The science mass at the gondola is assumed to be 50 kg. Reeled science mass is assumed to be 100 kg.

*Science Power*

Science power at the gondola is assumed to be 200 W during daylight and 100 W at night. For the reeled science, 200 W during the day is assumed. Nighttime science power at the gondola is assumed to be 20 W except for 1 nighttime descent measuring period in which the reeled science power is 200 W.

#### Power Systems

We assume a HighPower™ Solar Array System with terrestrial solar cells for both gondola and reeled science power. The HighPower™ Solar Array System is being developed by Global Aerospace Corporation under NASA SBIR funding. It is a lightweight and modular system specifically designed for stratospheric balloon applications. We assume energy storage is provided by Lithium-Ion rechargeable batteries. 75% depth-of-discharge is assumed to be acceptable.

#### Winch System

For options that require a separate winch subsystem, we assume that the winching distance is 10 km for the POC mission. The winch efficiency is assumed to be a conservative 0.5. (Harvard's Reel-Down system from the 1980s had efficiency of 0.8.) The ratio of the winch mass to reeled mass is assumed to be 2. This does not include batteries, the reel-up power system, or the reel-down energy dissipation system. For comparison, Harvard's Reel-Down ratio was 4 and the StratoSail® TCS being developed under SBIR funding is 0.25, although it does not include reel-up capability. The ratio of mass required to dissipate descent energy to the mass required to provide ascent is assumed to be 0.1. Harvard's Reel-Down ratio was 0.2. The baseline reel-up velocity is assumed to be 3 m/s, and the baseline reel-down velocity is assumed to be 5 m/s.

#### Tether

The tether is assumed to be a PBO tether, similar to the StratoSail® TCS tether. In all cases, the tether is re-sized to accommodate the weight of the reeled mass.

#### Balloon

The baseline balloon design is the June 2000 ULDB test flight balloon. The baseline float altitude is 26 km. In all cases, the balloon is re-sized to support the weight of the gondola plus reeled systems.

#### Gondola

It is assumed that gondola structure and engineering mass is 150 kg.

#### Trajectory Control System

The trajectory control system is assumed to be a StratoSail® TCS with mass of 45 kg.

### 4.3.2.2. Mass bookkeeping

The following figures show the mass bookkeeping that was employed for the mission design model. Items lower on the tree are summed to provide masses higher on the trees.

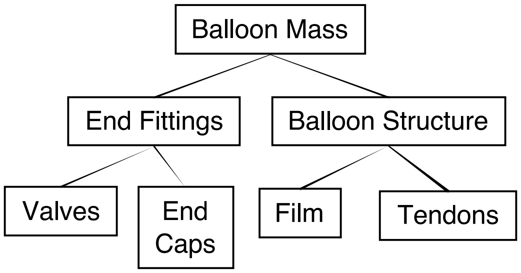


Figure 4-3. Balloon System Mass Bookkeeping

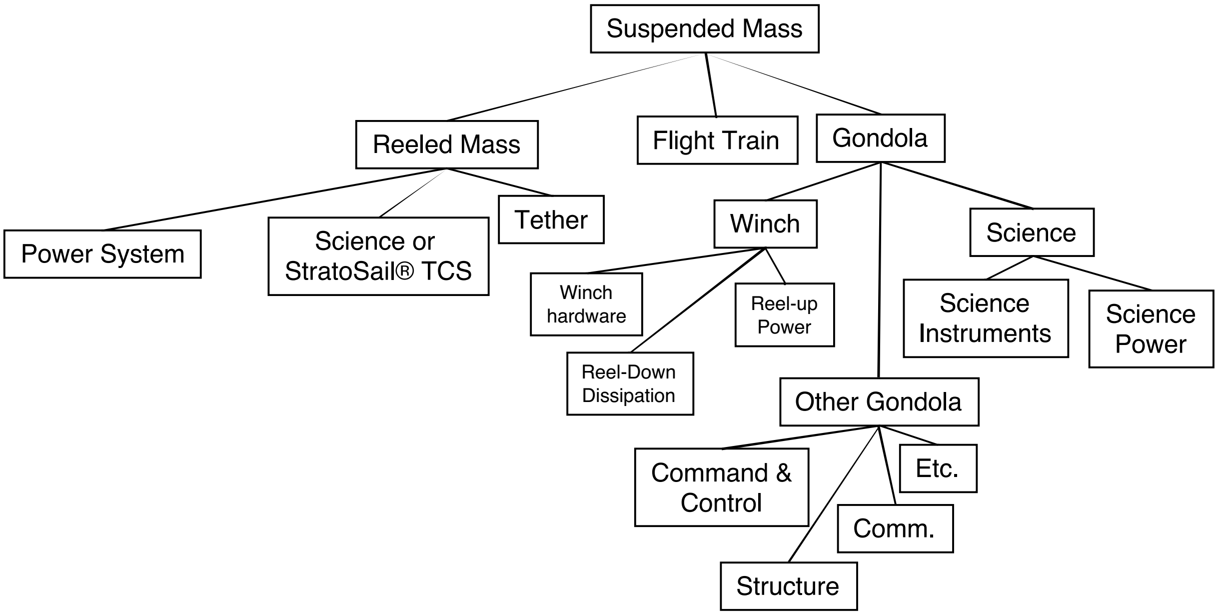


Figure 4-4. Suspended Mass System Bookkeeping.

### 4.3.3. Mission Options Evaluation

We used the mission design model described above to analyze system design trades for several candidate proof-of-concept missions. The following subsections show the results of these analyses in a series of graphs. On each graph, balloon surface area is presented on the vertical axis. Balloon surface area is an important parameter because it is proportional to balloon cost (to first order) because both material and labor (seaming) costs scale roughly with surface area. The model simultaneously solves all equations, thereby producing a consistent solution at each design point. The model provides capabilities for parametric studies. These capabilities were utilized to obtain the analysis results shown below.

#### *4.3.3.1. Trades*

##### 4.3.3.1.1. Gondola/Reeled Science Mass

The first graph shows the effect of reeled science mass on the balloon surface for different gondola science masses. The reeled-mass dominates gondola-mass in terms of balloon surface area and thus, balloon cost. This effect exists because winch and tether masses go up significantly when reeled science mass increases. Note that for a baseline mission (100 kg of reeled science mass), the balloon surface area required is only slightly larger than the test flight balloon and significantly less than the full scale balloon. For these low-altitude proof-of-concept missions, it may be possible to use a relatively inexpensive balloon that represents only a small modification of the test flight balloon.

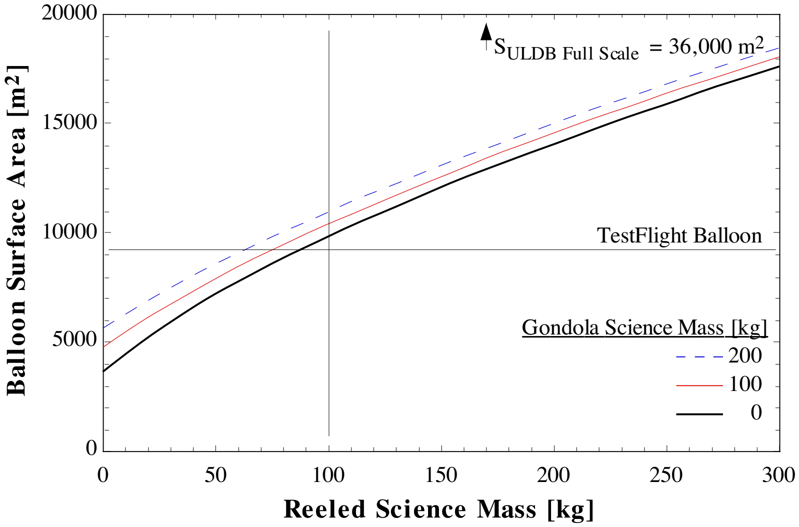


Figure 4-5. Gondola and Reeled Science Mass Trades.

#### 4.3.3.1.2. Reel-up Velocity

One key parameter for the system is the reel-up velocity. As reel-up velocity increases, the winch system mass increases and the balloon must be larger. The next graph shows the effect of reel-up velocity on balloon surface area. The effect is not as large as the effect of reeled science mass, but it is more significant than gondola science mass, particularly as reeled science mass increases.

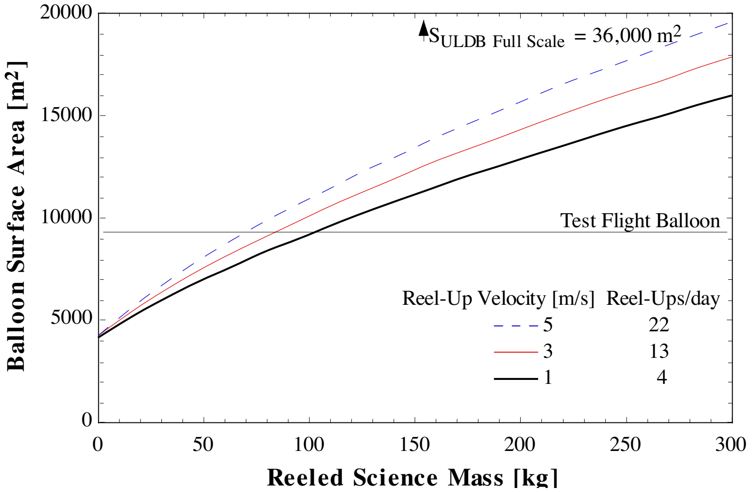


Figure 4-6. Reel-up Velocity Trades.

### 4.3.3.1.3. Float Altitude

The next graph shows the effect of balloon float altitude on balloon design for various reeled science masses. Note that the vertical scale has changed: the full-scale ULDB design is now visible at the top of the graph. This graph indicates that float altitude is a very significant parameter in terms of balloon design and cost.

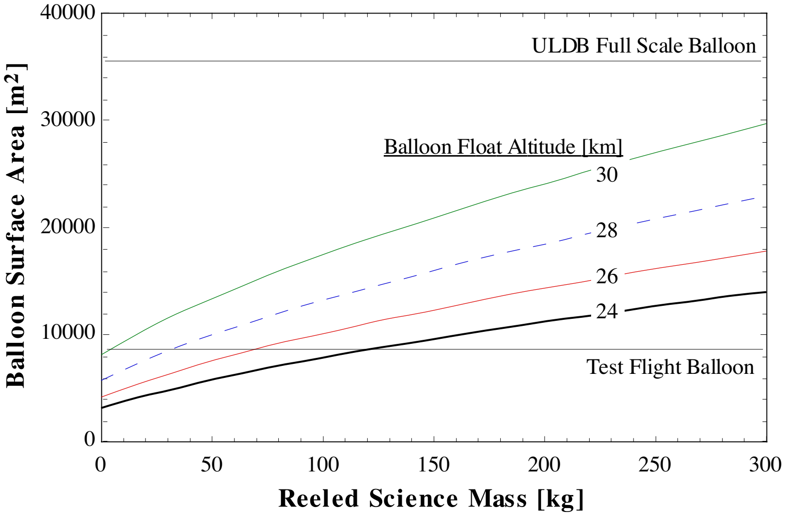


Figure 4-7. Float Altitude Trades.

### 4.3.3.1.4. Science Power

Finally, we looked at the effect of science power on the balloon design. The following graph shows that science power has a secondary effect on balloon surface are at both the gondola and on the reeled mass.

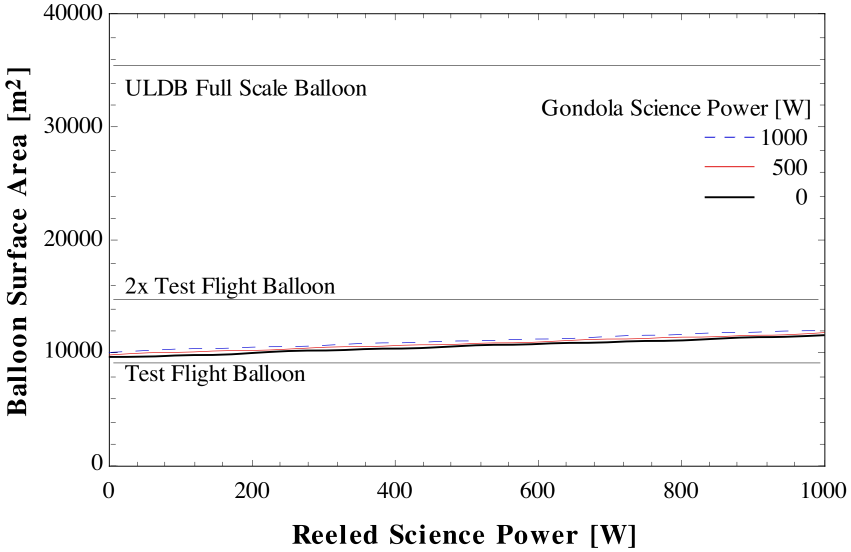


Figure 4-8. Science Power Trades for Gondola and Reeled System.

## 4.4. Demonstration Earth Radiation Balance Experiment (DERBE)

GAC has developed a concept for a possible Demonstration Earth Radiation Balance Experiment (DERBE). The DERBE mission consists of one balloon and prototype Earth Radiation Balance instrumentation. The system would orbit the Earth at 35-km altitude periodically overflying important atmospheric radiation monitoring sites, e.g. the Oklahoma Atmospheric Radiation Measurement (ARM) site and other targets of opportunity.

Earth weather and climate are driven by the balance between the amount of solar energy received by the Earth (both by its surface and its atmosphere) and the amount of energy emitted by the Earth into space. This energy balance, the incoming and outgoing energy, is called the Earth's radiation budget.

### 4.4.1. Mission Description

The long-term objective is to fly a constellation of balloons to measure the Earth radiation budget. A constellation of balloons would make this measurement better than satellites because a constellation of balloons would provide simultaneous, spatially dispersed measurements of Earth's outgoing long-wave and short-wave radiation. The DERBE mission would demonstrate that the science could be done from one trajectory-controlled balloon, and therefore, a constellation would be feasible and makes sense to pursue.

This demonstration mission involves the flight of Earth Radiation Balance instrumentation over an Atmospheric Radiation Measurement (ARM) Program Cloud and Radiation Testbed (CART) Site. The primary CART location is the Southern Great Plains (SGP) site, between Oklahoma City and Wichita (see Figure 4-9). The SGP CART site has been heavily instrumented to gather massive amounts of atmospheric, surface, cloud radiation and meteorological data. The other two CART sites are currently in a stage of development with an uncertain future, depending on budget. The ARM Program is a global change research program supported by the U.S. Department of Energy (DOE), but which involves several agencies and laboratories including NASA.

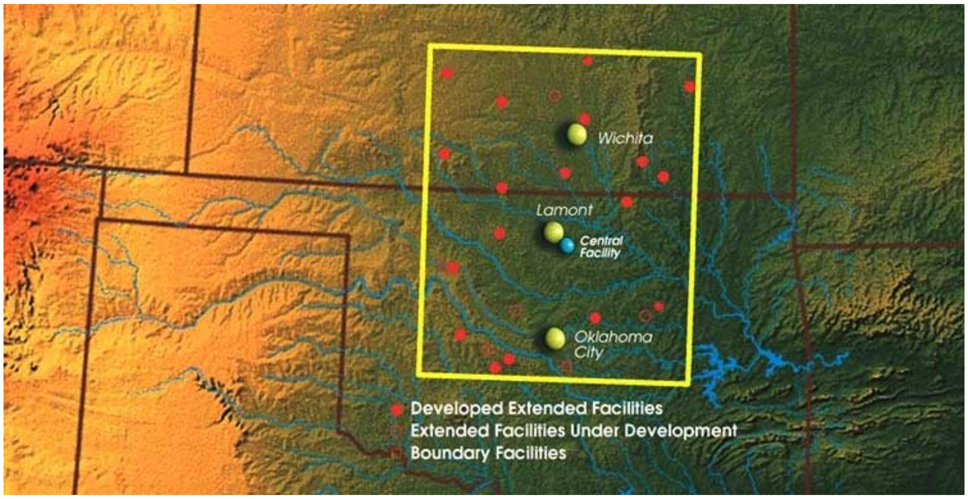


Figure 4-9. Oklahoma ARM Site

The objective of DERBE is to demonstrate advanced, calibrated Earth radiation budget measurements on guided balloons applicable to future global or regional constellations. Today, sun synchronous satellites carry radiation sensors (like the CERES instrument) that measure Earth radiation fluxes in a narrow field of view (FOV) as the satellite passes overhead. Modelers and analysts then process these data to estimate the flux emitted by the entire Earth at the top-of-the atmosphere (TOA). A ULDB balloon floats essentially at the TOA and thus could make direct broadband, wide FOV radiation measurements directly. Such measurements would eliminate the modeling required to convert the satellite-measured data to the TOA. In addition, for a global network of balloons, diurnal measurements can made, thus eliminating the extrapolation of one time of day coverage to all times of day.

Key features of this demonstration flight are multiple sensor and calibrated radiometry, a float altitude of about 35 km, flight duration of 100 days or more, and several overflights of the SGP CART site.

Key desired system elements for the demonstration mission include science instrumentation, a small ULDB balloon, a first generation trajectory control system (TCS), a support interface package (SIP) and gondola, and a possibly a guided termination and landing system. The science payload is roughly estimated at about 50 kg, which includes several radiometers and a solar calibration system. The Science Interface Package (SIP) needs to provide real-time data capability for the TCS when the balloon system is near populated areas. It is very desirable to keep the mass of the gondola to a minimum (<500kg) in order to improve safety, i.e. reduce the Casualty Estimate (CE), from terminated payloads and balloons. A highly reliable guided termination and landing system will be required to reduce the CE further, and possibly significantly, by ensuring a targeted landing in safe zones like airports or empty fields.

### 4.4.2. Gondola and Instrument System

We are assuming that a typical gondola structure is available. This gondola would support the SIP, the power system (solar array and batteries), the radiometers, and the radiometer calibration system. The calibrated and aligned radiometer system needs to have a clear view of nadir and zenith. Our alignment system needs to point to the nadir and zenith to within 0.1 degrees. Periodically we will re-orient the radiometers between nadir and zenith views, at a ~99% and ~1% duty cycle, respectively. We may include a separate narrow FOV radiometer pointed toward the balloon and/or flight train, whose signal will be subtracted from the solar calibration measurement. We may want the flight train to be a factor of five longer (~500 m) than is the usual case in order to reduce the balloon's signature for the solar calibration measurement. If this presents a launch problem, perhaps flight train deployment would become necessary. We will locate the radiometer instrumentation on a rigid structure horizontally as far as practical from the gondola in order to eliminate the gondola from the radiometers FOVs.

### 4.4.3. Launch Site and Example Mission Scenario

This flight scenario involves a launch from Palestine, TX or Ft. Sumner, NM during an appropriate time of the year to ensure a westward flight toward the Pacific coast. The TCS controls the trajectory to avoid major population centers. After crossing the coast, perhaps over Baja California, Mexico or above Santa Barbara, CA, the balloon system is guided by the TCS to the southwest to latitude about +15°. At this latitude it orbits the Earth (avoiding China and Libya) until crossing the Atlantic coast of Africa where the TCS guides the system toward a low population density crossing of the east coast of the US. The balloon then is guided through a low population corridor, avoiding dense urban areas, through the eastern US toward the SGP CART between Oklahoma City, OK and Wichita, KA. After SGP overflight the system is guided west toward a low population zone on the Pacific coast. After crossing the coast the TCS biases the trajectory southwest to again reach +15° latitude for another orbit of the Earth. The worldwide flight profile simulation is illustrated in Figure 4-10.

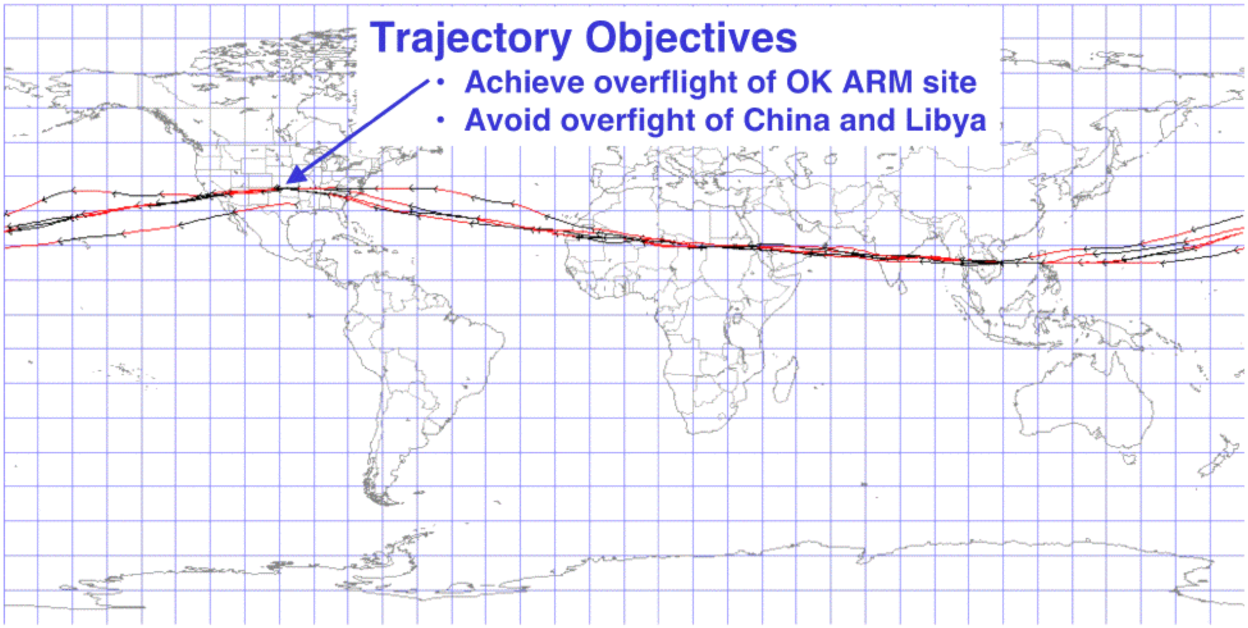


Figure 4-10. DERBE Worldwide Flight Profile

The advantages of this scenario are (1) a low cost launch from Palestine, TX, (2) a variety of terrain and cloud overflight opportunities around the world exist within latitude (+15 to +35°) range of the TCS in one orbit, and (3) nominal landing site is anywhere in vacant western US. Disadvantages of this scenario are (1) a great number of countries are over-flown and (2) overflight of moderate population density zones (India, Africa and the US) will result in relatively high CE.

### 4.4.4. Gondola Configuration

An early version of the DERBE gondola is shown in Figure 4-11 through Figure 4-14. This figure is a CAD of the gondola as viewed from below. It shows an optical bench that carries the radiometer instrumentation (here is shown Pyronometers and Pyrgeometers). The optical bench can rotate up in order to point the instruments toward the Sun for periodic calibration. The optical bench can also translate so it can be lowered in order to have the radiometer instrumentation avoid viewing any part of the gondola structure and also to raise the bench back up to stow it before termination to protect the instruments at landing.

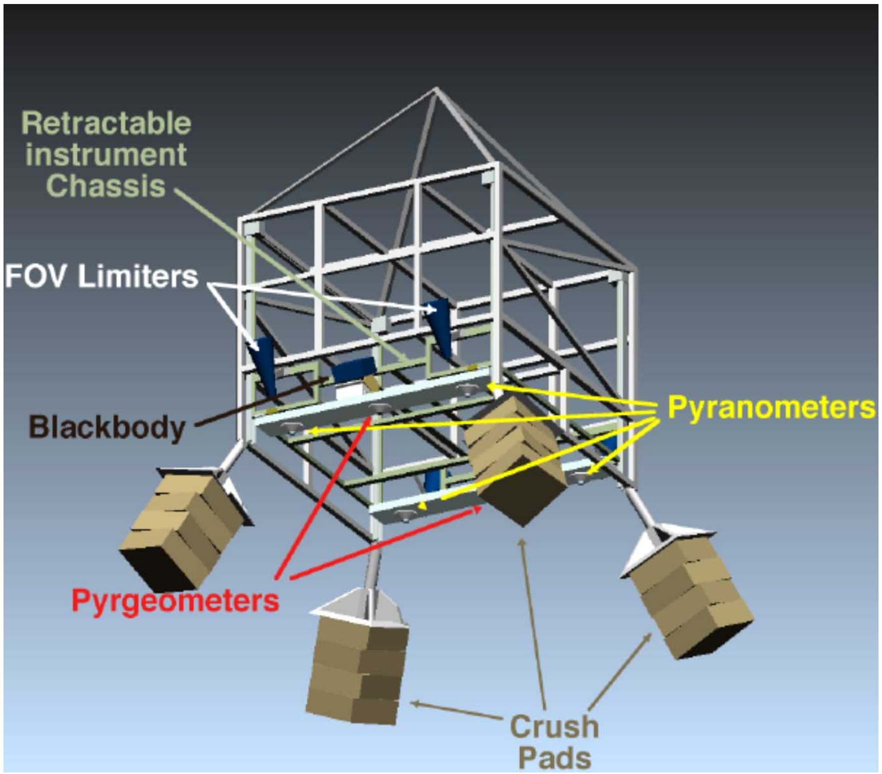


Figure 4-11. Example DERBE Gondola Configuration

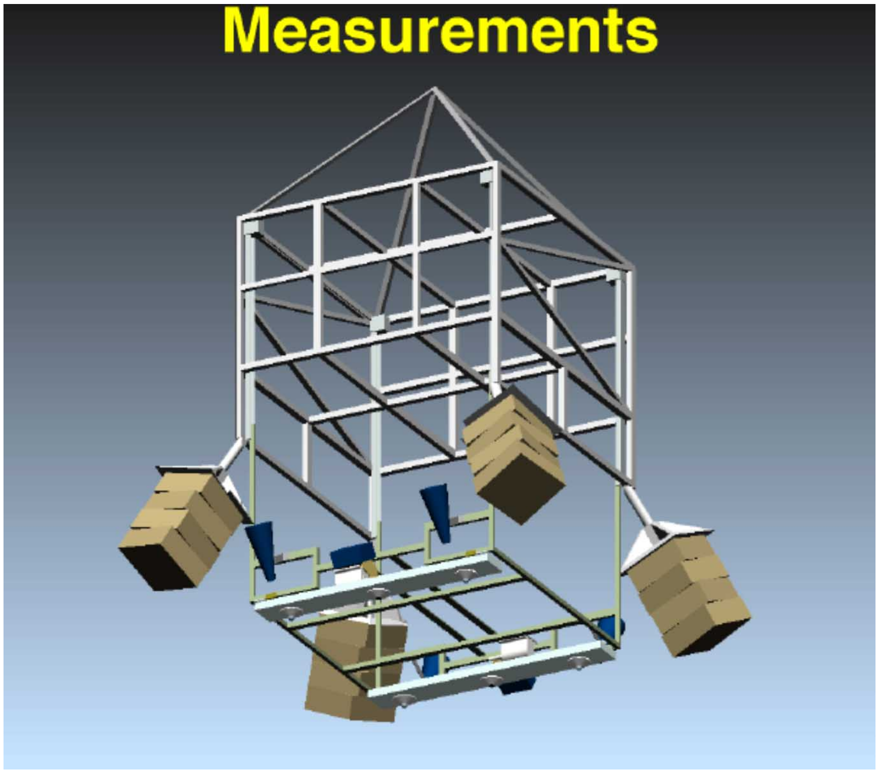


Figure 4-12. DERBE Instruments Making Measurements

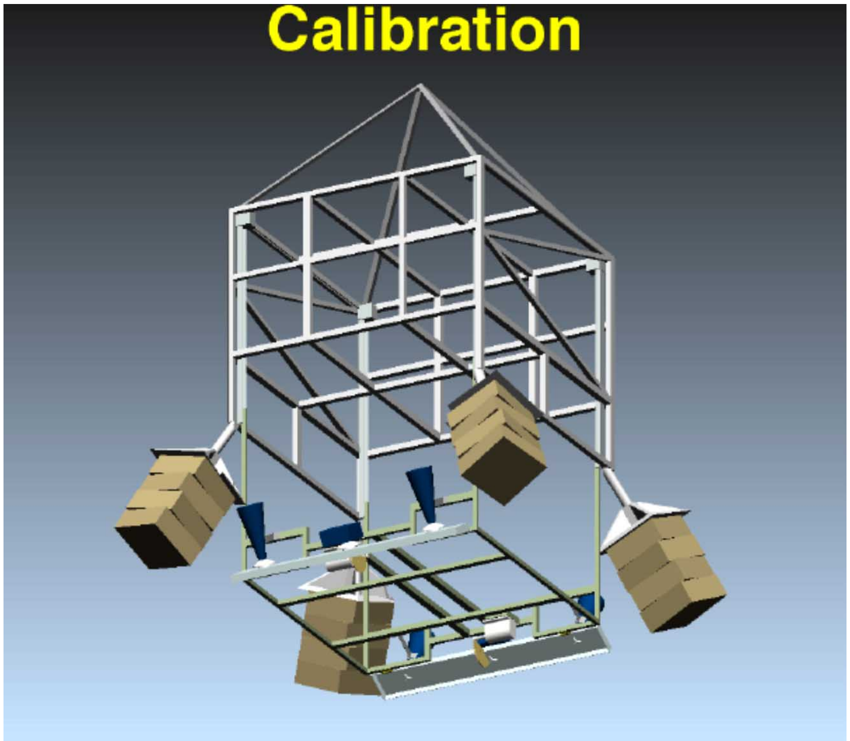


Figure 4-13. DERBE Instruments During Calibration

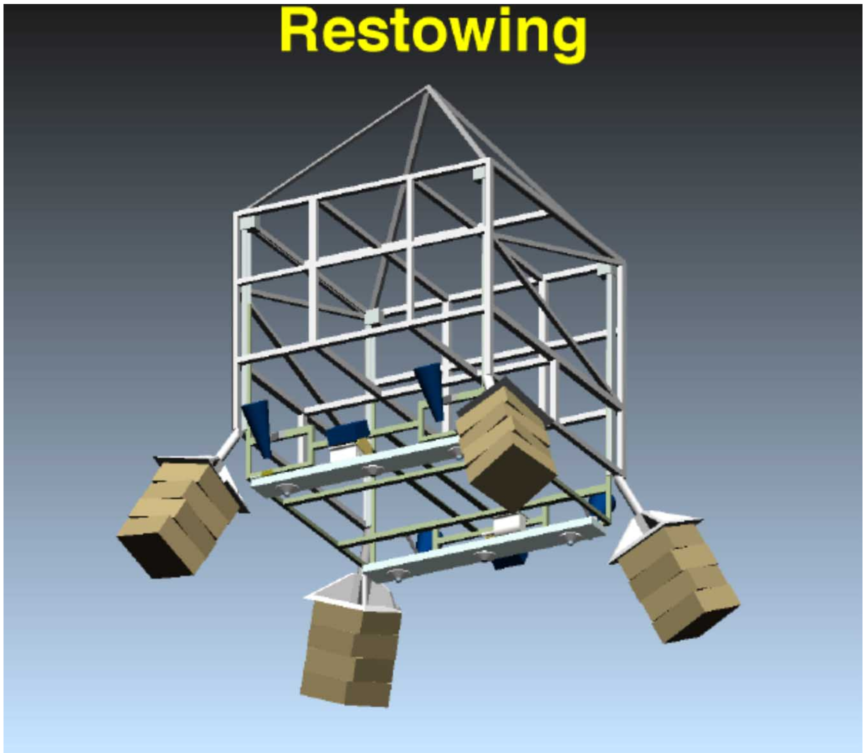


Figure 4-14. DERBE Bench being Restowed

### 4.4.5. Safety and Termination

The mission scenario for DERBE involves flights over population densities that are significantly higher than those currently allowable for the balloon program. The CE problem can be addressed by (a) guided parafoil descent systems to allow CE calculations to be conducted based on low-population locations (airports, etc.) in high-population-density regions, (b) proven high reliability of balloons to minimize probability of a "fall from the sky" failure, (c) TCS capable of guiding the balloon to avoid the most heavily populated areas (i.e. city centers).

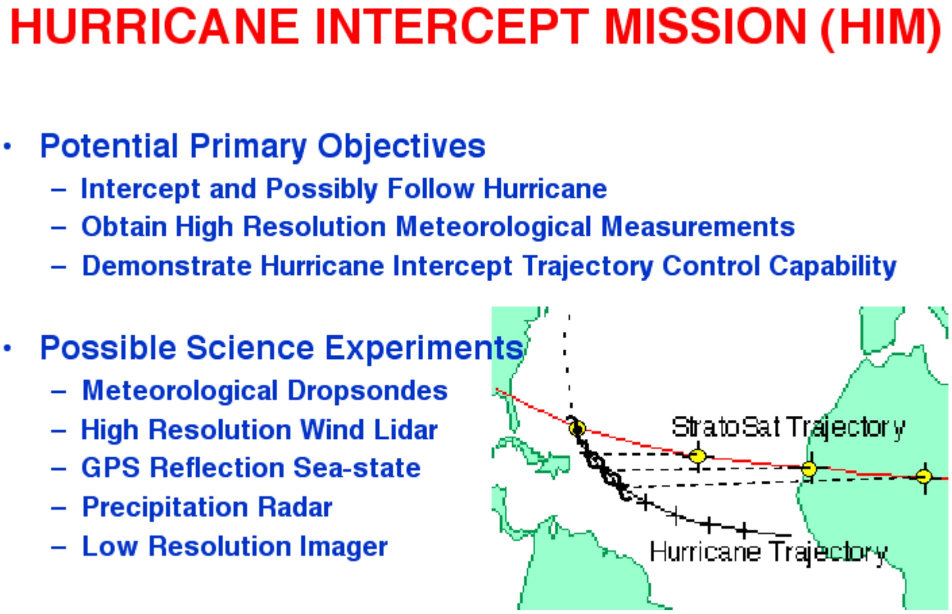
The IST Aerospace Orion™ precision GPS guided delivery system (see Figure 4-15) that was developed for the U.S. DOD as the Guided Parafoil Airborne Delivery System (GPADS) and also being tested by the French space agency (CNES) for balloon payload recovery, could safely provide payload termination. The CNES-developed system uses a free-fall from float to 10-km altitude to reduce landing uncertainty due to upper altitude winds, a parafoil to provide a 2:1 glide ratio and a GPS sensor to guide the system to a targeted landing.

Figure 4-15. IST Aerospace GPADS-Light during qualification testing

## 4.5. Hurricane Intercept Mission

As discussed earlier, a constellation of balloons could be used to address this problem. Orbiting in the tropics over the Atlantic (and Pacific) they could carry dropsondes to measure wind, temperature and pressure in he vicinity of the hurricane. With a projected sonde mass in ten years of 25 to 50 grams, each balloon payload could have more than 1000 sondes for this experiment, which provide profiles from balloon altitude to the surface. Each StratoSat™ platform would make temperature, pressure, and horizontal wind measurements on the tether, at approximately 3-km intervals.

One hurricane intercept mission concept is based on a "string-of-pearls" operational approach where several balloons are located around the world and moving in the pervasive zonal flow of which the HIM would represent a demonstration. As the balloons fly into hurricane zones they are periodically targeted, by the use of TCS systems, to fly over specific hurricanes. The following chart summarizes the current thinking on the string-of-pearls approach and possible experiments.



**HURRICANE INTERCEPT MISSION (HIM)**

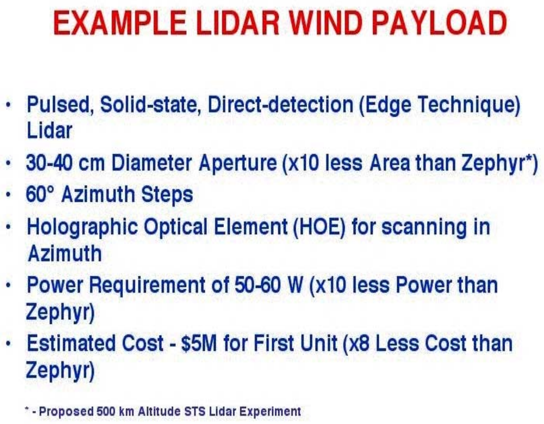
- Potential Primary Objectives
  - Intercept and Possibly Follow Hurricane
  - Obtain High Resolution Meteorological Measurements
  - Demonstrate Hurricane Intercept Trajectory Control Capability
- Possible Science Experiments
  - Meteorological Dropsondes
  - High Resolution Wind Lidar
  - GPS Reflection Sea-state
  - Precipitation Radar
  - Low Resolution Imager

Figure 4-16. Hurricane Intercept Mission Concept

## 4.6. Wind LIDAR Satellite Validation Mission Concept

The StratoSat™ platform operates lower therefore the SNR is high and that can be translated to lower operating power and/or higher sensitivity and/or reduced telescope aperture and thus size. For the same focal length, the footprint of the Lidar is smaller, meaning higher spatial resolution is possible. For a fully optimized experiment one expects to achieve significant improvements in spatial (2-4 km) and vertical resolution (100-200 m) and wind speed accuracy (<1 m/s).

A strawman payload definition has been generated and is shown below (note the comparison with the proposed STS payload). A holographic optical element (HOE) has been developed within a ground-based Wind Lidar instrument. The HOE enables scanning of both the Laser and the reflected signal with simple rotation of the HOE instead of rotating the entire telescope in azimuth along a cone.

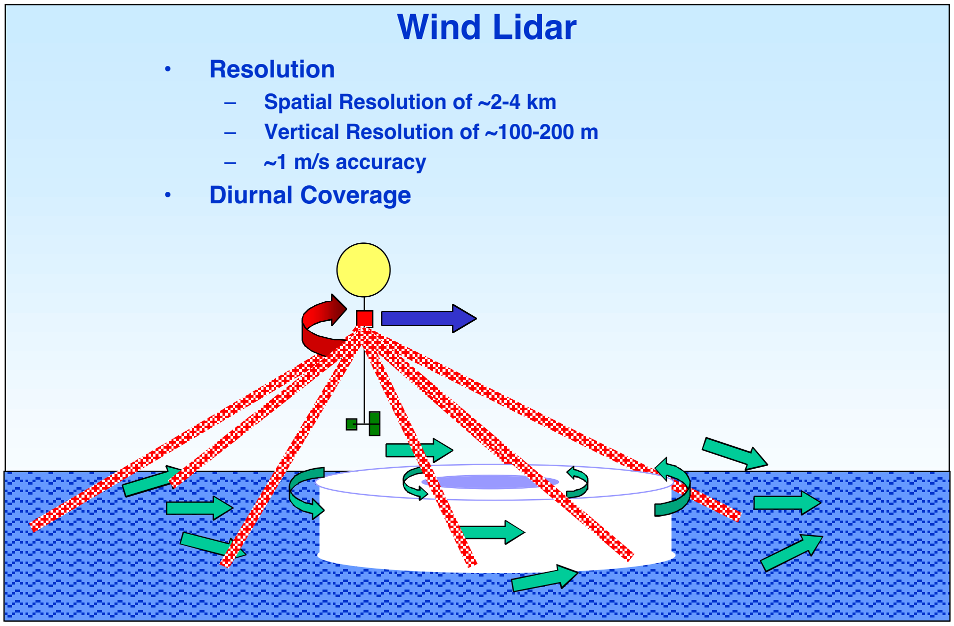


**EXAMPLE LIDAR WIND PAYLOAD**

- Pulsed, Solid-state, Direct-detection (Edge Technique) Lidar
- 30-40 cm Diameter Aperture (x10 less Area than Zephyr*)
- 60° Azimuth Steps
- Holographic Optical Element (HOE) for scanning in Azimuth
- Power Requirement of 50-60 W (x10 less Power than Zephyr)
- Estimated Cost - $5M for First Unit (x8 Less Cost than Zephyr)

* - Proposed 500 km Altitude STS Lidar Experiment

Figure 4-17. Example Wind Lidar Payload



**Wind Lidar**

- Resolution
  - Spatial Resolution of ~2-4 km
  - Vertical Resolution of ~100-200 m
  - ~1 m/s accuracy
- Diurnal Coverage

Figure 4-18. Wind LIDAR Mission Concept

The following figure illustrates one possible pattern of footprint coverage from a StratoSat Lidar system assuming a 45°-look angle, 60° azimuth steps and a 50 m/s StratoSat ground speed.

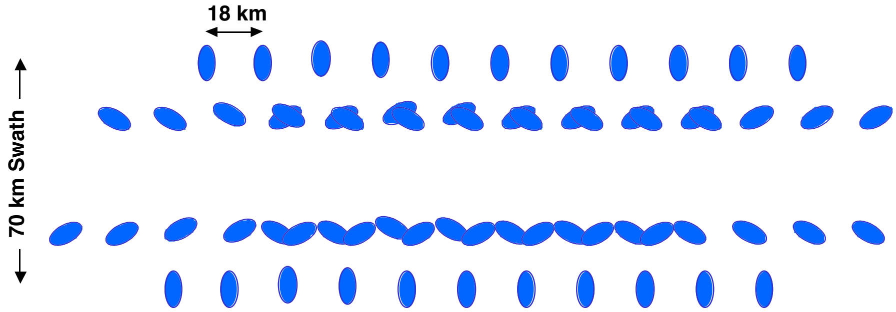


Figure 4-19. Example Wind Lidar POC Mission Surface Coverage Pattern

## 4.7. Precipitation in The Tropics Mission

A tropical stratospheric balloon constellation has been suggested as a means for obtaining high-resolution tropical rainfall data similar to the data being collected by the joint US/Japanese Tropical Rainfall Measuring Mission (TRMM). TRMM is making detailed spatial and temporal measurements of tropical rainfall between ±35 latitude. These data are helping to understand the global water cycle and its contribution to global energy balance. A key instrument used on TRMM is a Precipitation Radar (PR), provided by the National Space Development Agency of Japan (NASDA). TRMM operates from a 350-km altitude, 35°-inclination orbit.

A stratospheric balloon is potentially a good platform for PR measurements due to the very stable thermal regime, higher signal-to-noise for the same given radar, slower speed and the small footprint at 35-km altitude. The small footprint translates into a slightly wider swath width than available from an orbiting satellite. The PR on TRMM has a nadir footprint of 4 km and a swath width of about 215 km. Swath width limitation comes from the interference of the returned rain signal with the ground signal, which is strongest. When the radar antenna is pointed at nadir it is simple to gate the returned rain signals to avoid the larger ground returned signal. As the radar is pointed to the side of the ground track the rain signal begins to be lost near the ground due to interference with the ground reflection (see the figure below). The altitude for which one receives a non-interfered rain signal becomes higher as the radar is pointed further off nadir. For TRMM this angle is about ±17° from nadir for a 645-m rain altitude limitation (no rain measured below this altitude at the edge of the swath). This off nadir angle of ±17° provides a swath width of 215 km from the 350-km altitude. For a StratoSat at 35 km the footprint at nadir is 400 m. This smaller footprint results in a maximum off-nadir angle of 72.2° for the same 645-m rain altitude limitation. This off nadir angle of ±72.2° provides a 225-km swath width for a StratoSat at 35-km altitude. The table below compares the TRMM satellite and StratoSat system as PR platforms assuming the same radar system.

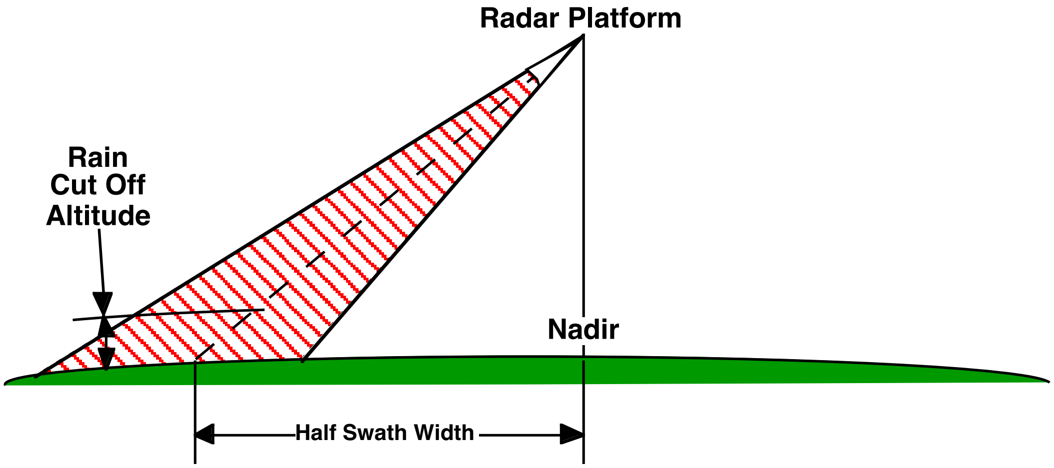


Figure 4-20. Precipitation Radar Geometry

Table 4-3. Precipitation Radar Platform Comparison

| **Parameter** | **TRMM** | **StratoSat** | **Comments** |
|---|---|---|---|
| Altitude, km | 350 | 35 | |
| Radar Footprint at Nadir, km | 4.0 | 0.4 | 0.3274 deg half FOV |
| Maximum Angle Off Nadir, deg | 17.0 | 72.2 | 645 m Rain Cutoff Altitude |
| Swath Width, km | 215 | 225 | for max off nadir angle |
| Radar Footprint at Swath Edge, km | 4.2 x 4.4 | 1.3 x 4.7 | Ellipse, long axis normal to ground track |
| SNR Increase (R^4) | 0 | 10,000 | nadir, same RF power |

The speed of the platform is an important parameter. If the speed is slow enough, the radar system can adapt to the returned signal. If there is no return signal, meaning no rain, the radar can be cycled off to reduce power requirements. However, if the platform is too slow, it takes too long to make the rain measurement compared to the time rain randomizes. This randomization period for rain is about 3 hours or so. For example, to observe the life cycle of a storm (i.e. how much water came out of it), one needs to look about once every 3 hours or so. One can interpolate the time between visits because the evolution is slow. If it take longer than 3 hours to traverse a feature (storm system) the value of rain information in determining storm energy is compromised. Satellite speeds are too fast to adaptively control transmissions and save power; hence the radar must always be on. For the StratoSat the speed is slow enough to be able to adapt to conditions, however, if the pervasive zonal flow at 35 km is too slow, important can be information may be lost. On the other hand, you get a much better picture of the evolution of that portion of the storm seen. Studies about storm evolution are still important as we learn more about cloud physics, but such a mission will be competing with ground-based radars.

A POC mission for a Precipitation in the Tropics Mission could utilize a standard or small ULDB envelope with a conventional LDB gondola carrying a precipitation radar. For a POC mission, this radar could be heavy and power hungry since a significant payload capacity would exist. Trajectory control would allow the balloon to be targeted over tropical areas where high precipitation would be expected.

# 5. Constellation Geometry Management

## 5.1. Introduction

A significant element of the Phase II work involved studies of various strategies for constellation management for a variety of StratCon applications. This work is important for the overall StratCon effort because it defines options for operational uses of constellations of stratospheric balloons. We begin the discussion of constellation geometry management with some definitions.

## 5.2. Definitions

### 5.2.1. Constellation Management

Constellation management (or constellation geometry management) is the process of maintaining a desired spatial distribution of balloons in a stratospheric constellation. Constellation management can be performed on global or regional constellations. Also, constellation management is not limited to a particular geometric arrangement of balloons. Constellation management assumes the availability of an underactuated and bounded Trajectory Control System (TCS) on each balloon. (Underactuated because the TCS may not be able to provide $\Delta V$ in all directions and bounded because the TCS $\Delta V$ capability is significantly less than the external flow field velocity.) Given the predominant wind patterns and the bounded trajectory control capability available from lightweight, low power trajectory control systems, constellation management will be an essential element of any operational StratCon system.

### 5.2.2. Constellation Objective

A constellation objective is the specific desired spatial distribution of balloons in the constellation. Constellation objectives may be constant or change with time. An example constellation objective is to maintain a uniform distribution of balloons around the planet. Another example constellation objective would be maintaining a dense and uniformly spaced network of balloons in the tropics (± 10° latitude). Yet another constellation objective might be to use a constellation of balloons to make as many observations as possible of a natural disaster site on the ground.

### 5.2.3. Adaptive Constellation

A constellation whose objective changes with time is called an adaptive constellation.

### 5.2.4. Constellation Management Strategy

A constellation management strategy is the manner of achieving the desired constellation objective. In the case of the uniform distribution objective, one could use a trajectory control system to continuously randomize the arrangement of balloons. Or, one could continuously push balloons away from their nearest neighbors. Both of these options are constellation management strategies.

### 5.2.5. Constellation Management Algorithm

A constellation management algorithm is the set of formulas and instructions that determine how each individual balloon should be controlled. Inputs to a constellation management algorithm could include

- the current constellation geometry,
- the forecasted evolution of the constellation's geometry,
- characteristics and capabilities of the trajectory control systems,
- current weather conditions, or
- forecasted weather conditions.

An example may help to illustrate these definitions. The next section discusses "molecular control."

### 5.2.6. Example: Molecular Control

One example constellation management option is molecular control. For the molecular control option, we view each balloon as though it was a molecule that interacts with other nearby molecules. The constellation objective is to maintain a uniform distribution of balloons over the entire globe.

The constellation management strategy is to use the trajectory control system to push each balloon away from its nearest neighbor, much like a gas molecule interacts with its neighbors to equalize pressure in an enclosure. This constellation management strategy would not be effective on a flat earth. But, given enough time and sufficient trajectory control capability, the strategy would produce a more-evenly-distributed network on a sphere.

The constellation management algorithm for molecular control is applied to each balloon in the network. The algorithm for a given balloon is listed below:

- Determine the balloon that is closest to the given balloon: its nearest neighbor
- Calculate a unit direction vector between the given balloon and its nearest neighbor
- Command the TCS to maximize the component of the given balloon's velocity in the direction opposite the unit direction vector
- Recalculate the unit direction vector for the given balloon every 4 hours

This algorithm produces a unit vector for each balloon that is updated every 4 hours. The update frequency is an adjustable parameter for this algorithm.

## 5.3. Options for Constellation Management

There are several options for constellation management. For the simulation work in Phase II, the selection of these options is driven by the tradeoff between computation time and modeling fidelity. Another consideration is the availability of information such as stratospheric forecasts.

### 5.3.1. Environment Information

There are several options for environment information. Typically, stratospheric information at 35 km, the nominal StratoSat™ platform altitude, is difficult to obtain because most weather forecasts utilize weather models that extend from the ground to 30 km. Available information can be classified in two categories: parameterized environment descriptions and detailed model output. Options for environment information are discussed below.

#### *5.3.1.1. Parameterized Description*

A parameterized description of the atmosphere is a simple model for the atmosphere that uses a few (less than 20, for example) parameters to describe the global environment. Such a model provides computational simplicity and speed of execution, even if it does not capture all the physics of atmospheric dynamics. Although they lack accuracy, parameterized descriptions of the global environment can provide a computationally fast environment for quick evaluation of various constellation management strategies and algorithms.

#### *5.3.1.2. Detailed Model Output*

Detailed model output can also be used for constellation management simulations. The detailed models are typically run on supercomputers and use very fine global grid resolutions. The detailed atmospheric model output is usually more accurate than a parameterized description, but it is computationally more expensive to use due to large storage space requirements and time-consuming disk read operations.

There are several options for detailed model output environment information that are discussed below.

##### 5.3.1.2.1. Successive Correction

Successive correction data sets are created by interpolating satellite measurements spatially and using remote temperature and pressure measurement to calculate wind fields. These data are typically stored in large binary files.

##### 5.3.1.2.2. Assimilations

Assimilation data sets are created by tuning a detailed and sophisticated General Circulation Model (GCM) with atmospheric measurements, such as pressure, temperature, and humidity. The atmospheric measurements are “inserted” into the atmospheric model as it runs to bring the model closer to reality during the run. Assimilation data are typically stored in large binary files.

#### 5.3.1.2.3. Forecasts

Forecasts are predictions of atmospheric conditions. They are generated using recent assimilations as initial conditions. Forecast data are typically stored in large binary files.

### 5.3.2. TCS Model Fidelity

The level of TCS model fidelity is another option for constellation management simulations.

#### *1.1.1.1. Omni-directional ΔV at balloon*

Under this TCS model option, the differential velocity (ΔV) applied to the StratoSat is omni-directional and of fixed magnitude. It is assumed that the ΔV can be applied in any direction at any time, without regard to actual atmospheric conditions either at the balloon or at the TCS. This is a simplifying approximation to the behavior of the StratoSail® TCS described elsewhere in this report.

This option requires the least computational effort of any TCS model options.

#### *5.3.2.2. Left-right ΔV at balloon*

This option models the TCS as a device with capability to steer the balloon 90° to the left or 90° to the right of the direction of travel. This option is a reasonable approximation to StratoSail® TCS capability when operating in lift mode with little directional difference between winds at the balloon and winds at the StratoSail® TCS.

#### *5.3.2.3. ΔV proportional to true relative wind at TCS*

With this option, the ΔV applied to the balloon is a function of the relative wind speed between the balloon and the TCS. It is assumed that the ΔV can be applied in any direction, without regard to actual atmospheric conditions either at the balloon or at the TCS. But, a higher relative wind speed will give a higher control authority.

#### *5.3.2.4. Actual TCS aerodynamic model*

By employing an actual TCS aerodynamic model, one ensures that the simulation behavior comes as close as possible to the expected behavior of a TCS. The aerodynamic model predicts the control authority available in any control direction based on the available relative winds between the balloon and the TCS. Sophisticated TCS control algorithms select the proper operating parameters (rudder angle, etc.) for the TCS to maximize control authority in a desired direction.

This model is the most computationally-intensive option of any discussed here.

### 5.3.3. Coordinate System

#### *5.3.3.1. Planetary*

A natural option for the coordinate system is the planetary coordinate system. For Earth, this means that control algorithms are evaluated relative to the longitude-latitude grid.

#### *5.3.3.2. Mesoscale*

Another option for control algorithm coordinates is mesoscale (cyclone-size) coordinates. For example, balloons that are captured by the polar vortex can be analyzed in a coordinate system that is relative to the current position of the vortex rather than to the Earth's coordinates. This may become important in cases where the center of the polar vortex is not located at the pole or where the polar vortex splits into two or four smaller vortices.

### 5.3.4. Feature Identification

Constellation management can take advantage of observed features in the stratospheric wind field. For example, a cyclonic feature can be utilized to provide multiple observations over a given site in a short amount of time (2-4 days for a single balloon). The "return trips" provided by a cyclone can happen very quickly compared to a circumnavigation of the Earth, which could take as long as 14-21 days for a single balloon in typical winds.

### 5.3.5. Constellation Management Strategies

There are several options for constellation management strategies that can be applied. Some are briefly described in the sections below.

#### *5.3.5.1. Randomization*

The purpose of randomization control is to break up any coherence that develops in the constellation geometry as a result of regional meteorological features such as the polar vortex, high-speed jets, Stratwarm cyclones, or other cyclonic or anti-cyclonic features. Under randomization control, StratoSats are moved northward or southward randomly to move them away from the influence of these meteorological features.

Under molecular control (see Section 5.2.6), each StratoSat responds only to it's nearest neighbor like gaseous molecules. Given a constant-altitude constellation and the spherical geometry of the Earth, molecular control provides a means of generating and maintaining a uniform distribution of StratoSats around the globe.

#### *5.3.5.2. Zonal Management*

With zonal management strategies, the entire network is managed, and balloons are moved between defined zones to maintain an appropriate global distribution. Under zonal management, individual StratoSats could be selected for movement between adjacent zones based on a desired number of balloons in each zone.

Zonal management can be used in conjunction with other techniques. When a balloon is selected for a zone jump, it is typically removed from consideration by any other technique.

#### *5.3.5.3. Gradients of Artificial Potentials and Weak Stability Boundary Theory (AP/WSB)*

This constellation management technique is described in detail in Section 5.6.

#### *5.3.5.4. Trajectory Forecasting*

Another constellation management strategy involves use of trajectory forecasts. This strategy is often used in conjunction with constellation objectives that involve overflight of specific targets. Trajectory forecasting is computationally intensive, so it is often performed only for balloons that are within a certain distance of the target.

### 5.3.6. Constellation Objectives

During Phase II, we developed simulations that utilize several different constellation objectives. The following sections discuss those objectives

#### *5.3.6.1. Constellation Objective Options*

##### 5.3.6.1.1. Maintain Latitude

This objective computes the velocity vectors needed so as to maintain all of the balloons within a constellation at a given latitude. It does so by computing how many meters each balloon would have to move directly to the North or South in order to put it at the desired latitude. These distances are then divided by the update interval to determine the desired velocity which, to the extent it is actually achievable, will place the balloons at the desired latitude.

##### 5.3.6.1.2. Minimize the Standard Deviation of the Nearest Neighbor Separation Distance

This objective attempts to create a uniform distribution of the balloons in the constellation. For each balloon in the constellation the distance between it and each of the other balloons in the constellation is computed and the smallest such distance for that balloon is saved. When all of these distances have been computed, their mean is determined. Then, for each balloon, one half of the difference in its distance from its nearest neighbor and the mean distance determined above is computed. This is then divided by the update interval to determine the desired velocity at which it should approach or recede from its nearest neighbor to bring their separation distance to the mean.

##### 5.3.6.1.3. String of Pearls

This objective attempts to keep a constellation of balloons evenly spaced in longitude. First the balloons in the constellation are sorted according to their longitude. For each balloon, the difference in longitude from its current location to the location half way between the balloon in front of it and the one behind it in the sorted list is computed. The velocity which causes the balloon to move that far in longitude at the average latitude of the constellation by the next update time is then computed.

#### 5.3.6.1.4. Artificial Potential Function within a Latitude Band

This objective attempts to maintain the constellation of balloons such that they conform to an artificial potential function as described in Section 5.6.1.1.2 Artificial Potentials, while staying between a pair of latitude limits.

#### 5.3.6.1.5. Zone Avoidance

This objective attempts to keep the balloons from entering a given zone. For each balloon, its path is forecast for a specified look ahead time and for a variety of trajectory control system settings in turn. If the balloon does not enter the zone anywhere along the forecast path for a given TCS setting then the velocity that results from that setting of the TCS is returned otherwise, a new TCS setting is attempted. This process can become quite computationally intensive.

#### 5.3.6.1.6. Overfly latitude

This objective attempts to have the balloons overfly a given latitude. As with the previous objective, a path is forecast for a given look ahead time and TCS settings. The TCS setting that causes the balloon to come closest to the desired latitude somewhere along its path is used to compute the velocity to be used. Note that this differs from the Maintain Latitude objective in that it uses the TCS settings that can be achieved to determine the velocity rather than computing the velocity that will accomplish the objective without regard to whether it can actually be achieved by the control system.

#### 5.3.6.1.7. Overfly target

This objective attempts to have the balloon fly directly over a given target. It uses a computed path for selected TCS settings to find one that causes the balloon to come the closest to the target. As with the preceding objectives, this TCS setting is then used to compute the velocity to be used. The target to be overflown can be either a fixed location or one whose location varies in time. Another variation on this objective is one that attempts to maintain the latitude of the target if the balloon is flying away from it and overfly the target if the balloon is flying towards it. Alternatively, if the balloon is more than a given number of degrees in longitude from the target at the first point in the forecast, the objective attempts to maintain the latitude of the target and only attempt to overfly the target if the balloon is closer than the given angle in longitude.

### *5.3.6.2. Constellation Objective Prioritization*

During Phase II, we developed software that provides the capability to utilize multiple objectives for a given constellation during a single simulation. The objectives have associated priorities that are used when calculating the desired ΔV for any given balloon.

Given a set of competing objectives, the desired ΔV for a balloon is calculated by the following equation:

$$\Delta \vec{V}_i = \frac{\sum_j p_j \Delta \vec{V}_{ij}}{\sum_j p_j} \tag{5.1}$$

where

$\Delta \vec{V}_i$ = the desired $\Delta \vec{V}$ for balloon $i$,

$\Delta \vec{V}_{ij}$ = the $\Delta \vec{V}$ calculated for balloon $i$ from objective $j$, and

$p_j$ = the priority for objective $j$.

Note that the summation over the objectives $j$ is a vector summation. Note also that the priority of an objective can change throughout the course of a simulation. Priority modifications can be pre-programmed to happen at certain times, or they can happen in response to observed conditions in the atmosphere. If the priority of an objective is changed to a mandatory setting, then the results from the other objectives will be ignored (and may not even be computed) and only the results from the mandatory objective will be used to set the trajectory control system.

### 5.3.7. Adaptive Constellations and Sensor Webs

For several years, NASA has been interested in adaptive systems for Earth observations. And, NOAA is also very interested in adaptive observations for weather forecasts. Studies have shown advantages of adaptive observations for weather forecasts and have identified high-sensitivity areas for initial conditions for weather forecasts. Improved observations (quantity and accuracy) in those regions yields improvements in weather forecast skill.

In most concepts of adaptive observing systems, available observing system assets (satellites, aircraft, ground stations, balloons, microsensors, etc.) are positioned according to observational objectives determined by either (a) an external analysis that evaluates all incoming data and determines regions of high sensitivity or (b) the observing system assets themselves via on-board processing capabilities. NASA has dubbed their approach a "sensor web." Figure 5-1 shows the sensor web concept.

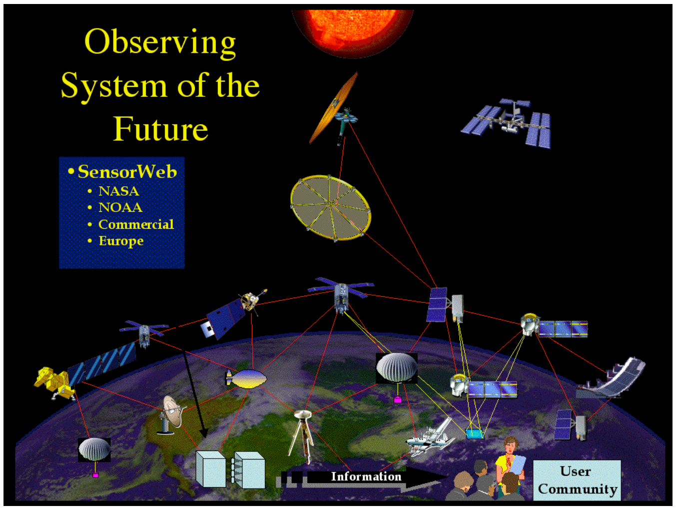


Figure 5-1. NASA Sensor Web Concept.

One key element of sensor web concept is the decision-making process for organizing observing system assets. Simply stated, the problem is this: “Given 100 vehicles in an observing system (constellation) and given a competing set of objectives for that observing system, how should each individual vehicle respond?”

During Phase II, we developed software that demonstrates the feasibility of constructing an adaptive observing system using a constellation of stratospheric balloons. We successfully answered the question posed above in several different mission applications for the StratCon concept.

## 5.4. Summary of Phase I Constellation Management Work

This section summarized the results obtained during Phase I of the StratCon constellation management work. This summary is helpful to include here because it provides the basis for the Phase II work.

### 5.4.1. Constellation Objective: Uniform Distribution

During Phase I, we considered one constellation objective, namely uniform distribution of balloons around the globe. Given the objective of global and uniform balloon coverage, we can define a measure of the quality of any given arrangement of balloons with the concept of "Nearest Neighbor Separation Distance," or NNSD, which is the distance between a given StratoSat and its nearest neighbor. At any instant in time, one can calculate the NNSD for a given balloon in the constellation. So, for example, a 100-balloon network has 100 NNSDs at any given time. Statistical calculations can be run on the set of NNSDs and the average, minimum, and maximum NNSD can be calculated for the entire network. Or, the standard deviation of all the NNSDs in the network ($\sigma_{NNSD}$) can be determined.

The constellation management objective for uniform distribution ensures that NNSD is uniform and large. In mathematical terms, the constellation management objective is minimization of the standard deviation of NNSD in the network ($\sigma_{NNSD}$). When $\sigma_{NNSD}$ reaches zero, the constellation is perfectly distributed. With high $\sigma_{NNSD}$, the network will exhibit clusters and voids. We can graph $\sigma_{NNSD}$ as a function of time to track the quality of the constellation as it evolves.

### 5.4.2. Constellation Management Algorithm Evaluation

The following table summarizes the constellation management options that were evaluated during Phase I.

Table 5-1. Constellation Management Algorithms Studied During Phase I.

| Algorithm Name | Type (Technique) |
|---|---|
| Uncontrolled Network | n/a |
| Move to Equator/Poles | Randomization |
| Randomizer 1 | Randomization |
| Randomizer 2 | Randomization |
| Simple Push-Apart | Molecular |
| Paired North-South | Molecular |
| Paired North-South/Zonal | Molecular/Zonal |

The technique that provided the most-uniform distribution was the Paired North-South/Zonal algorithm.

We made several simulations of the evolution of free-floating networks of balloons at 35 km. Figure 5-2 shows an initial configuration of the network. The network consists of 100 balloons, and the initial configuration has NNSD > 1500 km.

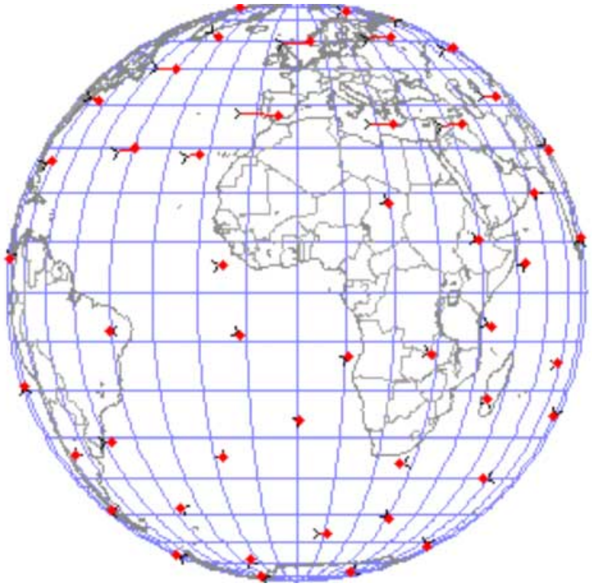


Figure 5-2. Initial Configuration of Free-Floating Network.

Figure 5-3 shows the configuration of balloons after 82 days of free-floating simulation. The alternating colors on the trajectories indicate 24-hour periods. The arrows on the trajectories indicate the direction of motion, and the dots on the ends of the trajectories indicate the current position of the balloon. In this example, significant voiding and clustering can be seen. Without trajectory control, non-uniform coverage results.

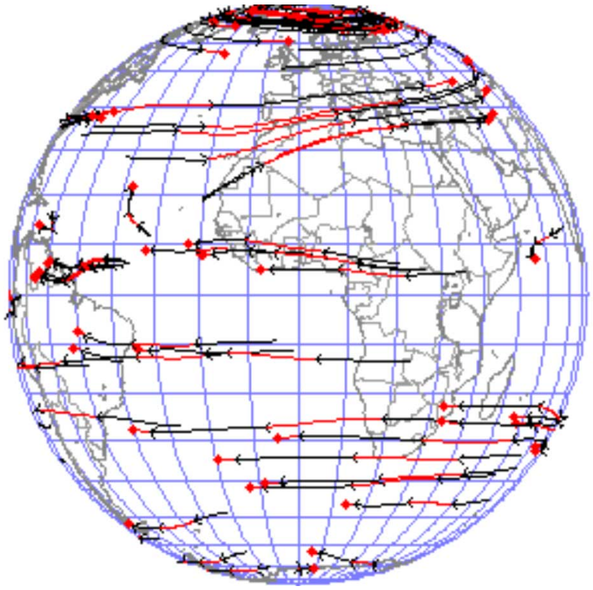


Figure 5-3. Free Floating Network After 82 Days.

The results of the Paired N-S/Zonal control are shown in Figure 5-4. (Note that the initial starting network is shown in Figure 5-2.)

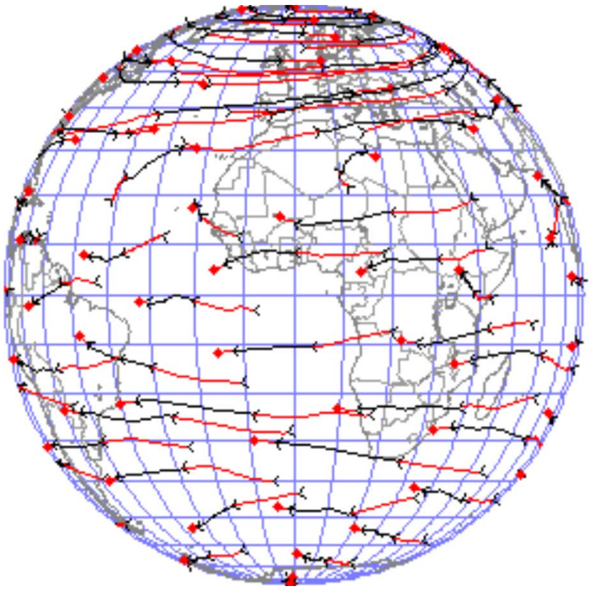


Figure 5-4. Paired N-S/Zonal Control Algorithm After 82 Days.

Figure 5-5 compares the evolution of $\sigma_{NNSD}$ for free-floating, Paired N-S, and Paired N-S/Zonal cases, all starting from an identical initial network. The Paired N-S and Paired N-S/Zonal cases utilize 5 m/s control authority.

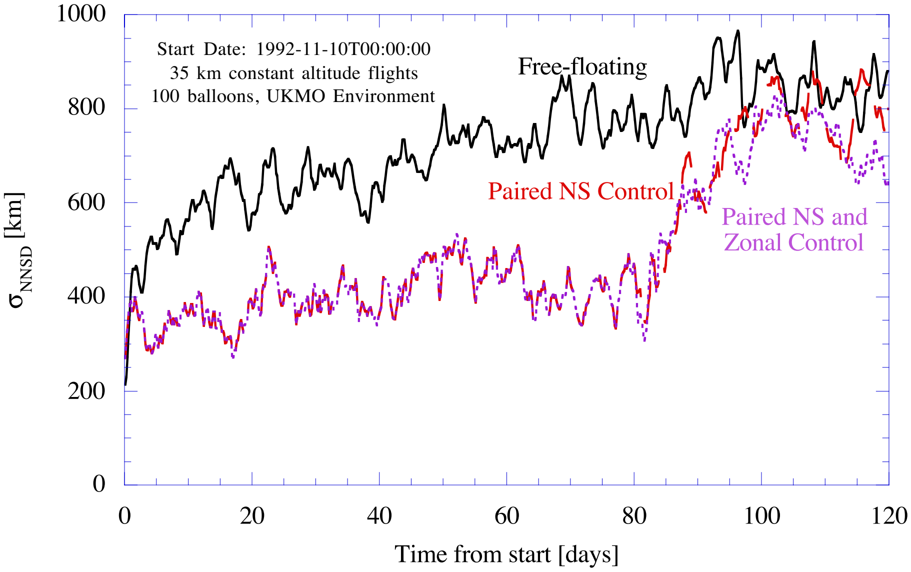


Figure 5-5. Comparison: Free-floating, Paired N-S, Paired N-S/Zonal Control Algorithms.

## 5.5. Phase II Constellation Management Work and Results

### 5.5.1. Overview

During Phase II, we have enhanced our global network modeling capabilities significantly, and we have applied these capabilities to look at several new areas:

- Global Coverage Options
- Wind Field Analyses
- Parameterized Environment Description
- Atmospheric Feature Identification
- New Framework for Constellation Management
  - Related Research Areas
  - New Framework for Constellation Management
  - Artificial Potential (AP)/ Weak Stability Boundary (WSB) Framework Simulations
  - Future Directions for AP/WSB Work
- Simulations of StratCon Applications
  - Zone Avoidance
  - Polar Atmospheric Chemistry
  - Target Overflight
  - Hemispheric Constellation
  - Adaptive Observation Systems

The following sections discuss these new areas of research.

### 5.5.2. Global Coverage Options

For many of the science applications described above, it is desirable to "see" a large portion the Earth's surface. To provide an initial assessment of the feasibility of the StratCon concept for these science objectives, we evaluated the percentage of Earth coverage that could be obtained from a constellation of stratospheric balloons. We calculated this percentage with the following equation:

$$\%Coverage = \frac{N \bullet S_i}{S_{Earth}} \qquad 5.2$$

where

$N$ = number of balloons in the network

$S_i$ = Earth surface area seen by 1 balloon [m$^2$]

$S_{earth}$ = Earth surface area [m$^2$]

The following graphs show the surface coverage obtainable from a network of balloons at 35 and 20 km as a function of the number of balloons and the allowable view angle. The graphs show that 400 balloons at 35 km would be able to see 10 % of the Earth's surface simultaneously, provided that the balloons are evenly distributed and that a 75° look angle is acceptable. At a typical StratoSail® TCS altitude (20 km), a smaller percentage of the Earth's surface is visible.

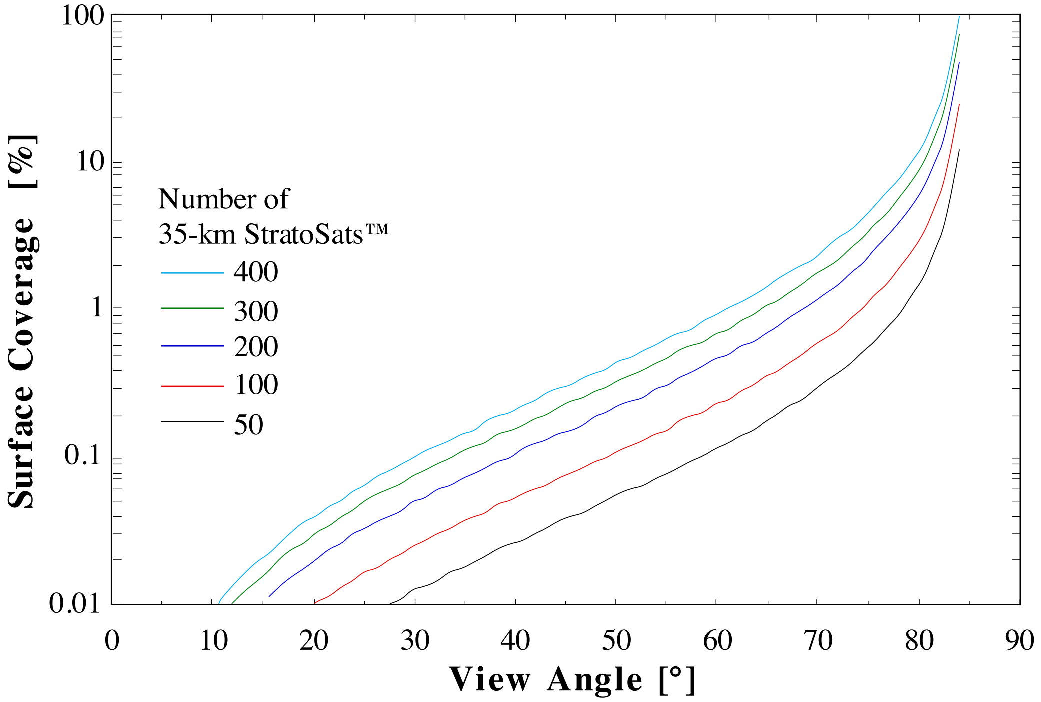


Figure 5-6. Surface Coverage from 35 km Altitude.

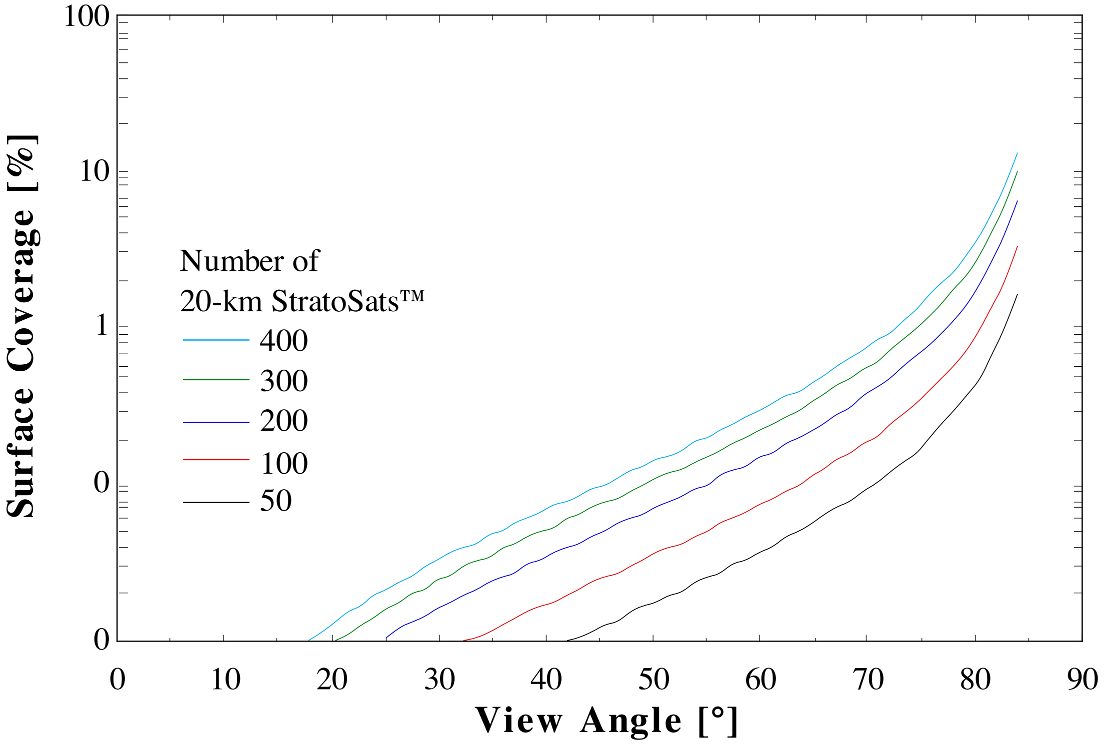


Figure 5-7. Surface Coverage for 20 km Altitude.

### 5.5.3. Wind Field Analyses

We performed evaluation of the expected wind fields at planned operating altitudes. The first study involved wind velocity differences between 35 km and 20 km. The second study looked at approach velocities between two balloons at 35 km.

#### *5.5.3.1. Wind Velocity Differences*

To describe the operating environment for the StratoSail® Trajectory Control System (TCS), we evaluated the wind velocity differences between 35 km (balloon altitude) and 20 km (StratoSail® TCS altitude). The wind velocity difference analyses were performed for one year, namely 1990. The differences were graphed as a function of the time of year.

The graphs are presented below in order from north to south, with the average graph for each region followed by the standard deviation graph for each region. Commentary follows the graphs.

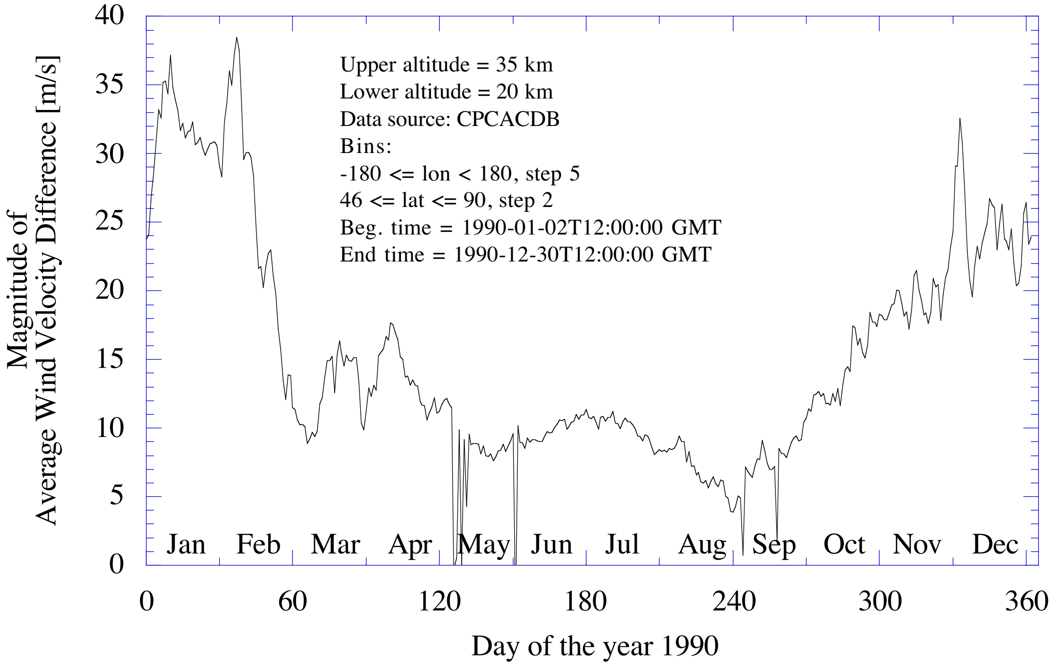


Figure 5-8. Wind velocity differences for northern latitudes.

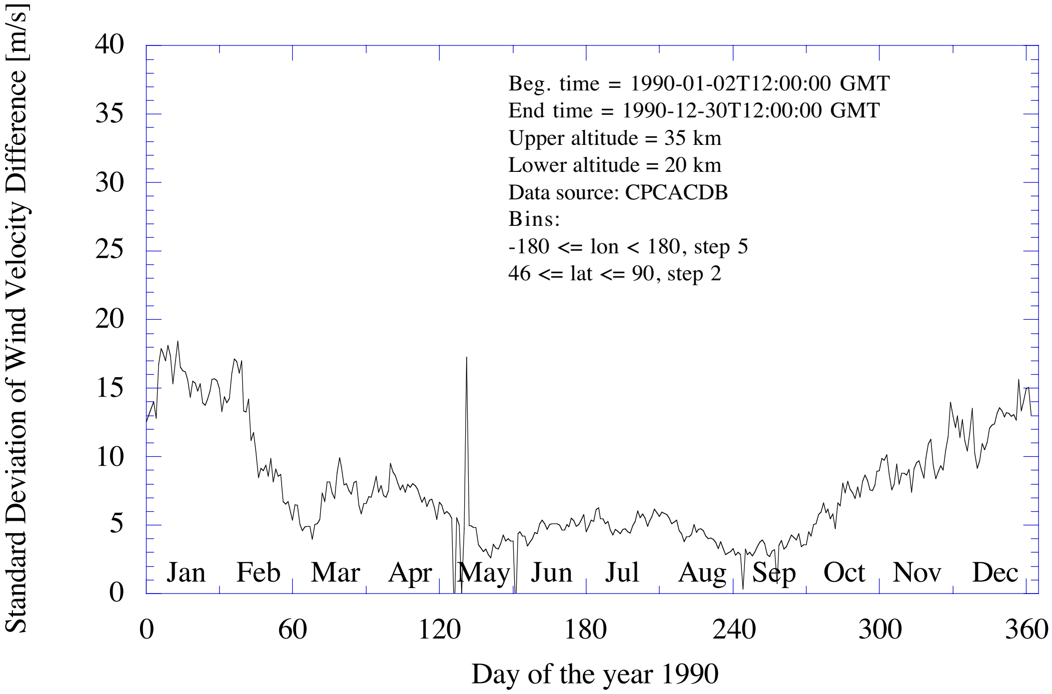


Figure 5-9. Standard deviation of wind velocity differences for northern latitudes.

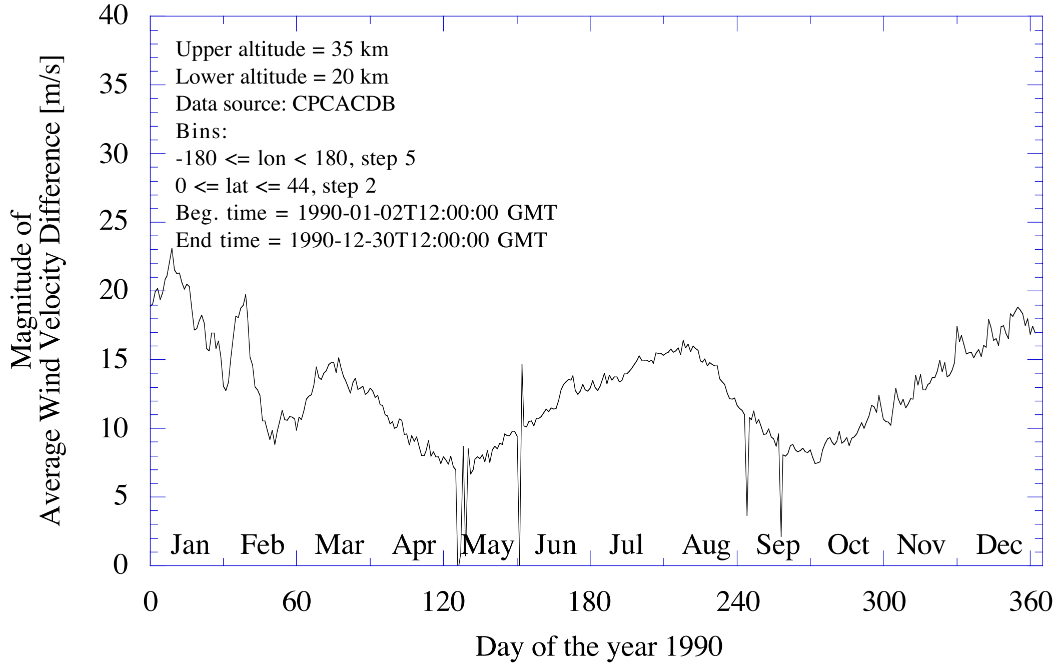


Figure 5-10. Wind velocity differences for northern mid-latitudes.

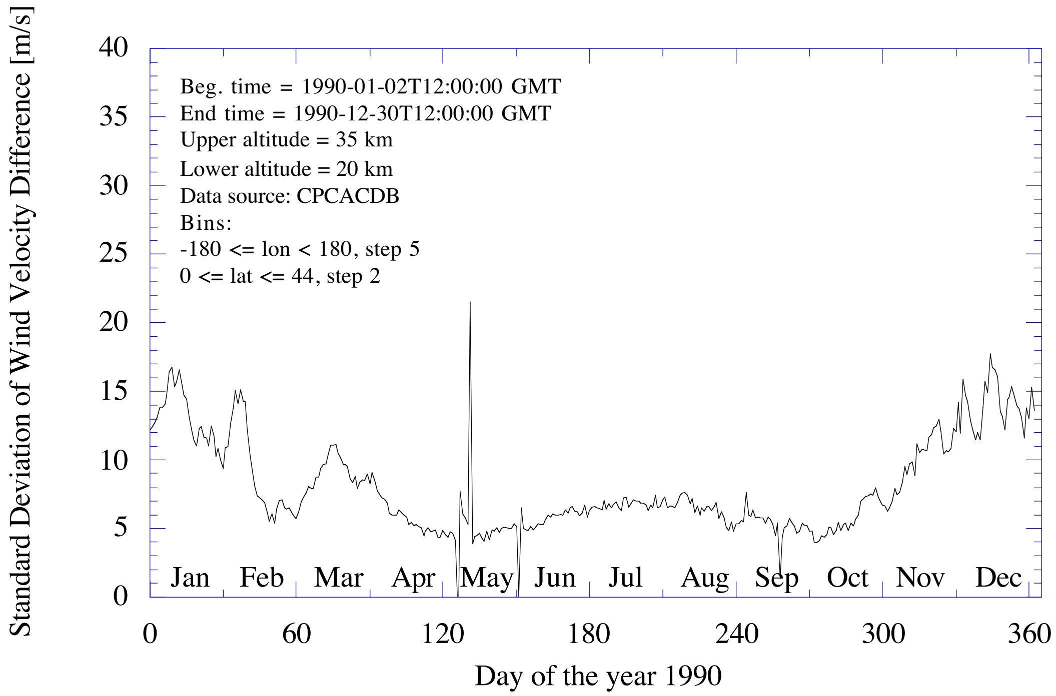


Figure 5-11. Standard deviation of wind velocity differences for northern mid-latitudes.

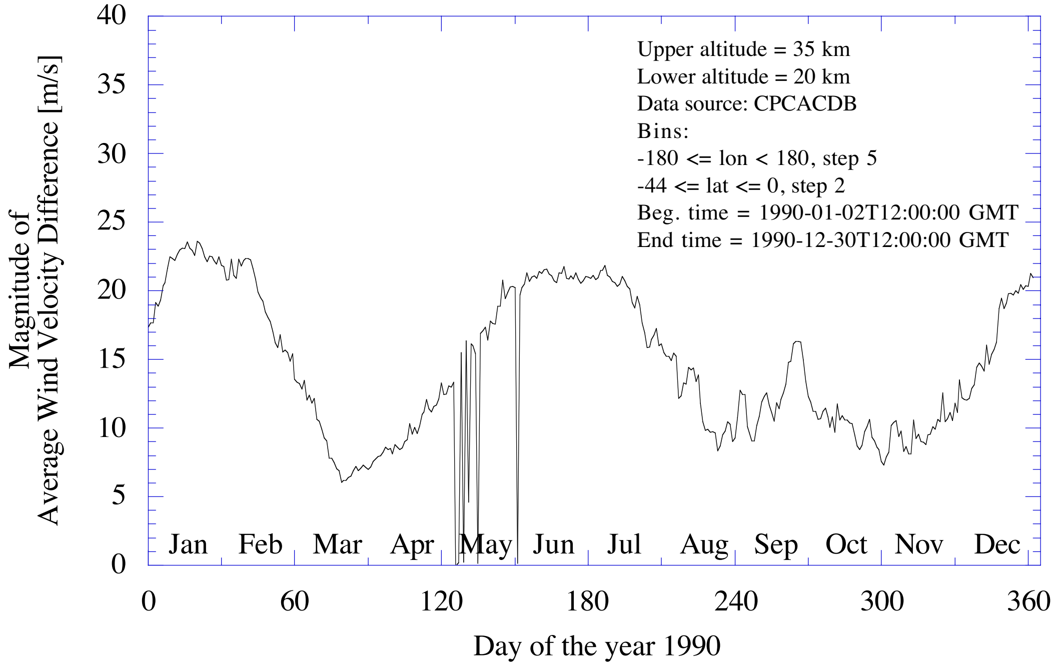


Figure 5-12. Wind velocity differences for southern mid-latitudes.

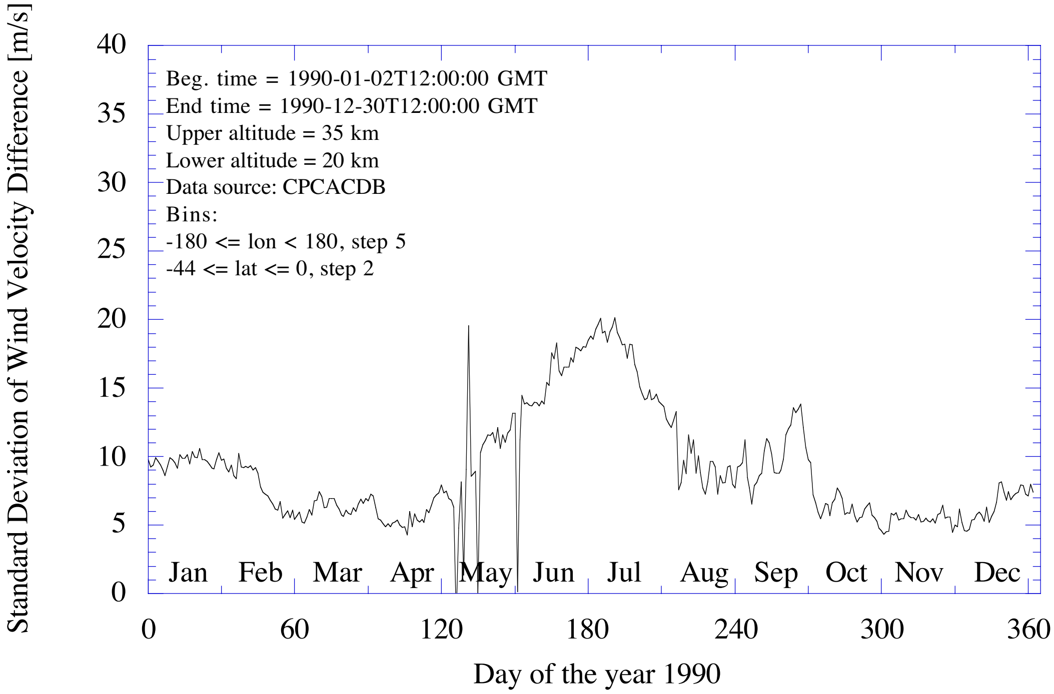


Figure 5-13. Standard deviation of wind velocity differences for southern mid-latitudes.

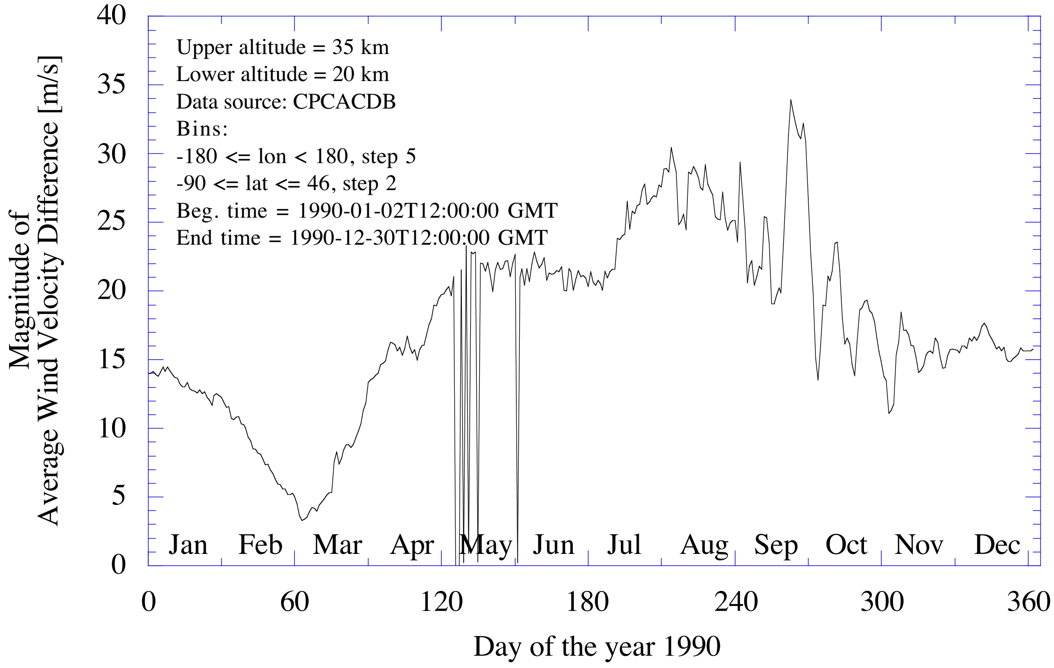


Figure 5-14. Wind velocity differences for southern latitudes.

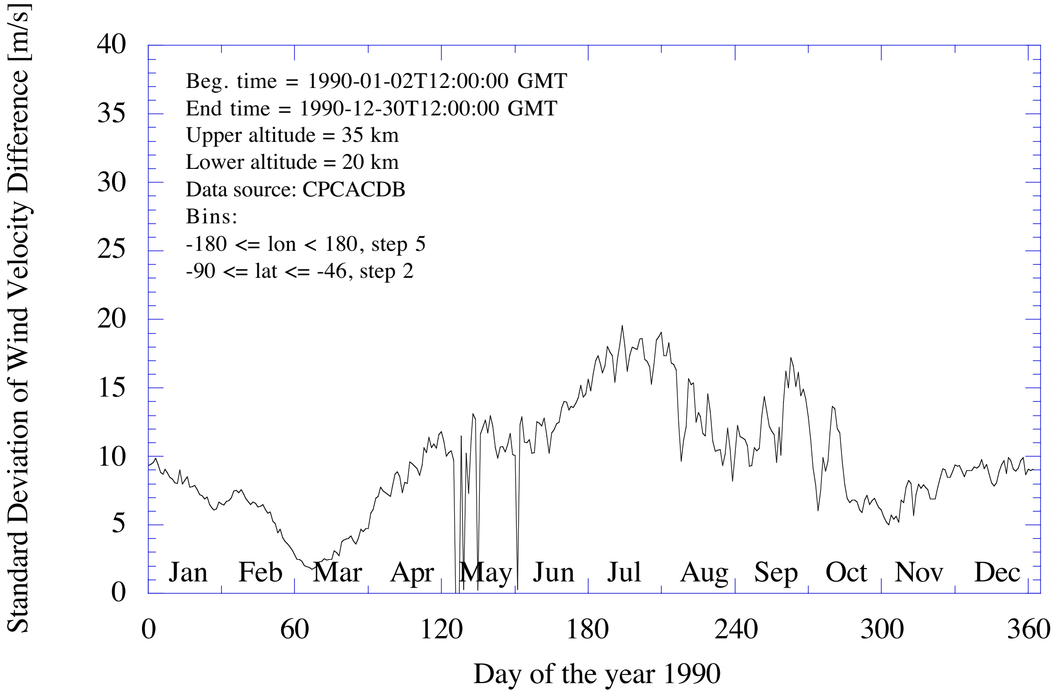


Figure 5-15. Standard deviation of wind velocity differences for southern latitudes.

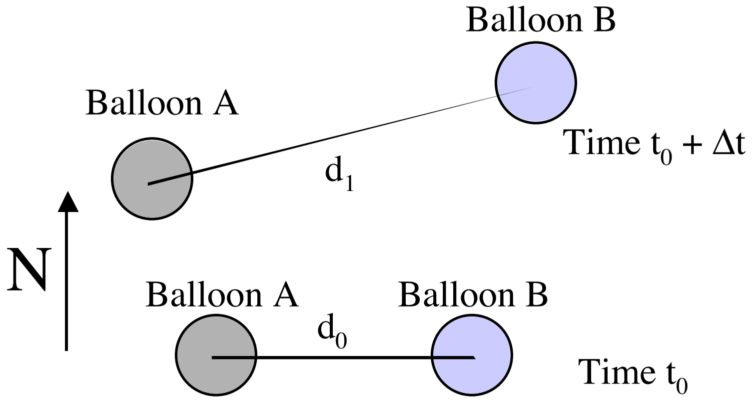
It is interesting to note that in most cases the standard deviation about half of the magnitude, indicating that it would be a surprising event to have zero wind difference between 35 km and 20 km.

The figures above indicate reasonable values for wind velocity differences in terms of the capabilities envisioned for the StratoSail® Trajectory Control System and indicate the feasibility of using such a system for maintaining the geometry of the global constellation throughout a year.

### *5.5.3.2. Approach Velocity Maps*

We have developed "Approach Velocity Maps" (AVMs) which provide a visual image of the rate at which balloons will approach each other (positive approach velocity) or move apart from each other (negative approach velocity) at any instant in time. These AVMs provide a visual means of evaluating meteorological features and identifying those regions where balloon trajectory control is required or not. They also provide a simple and visual means of determining the required level of trajectory control capability to maintain uniform separation in a global network.

AVM maps are constructed by simulating two balloons in close proximity to each other and calculating the rate at which an imaginary line connecting the two balloons lengthens or shortens: the approach velocity. Approach velocities are calculated over the entire globe at a given altitude, and contours are determined. The following figure illustrates the calculation method for approach velocity.



$$\text{Approach Velocity} = -(d_1 - d_0) / (\Delta t)$$

Figure 5-16. Approach Velocity Calculation Method.

The approach velocity is a function of the orientation of the balloons with respect to each other. For an initial examination of the approach velocity contours, we chose two orientations for the balloon pairs, namely north-south and east-west. The following figures show Approach Velocity Maps (AVMs) for both orientations.

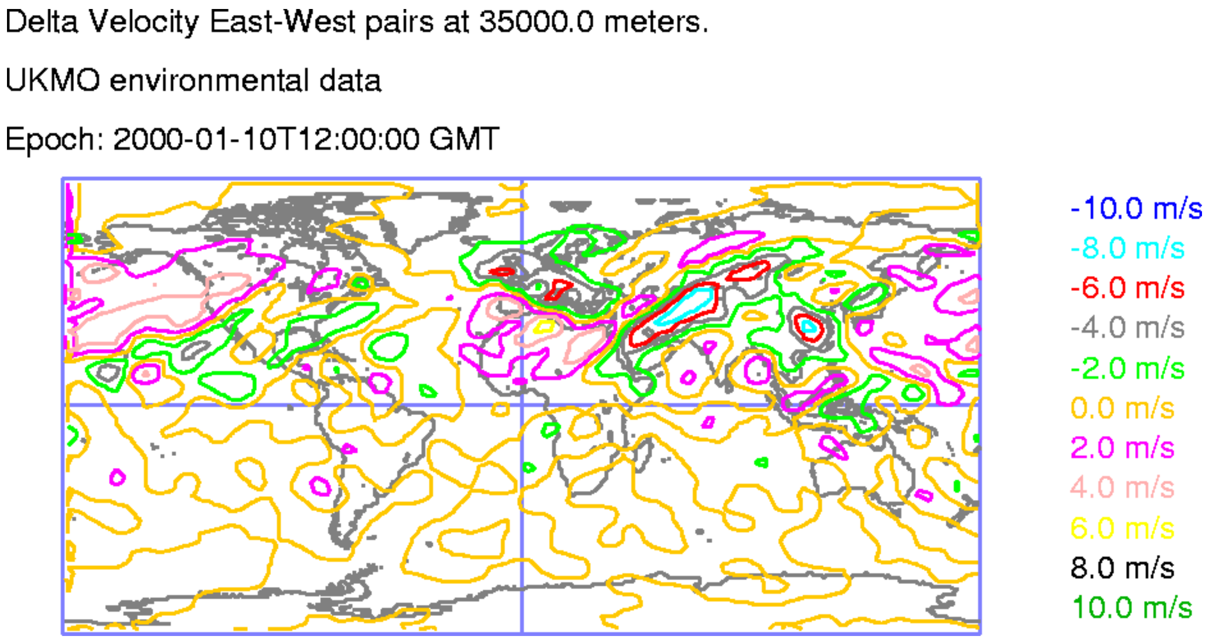


Figure 5-17. Approach Velocity Map for East-West Pairs.

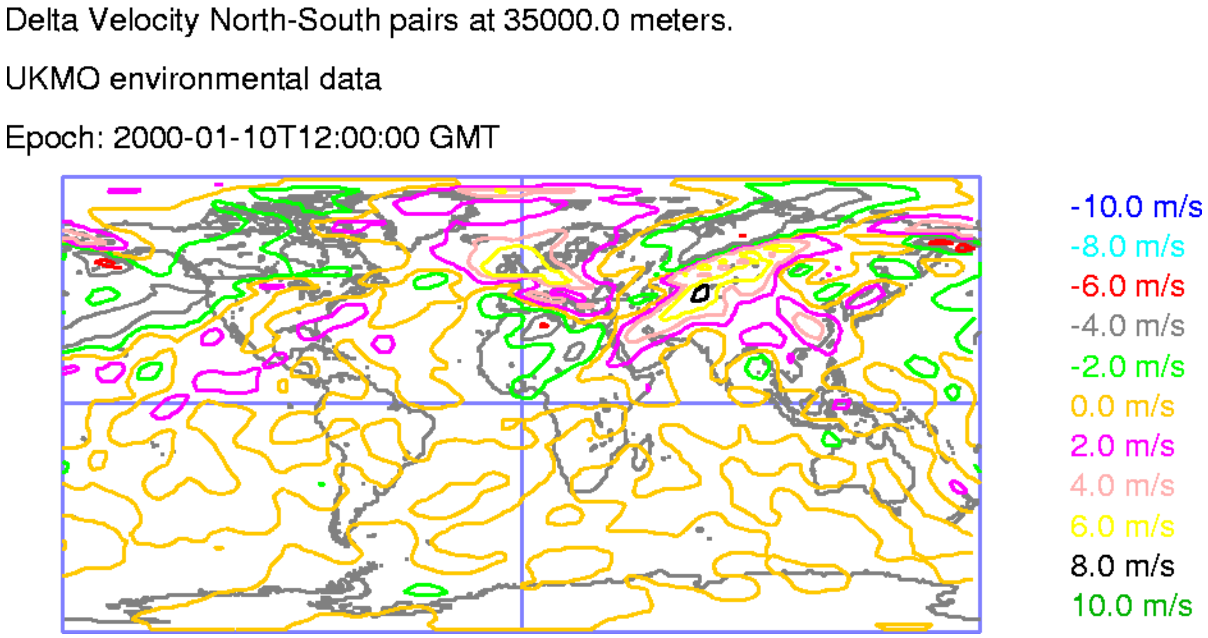


Figure 5-18. Approach Velocity Map for North-South Pairs.

Some general trends are apparent from the AVMs. First, the figures show Northern Hemisphere winter (Southern Hemisphere summer) conditions. As expected, approach velocities are very low in the Southern Hemisphere, and little trajectory control capability would be required to maintain a uniform constellation in the Southern Hemisphere, between 0 and ±2 m/s almost everywhere. This observation is consistent with global network simulations that we performed during Phase I of this activity. Second, the approach velocities shown here are consistent with the expected level of trajectory control authority of the StratoSail® Trajectory Control System, about 5 m/s. Finally, there are small regions where more than ±5 m/s approach velocity is observed. Depending on the available level of trajectory control authority, the constellation geometry may temporarily degrade slightly in regions with the highest absolute values of approach velocity.

Another interesting trend is that the regions where east-west pairs tend to cluster (positive approach velocity) is also the region where north-south pairs tend to produce voids (negative approach velocity). Because atmospheric gasses are essentially incompressible and because vertical velocities are significantly less than horizontal (wind) velocities, compression of the atmosphere in one direction typically means expansion of the atmosphere in an orthogonal direction. Thus, it is not surprising that approach and divergence velocities are orthogonal in the manner observed here.

But, given that the approach velocity is a strong function of the orientation between two balloons, it appears that with sufficient planning beforehand, it may be possible to put adjacent balloons in an advantageous orientation relative to each other before reaching the zone of high approach velocity. These observations are consistent with the new approach to constellation management developed by Princeton University and presented in Section 5.6.

### 5.5.4. Parameterized Environment Description

In Phase II we performed studies that would allow parameterization of the stratospheric wind field. To develop efficient methodologies we need to better understand the behavior of the uncontrolled balloons in the atmosphere. In other words, we need to know what forces and trends we need to counteract to maintain the desired constellation configuration. With this purpose in mind, we performed a long-term continuous simulation (987 days) of the balloon constellation evolution in the stratosphere. The constellation consists of 100 balloons that are initially distributed randomly (not necessarily uniformly) around the globe (see Figure 5-19). The red dots on Figure 5-19 represent balloons, the yellow circles around them are surface viewing area assuming horizon-to-horizon viewing geometry, regions where viewing areas of different balloons overlap are indicated in green. The simulation uses assimilated winds from the UKMO data set. The simulation starts on September 14, 1999 and continues for 987 days.

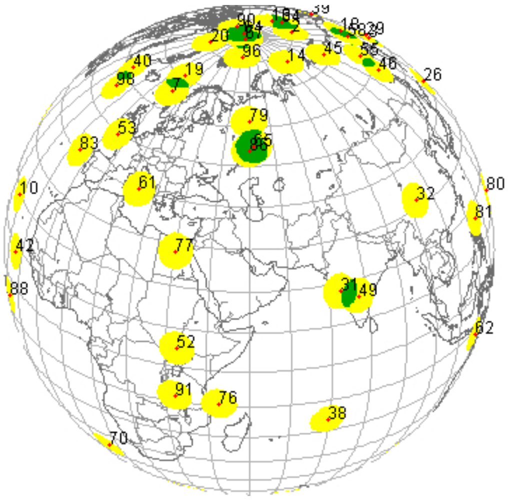


Figure 5-19. Distribution at the start of the simulation (day 0, September 14, 1999)

The constellation configuration by the end of the simulation is shown on Figure 5-20. The majority of the balloons migrated towards northern Polar Regions. This is a somewhat surprising result, because intuitively we would expect to find concentrations of balloons in the vicinity of both Poles. This is because the strong wintertime circulation pattern developing in the polar regions ("polar vortex") effectively "collects" balloons in the polar region during a winter (see Figure 5-21 showing the balloons trapped in the Northern polar vortex). Starting with a random distribution, with a roughly equal number of balloons in both hemispheres, we would expect to find most of the balloons in the Polar Regions eventually. This is apparently not the case. Simulations with different random initial distributions yield similar result. There are two possible explanations. First, the final distribution could be biased by the date the simulation starts – the start of northern autumn. Atmosphere, being a chaotic system, can have preferred states or "regimes" that are more favorable than the others – the so-called attractors. In our example, one of these states can be the one with all the balloons gathered in the vicinity of the North Pole, the other - with all the balloons gathered in the vicinity of the South Pole. Since we start from the state that is closer to the regime with the balloons at the North Pole, the balloon constellation in the chaotic flow evolves towards this particular final state – with all the balloons at the North Pole. The way to test this hypothesis is to start the simulation at a different date that is closer to the other probable "regime" - all balloons at the South Pole – for example, on March 22, the start of Southern autumn.

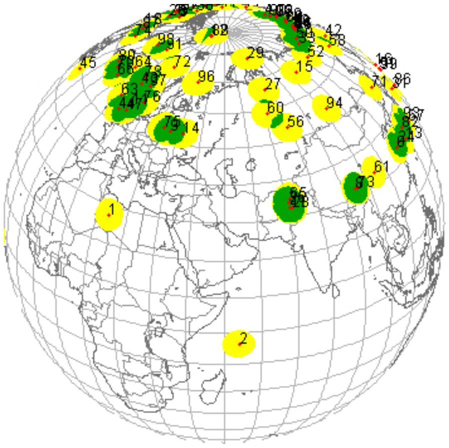


Figure 5-20. Distribution at the end of the simulation (day 987, May 28, 2002)

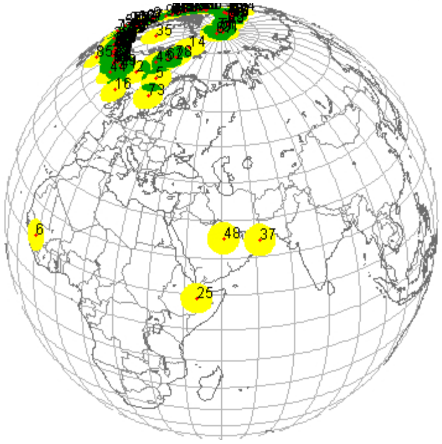


Figure 5-21. Winter constellation configuration (Day 830, December 22, 2001)

The other possible explanation is that northern winter circulation is stronger, or persists for longer time, than the southern winter circulation, and is more effective in keeping the balloons in the high northern latitudes. Another possibility is that there is a net northward seasonal flow at this altitude.

Knowing the peculiarities of the atmospheric circulation like this one may allow us to develop simplified models of the circulation that can be employed to test and develop the constellation control methodologies. For example, the famous Lorenz system – the system of three non-linear equations with chaotic solutions – has two dominant regimes. The system varies irregularly between those two regimes. If we can show that this behavior of the Lorenz system is analogous to the behavior we observe in the real atmosphere (as described above), we could employ the Lorenz system to test and develop control methodologies, rather than run computationally intensive simulation with real wind data.

### 5.5.5. Atmospheric Feature Identification

We developed an algorithm that allows us to numerically identify atmospheric features such as vortices and jets. The presence of atmospheric features can be exploited to achieve trajectory objectives.

The problem of identification of vortices is complicated by the fact that there is no single definition of a vortex in fluid mechanics. Several criteria have been developed to date, but none of them is entirely satisfactory. The criteria can be roughly divided into two groups:

- Point-based criteria, for which a local (differential) quantity is calculated at every grid point of the flow field and
- Curve-based (Lagrangian) criteria, for which non-local (integral) properties of the field are calculated along the streamlines.

Examples of the point-based criteria include determining extreme values of vorticity, helicity, and excess of vorticity over strain. These methods work well for numerically simulated turbulence, but fail for many “real” geophysical flows. One plausible explanation for the failure of these techniques is that vortices are a macroscopic phenomenon, and locally calculated properties of the flow do not always translate into regional characteristics.

The Lagrangian criteria are based on characteristics of the streamlines. There are two approaches. By following the streamlines, one can (1) subdivide the flow into stable and unstable regions and define vortices as boundaries between those regions and (2) recognize swirling patterns characteristic of vortices.

One problem with the first approach is that vortices are not necessarily regions of stable flow: streamlines can spiral out of vortices. Another problem with the first approach is specifying the timescale for determining stability. In real geophysical applications, the flow may be confined to a basin (or domain) and streamlines may diverge on shorter timescales and converge on longer timescales, and vice versa.

The second set of Lagrangian criteria is based on recognition of swirling patterns. One can determine a center of curvature at every point on the streamline. If the streamline is nearly circular, the centers will be concentrated in a small region. The density of the centers can be accumulated into a field and the maxima of this field will indicate vortices. This method works well for circular vortices, but fails for elongated or irregularly shaped vortices. The problem is that real vortices in real geophysical flows are almost always non-circular.

The method that we've implemented, after experimenting with several other methods, is based on measuring the so-called winding angle of streamlines. The winding angle can be defined as the angle between a reference vector and the vector in the direction of the motion along the curve. For a closed curve the winding angle is $2\pi$ radians. For our purposes, we define vortices as a contiguous collection of originating points for streamlines for which the streamline has a winding angle of $2\pi$ radians *and* the endpoint lies close to the starting point (≤5° angular separation will probably be sufficient).

The method works very well, as can be seen on the following figures. Figure 5-22 shows the wind field at 35 km on 2 January 2001 overlaid on the continental outlines and a latitude-longitude grid. Two major vortices are easily seen: one over Greenland and another one south of Alaska. Figure 5-23 illustrates the results of the vortex identification method to the wind field in Figure 5-22. Figure 5-23 shows the distribution of the starting points (marked by squares) of the (almost) closed streamlines in the North polar stereo projection. The streamline was considered closed in this analysis if the angular separation of the end points on the streamline separated by $2\pi$ winding angle is less than 5° (~600 km). The method picks up both of the large vortices visible in the wind filed plot. In addition, what looks, to a human observer, like a jet in the polar regions of Figure 5-22 is correctly interpreted by the method as a large polar vortex containing the smaller vortex over Greenland. The method correctly identifies the edges of the polar vortex stretching over mid-latitudes of the USA, Atlantic Ocean, Europe and closing over the North Pole.

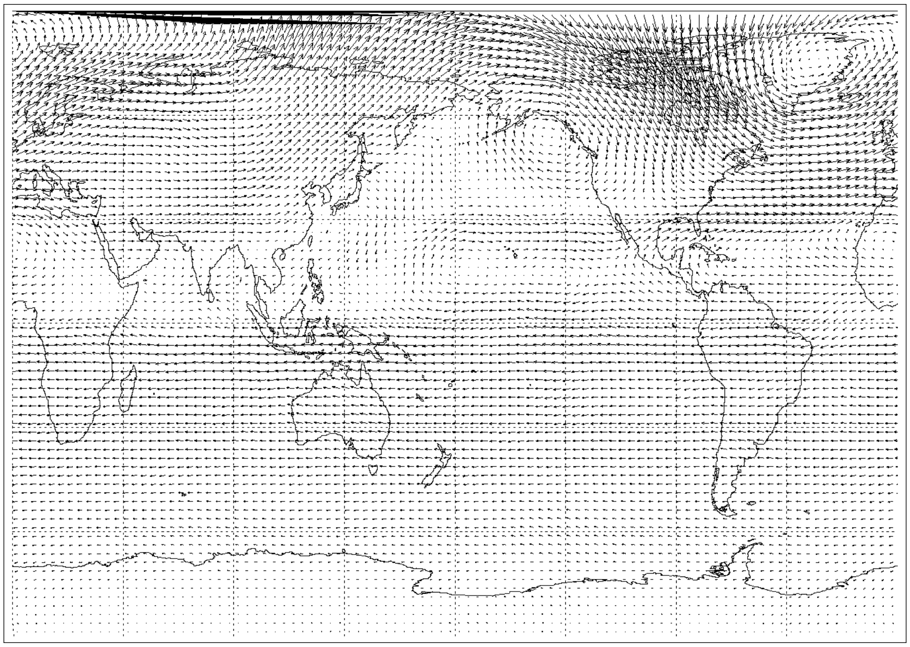


Figure 5-22. Wind Field at 35 km on 2 January 2001.

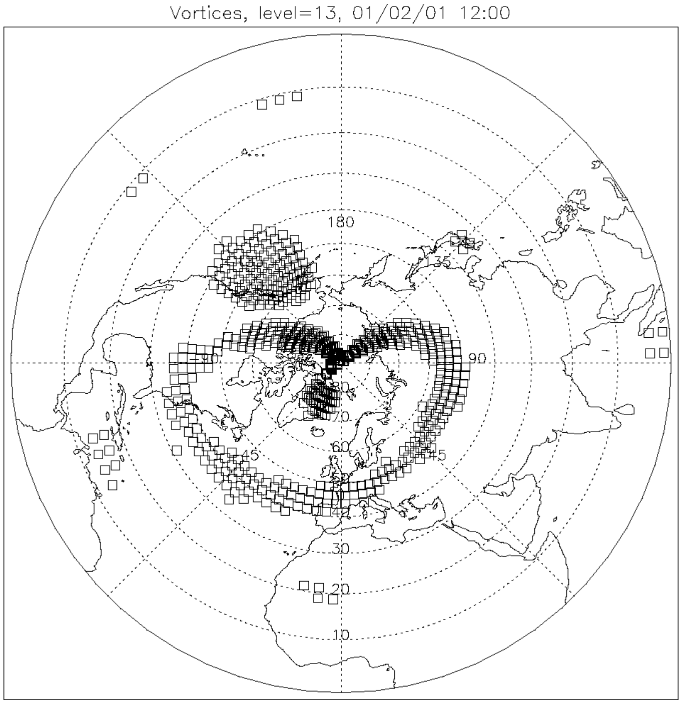


Figure 5-23. Results of the Vortex Identification Method

In another example of the successful method application, Figure 5-24 shows the wind field at 20 km for the same date as on Figure 5-22 and the result of the feature identification analysis is shown on Figure 5-25. The wind field on Figure 5-24 shows more vortices than the wind field at 35 km because it is much lower in the atmosphere and is closer to more turbulent troposphere. In this particular case the method was implemented to look for vortices that do not extend over Polar Regions. Again, the method correctly identifies all the vortices (except for polar vortices over North and South poles – as expected in this particular case).

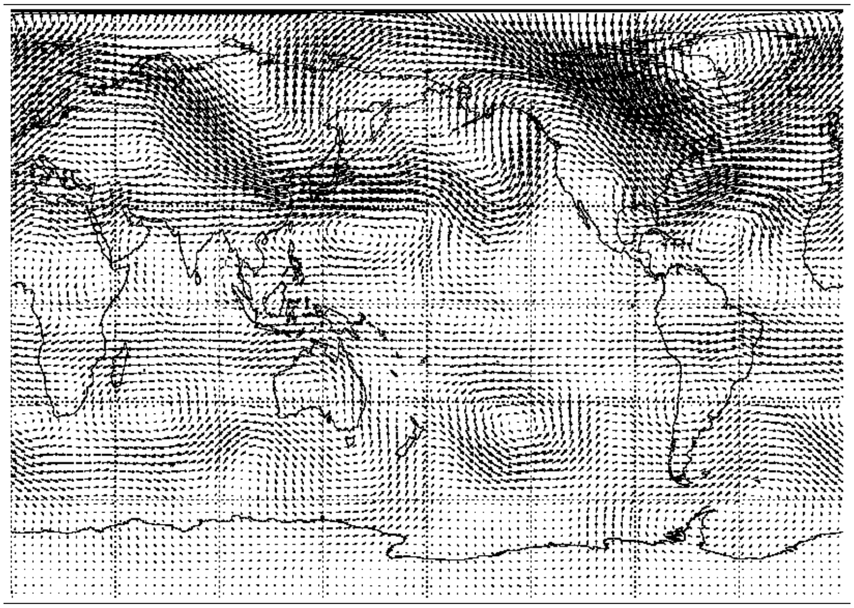


Figure 5-24. Wind field at 20 km on 2 January 2001

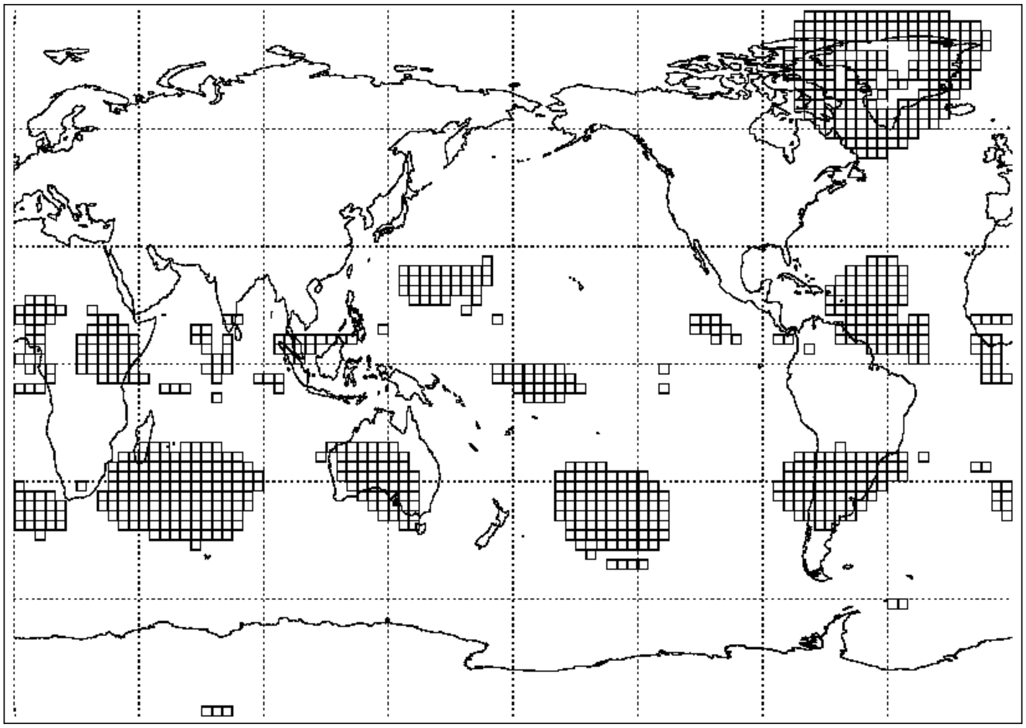


Figure 5-25. Results of the Vortex Identification Method for Figure 5-24

The advantages of the method are that it:

- identifies not only all the vortices visible to the human observer on the wind vector field plots, but also the vortices that are not so obvious to the human observer (for example, the polar vortex or small vortices in north-western Africa, in the Caribbean, over Japan, and in the Pacific ocean)

- does not depend on the strength or shape of the vortex for identification; it can be modified to give locations of turning points (winding angle $\pi$) or other points important for balloon "traffic" control.

Two drawbacks of the method are (1) the need to decide, in advance, the integration time and (2) the computational time required to calculate every streamline. These issues will be addressed as we move forward with this scheme.

Numerical identification of vortices in the flow is necessary for the implementation of the AP/WSB framework to constellation control, discussed in the next section.

## 5.6. New Framework for Constellation Management

One component of the Phase II work was a subcontract with Princeton University for investigation of new methods for constellation management. There are several areas of ongoing research at Princeton that are related to the StratCon concept.

## 5.6.1. Related Research Areas

### *5.6.1.1. Group Behavior*

The first area of related research is the dynamics of group behavior. The following figure shows a pod of dolphins. The dolphins react naturally to each other and maintain formation as the group moves.

Figure 5-26. A pod of dolphins.

Flocks of birds and pods of dolphins exhibit similar behavior. Such behavior resembles the desired motions of a uniformly distributed network of balloons. Each individual in the school, flock, or pod responds to its neighbors. This mechanism allows group-level characteristics to emerge from individual-level behaviors.

#### 5.6.1.1.1. Coordinated Control of Distributed Systems

Another related research area is the coordinated control of distributed systems. Example applications of these concepts include robotic obstacle avoidance, micro-satellite formation flying, and autonomous underwater vehicles for adaptive ocean sampling. The following sequence of images shows coordinated control of underwater vehicles. There is one “leader,” the circle. The five “X” marks show followers. By controlling their position relative to the leader and other followers, a stable group behavior and formation emerges.

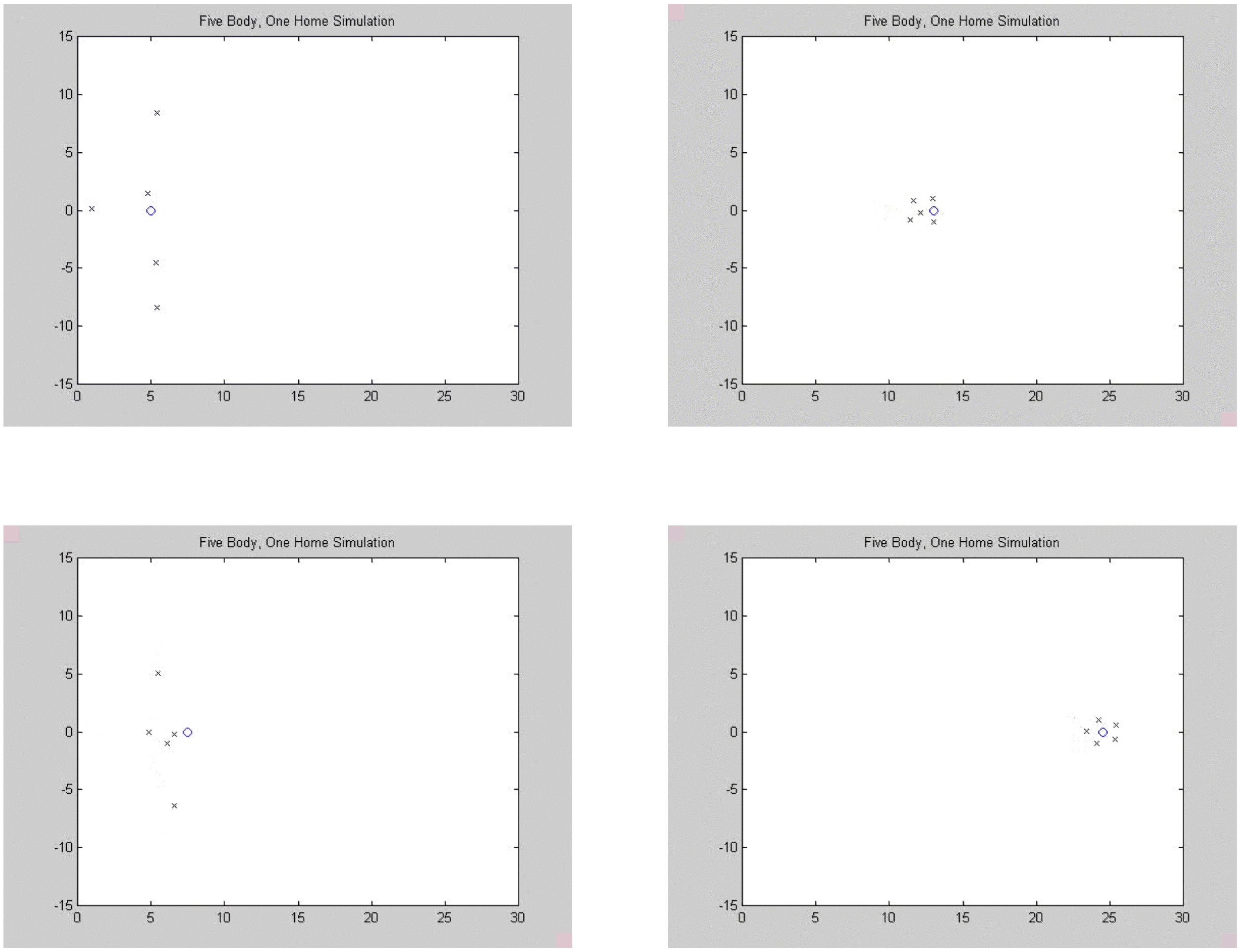


Figure 5-27. Example Underwater Vehicle Simulation.

### 5.6.1.1.2. Artificial Potentials

Artificial potentials are used to determine control actions for simulations in which group-level characteristics emerge from individual-level behaviors. The method of artificial potentials is a generalization of the Molecular Control method discussed above. Artificial Potentials utilize information from *all* nearby balloons in the constellation, not just the nearest neighbor.

The following figure shows three group members. The velocity of each member is given by u. In the absence of any control, the group members would float with the wind at velocity $\mathbf{u}_{wind}$. However, one can calculate ΔVs that should be applied due to the presence of neighboring group members. When these ΔVs are applied, the group-level characteristics emerge. The ΔVs are represented in the figure as $u_{21}$, $u_{31}$, $u_{23}$, and $u_{32}$.

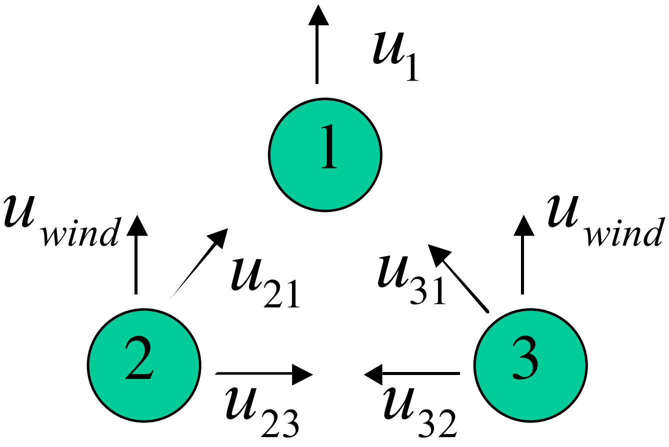


Figure 5-28. Artificial Potentials Schematic Drawing.

To calculate values for the ΔVs, one uses the concept of artificial potentials. The distance from one group member to the other is $r_{ij}$. The gradient of a potential function with respect to $r_{ij}$ provides the magnitude of the ΔV that should be applied between two group members i and j.

$$\left\| u_{ij} \right\| = C \nabla \Psi\left(r_{ij}\right), \tag{5.3}$$

where

$\mathbf{u}_{ij}$ = ΔV vector between group member i and group member j,

$C$ = a constant that represents the conversion from forces to velocities, and

$\Psi\left(r_{ij}\right)$ = artificial potential function.

The direction of $\mathbf{u}_{ij}$ is from i to j.

Note that the quantity $\nabla \Psi\left(r_{ij}\right)$ represents a force that acts on the system. An aerodynamic model of the floating balloon system is required to convert those forces to velocities. That aerodynamic model is represented in this equation as the constant *C* that is, in general, a function of the operating point and environment conditions. For the purposes of calculating desired control directions and velocities, it is often sufficient to assume *C* is a constant. We used this approximation during our modeling activities in Phase II.

One example potential function is

$$\Psi = k\left[\ln\left(r_{ij}\right) + \frac{d_0}{r_{ij}}\right], \tag{5.4}$$

where

k = a scale factor, and

$d_0$ = the desired separation distance.

Such a function provides attraction when $d_0 < r_{ij} < d_1$ and repulsion when $r_{ij} > d_0$. The following figure illustrates this relationship.

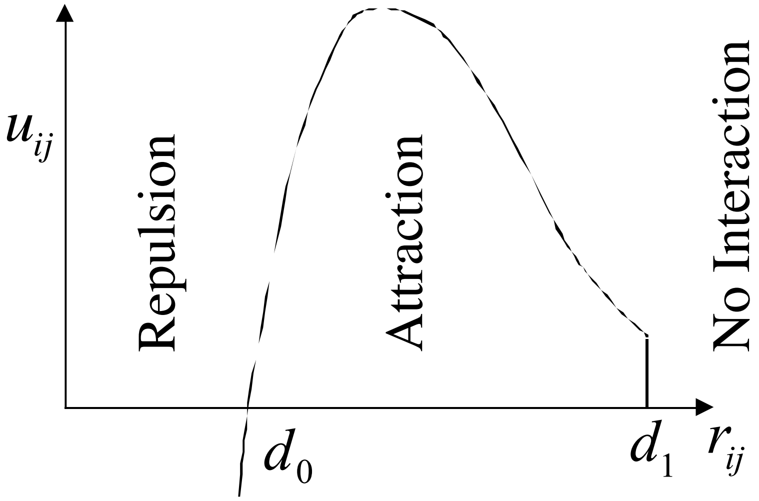


Figure 5-29. Magnitude of ΔV vector $\mathbf{u}_{ij}$ for example potential function.

Another option for potential function is

$$\Psi = \frac{k}{\Delta t}\left[\frac{r_{ij}^2}{2} - d_0 r_{ij}\right] \tag{5.5}$$

where

$\Delta t$ = the synchronization interval for all balloons in the network and

$k$ = a scale factor.

The gradient of this potential function with respect to $r_{ij}$ provides a value that is proportional to the velocity required to make $r_{ij}$ equal to $d_0$ in the next time step. Using the scale factors k=0.5 and C=1.0 worked well in our experience.

In this framework, it is possible to introduce "virtual" group members and to have different values of the scale factor or potential function for any group member. Thus, for example, it is possible to model zones of overflight exclusion (see Section 5.7.1) by inserting a virtual member with strong repulsive characteristics. Or, it is possible to insert strong virtual attractors where science observations are desired. And, the use of potential functions provides a useful characterization of the problem for stability and robustness proofs.

#### *5.6.1.2. Weak Stability Boundary (WSB) Theory*

Another area of related research at Princeton University is Weak Stability Boundary (WSB) theory. WSB theory was developed for application to spacecraft. WSB theory was first used to control spacecraft for low-energy routes through space. A Weak Stability Boundary is a multi-dimensional position/velocity surface. In other words, to be "on the WSB," a body must be at the correct velocity and position. WSB theory uses chaos principles to control the motion of bodies in regions where competing and nearly-equal dynamic forces exist. For example, WSB can be used to control spacecraft in regions where the gravitational attraction from two celestial bodies is nearly equal. At that point, a small nudge in either direction will send the spacecraft on a dramatically different trajectory.

WSB theory was operationally demonstrated in 1991 by the Japanese spacecraft, Hiten, when it performed a new type of lunar transfer. Upcoming uses of WSB theory include the SMART1 mission by ESA in 2003 and the Lunar A mission by the Japanese in 2003.

Princeton extended WSB theory to work in the atmosphere. WSBs do not exist everywhere. Rather, they exist at the interfaces between atmospheric vortices and the surrounding air flow. These regions of high atmospheric instability can be modeled by WSB theory. So, WSB theory can provide significant and controlled trajectory modification in regions of high atmospheric instability, exactly the place where it is needed.

## 5.6.2. New Framework for Constellation Management

The Artificial Potential (AP) and Weak Stability Boundary (WSB) concepts have led to the development of a new framework for constellation management. This new framework is called AP/WSB.

### *5.6.2.1. Motivation*

The motivation for the new framework can best be shown in the following figures.

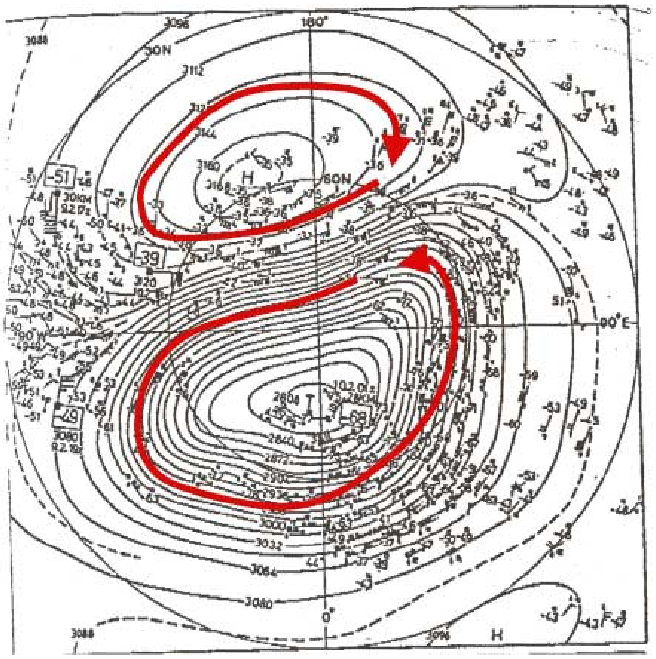


Figure 5-30. Winter Arctic Vortex.

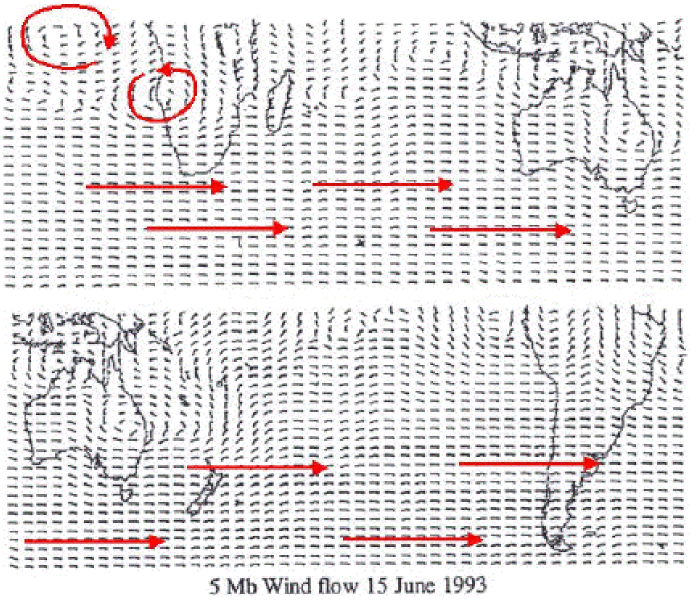


Figure 5-31. Southern Hemisphere StratWarms and Smooth Flow.

Both figures show mesoscale vortices of various strengths. In addition, there are regions of smooth and regular flow that interface with the vortices. The new framework utilizes artificial potentials to determine the control settings for trajectory control systems in the steady flow regions. Weak Stability Boundary theory is used to (a) determine the interfaces between smooth flow and areas where chaotic conditions exist and (b) calculate trajectory control system settings in the region of chaotic flow. The following figure illustrates the concept schematically.

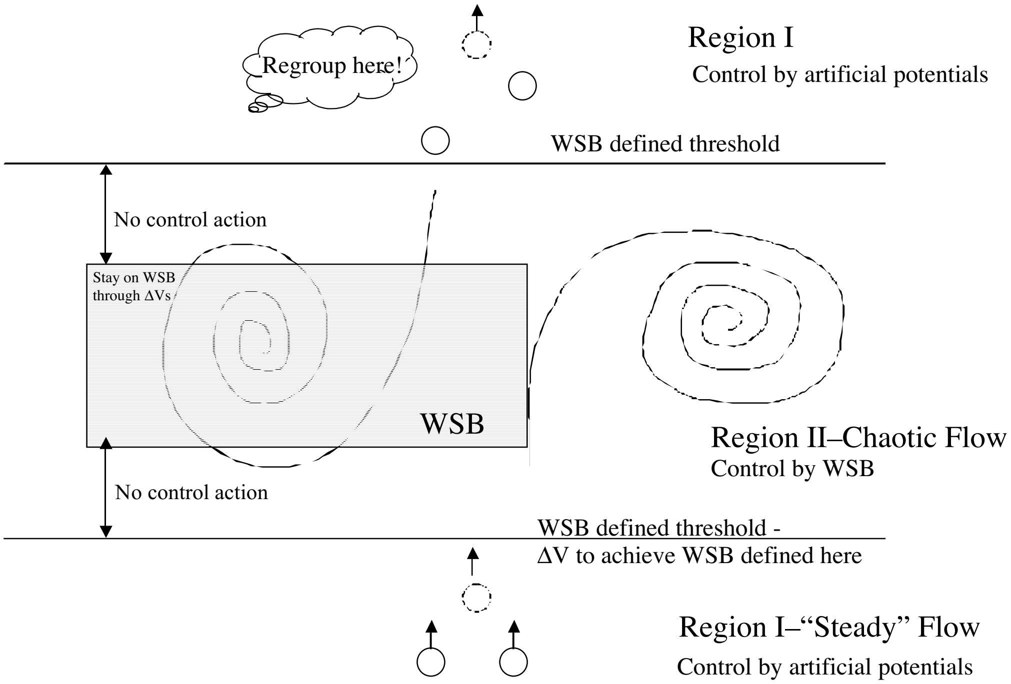


Figure 5-32. Zones for AP/WSB Framework.

When the balloons approach a region with chaotic flow (bottom of the figure), they cross a threshold. Before the threshold, artificial potential theory is used to determine the control actions. Beyond the threshold, there is likely to be a region within which control actions are unlikely to provide much effect. However, on the WSB itself (shown a s a gray region in the figure), control actions will significantly affect the trajectory. After passing through another region where control actions are unlikely to have much effect, the balloon emerges on the other side of the region. In the figure above, the goal is to emerge on the other side and maintain group geometry as much as possible. But there may be other objectives that are possible.

Within this framework, Princeton researchers evaluated feasibility of both artificial potentials and WSB for controlling balloon trajectories. The following sections show some results from those analyses. The regions to implement the WSB theory (i.e. in the vicinity of vortices) would be identified numerically using the algorithm described in Section 5.5.5.

### 5.6.3. AP/WSB Framework Example Simulations

The figure below shows a simulation of two vehicles and one virtual leader. The external wind field is 20 m/s easterly, and the virtual leader moves at 20 m/s. The simulation progresses from the bottom of the chart to the top. Not surprisingly, a stable formation of the three vehicles is achieved.

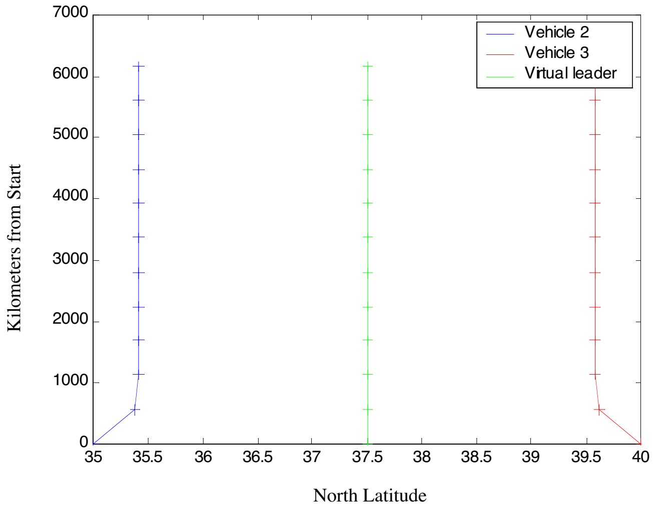


Figure 5-33. Example Simulation in Uniform Wind Field.

In the presence of a non-uniform external flow field, it is not clear whether the artificial potential scheme will provide stable arrangements of the constellation members. The next figure again shows two vehicles and one virtual leader. In this case, there is a 3rd order polynomial for the variation of easterly wind velocity with latitude. The polynomial fits the points 10 m/s at 10° north latitude, 35 m/s at 45° north latitude, and 45 m/s at 90° north latitude. In addition, there is a constant 1 m/s drift velocity from south to north, which approximates the normal poleward flow at 35 km. In this case, the artificial potential concept again produces a stable but different arrangement of the members of the group.

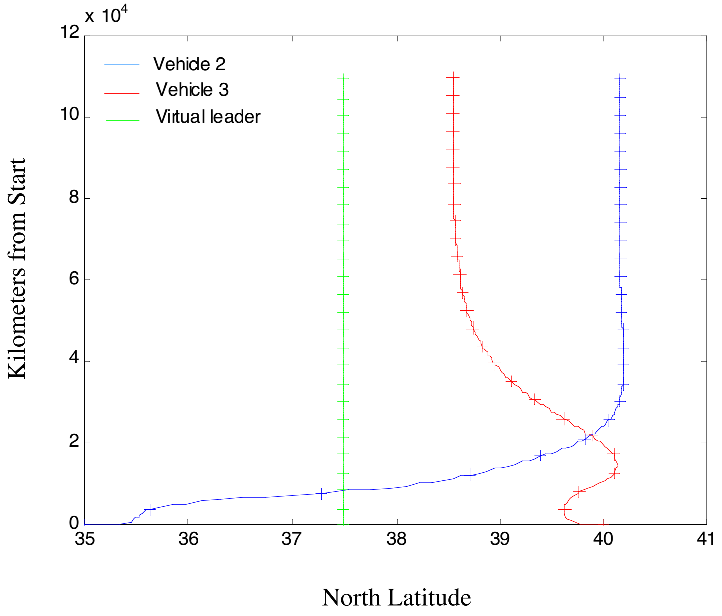
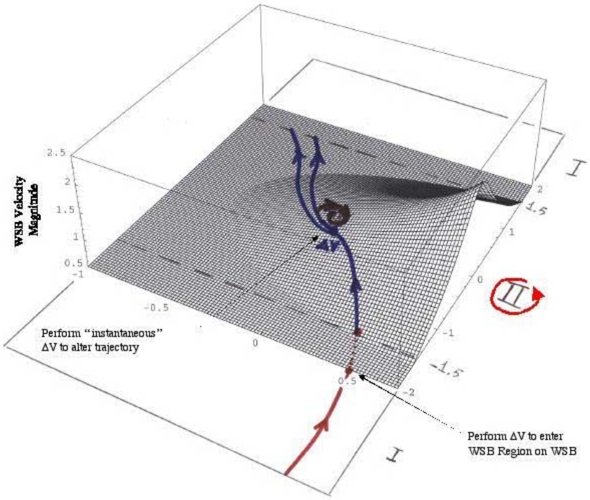


Figure 5-34. Example Simulation in Non-uniform Flow Field.

These simulations show the initial feasibility of using artificial potentials to produce stable arrangements of balloons in non-uniform external flow fields.

In addition to the above artificial potential simulations, Princeton also modeled trajectories in WSB regions. The following figure shows part of a WSB surface (location and velocity magnitude on the vertical axis) between two vortices. The figure also shows two example trajectories. One trajectory is uncontrolled and the other includes an "instantaneous" ΔV applied at the point indicated. Because the ΔV is applied on the WSB surface, the effect on trajectory is significant.



Perform "instantaneous" ΔV to alter trajectory

Perform ΔV to enter WSB Region on WSB

Figure 5-35. Example WSB Simulation Near a Vortex Pair.

The next figure shows numerical results for a similar situation. An instantaneous 5 m/s ΔV applied at x = -0.1 causes a shift of about 2000 km in 12 days. Continuous ΔV application with a TCS over the same time range would produce significantly more trajectory modification.

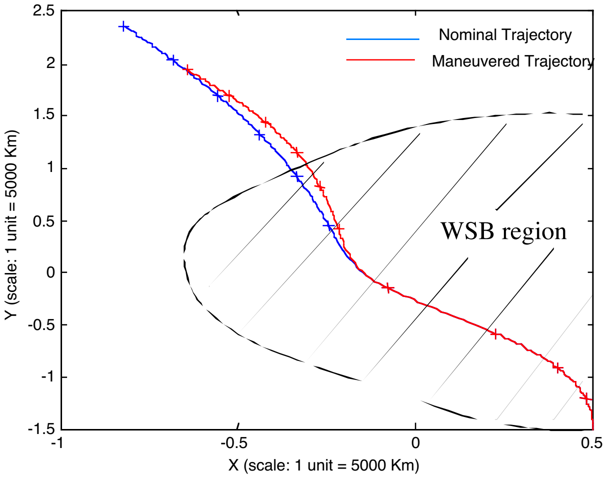


Figure 5-36. Example WSB Simulation.

During Phase II, we used the this new framework to develop some sophisticated simulations of constellation applications using Artificial Potential methods.

### 5.6.4. Future Directions for AP/WSB Work

There are several AP/WSB areas that should be studied in the future.

- An in-depth analysis of AP/WSB should be conducted. This would include a formal analysis of artificial potentials for a parameterized atmosphere, stability analyses for various balloon configurations, and, possibly, experiments in water.
- A systematic design methodology should be developed for AP/WSB that enumerates stable arrangement of vehicles and describes those arrangements with parameters, finds artificial potential prescriptions for moving from one arrangement to another, and that finds WSB prescriptions for continuous force application situations. In short, the work to date has been descriptive. The next step is to be able to specify the desired arrangement of balloons and calculate the control actions necessary to achieve the desired arrangement.
- Implementation issues and design constraints should be investigated. We need to find the limitations to the advanced framework for bounded and underactuated control systems and investigate the sensitivity of the algorithms to the frequency of control law updates.
- Finally, performance should be assessed by implementing the advanced framework for some realistic control cases.

## 5.7. Simulations of StratCon Applications

During the Phase II activity, we performed many simulations to demonstrate the utility of a constellation of stratospheric balloons. We describe these simulations in the sections below.

### 5.7.1. Zone Avoidance

One constellation objective that we studied is zone avoidance.

#### *5.7.1.1. Motivation for Zone Avoidance*

The primary motivation for the zone avoidance constellation management objective arises from safety considerations. Safety issues are important for both global constellations of stratospheric balloons and single balloons.

History shows that the NASA Scientific Balloon Program has been forced to significantly alter or cancel single-balloon flight campaigns due to safety concerns. For example, the flight gondola for the ULDB balloon test flight (February 2001) was removed from the flight plan due to concerns that safety considerations would compel early mission termination over populated regions surrounding Rio de Janeiro and Johannesburg. In that event, the investment in the flight gondola would have been lost.

A second motivation for zone avoidance is international overflight considerations. (See Section 8) We expect that international pathways exist for global stratospheric balloon constellations to become accepted by the world community. However, there may be instances where overflight is not allowed due to geopolitical tensions. In such circumstances, it is desirable avoid flights over certain countries.

#### *5.7.1.2. Zone Avoidance Strategy and Algorithm*

To evaluate the options for zone avoidance, we developed a simple zone avoidance strategy and algorithm. The strategy is to fly in the natural zonal winds and make forecasts of balloon trajectories. If the trajectory is forecasted to cross an zone in which flight is not desired, a sufficient left or right $\Delta V$ is applied by a trajectory control system to avoid the exclusion zone.

The zone avoidance algorithm that we implemented assumes a TCS that can impart $\leq 2$ m/s $\Delta V$ to the balloon in either the left or right direction. The algorithm is as follows:

- Forecast the trajectory of a balloon for 5 days.
- Determine whether the trajectory crosses into an zone of overflight exclusion any time during the forecast.
- If the balloon does not enter the zone, no trajectory control is necessary.
- If the balloon enters the zone, push left or right in continuous steps of 0.4 m/s and re-forecast the trajectory until forecast trajectory does not violate the zone.
- When a successful trajectory is found, provide the desired $\Delta V$ command to the TCS. Re-evaluate TCS settings every 4 hours.

### *5.7.1.3. Zone avoidance simulation*

The following figure shows an example balloon trajectory (alternating green and black line). Each color change and arrow represents 24 hours. The trajectory starts from Alice Springs, Australia (an existing NASA Balloon Program launch site) but avoids populated areas around Johannesburg, South Africa and Rio de Janeiro, Brazil. The avoidance zones are 4° latitude by 4° longitude in size and marked with red in the figure below. The balloon is assumed to be travelling in 30 m/s easterly winds. The trajectory control system is assumed to have 2 m/s trajectory control authority.

The trajectory control system utilizes 5-day look-ahead predictions of the trajectory to determine whether or not trajectory control should be applied in an effort to avoid the zone. After launch, the TCS brings the balloon slightly north to avoid Johannesburg. Then, it goes south to avoid Rio de Janeiro. On the second orbit, it goes further south to avoid Johannesburg.

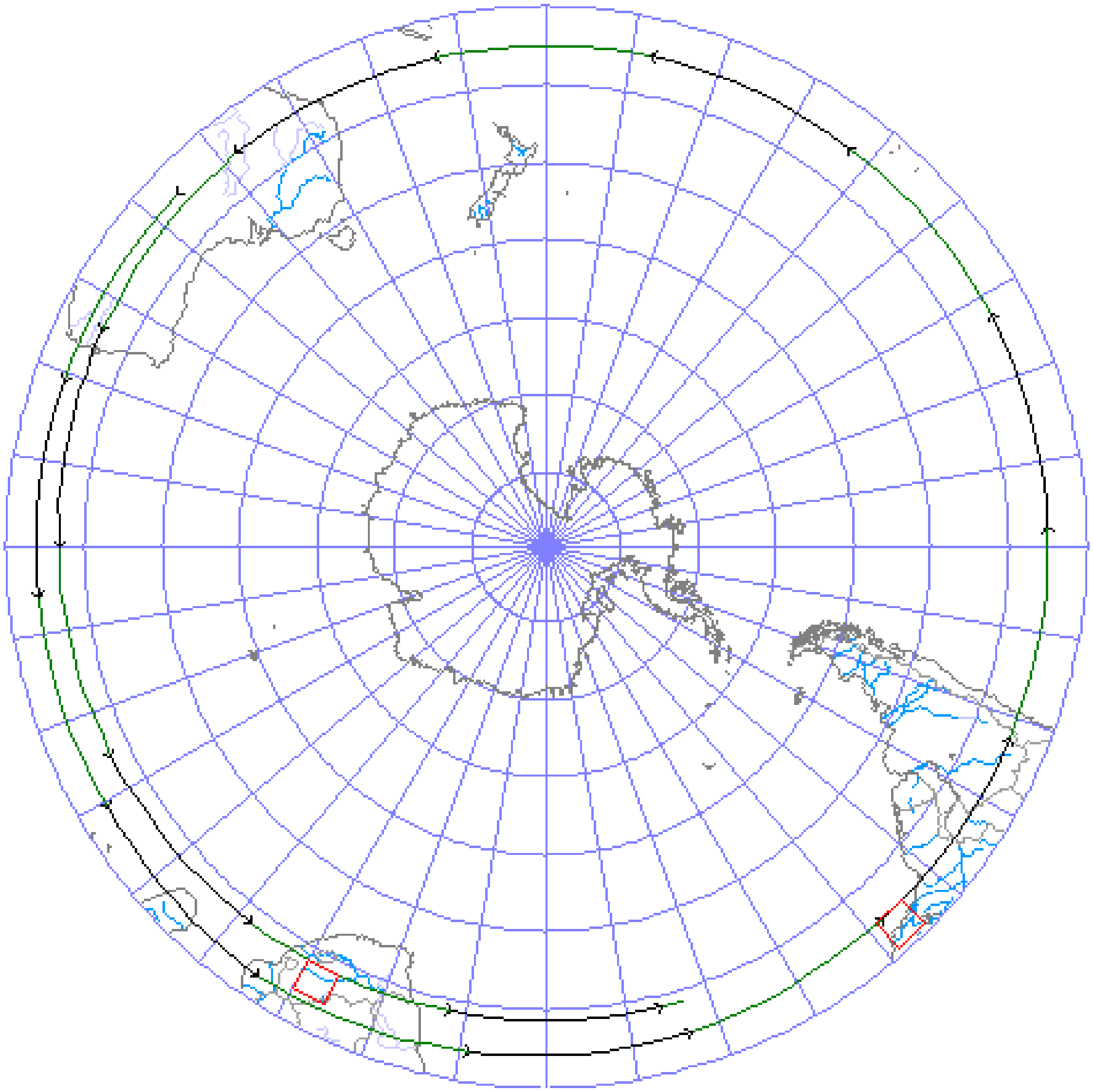


Figure 5-37. Example Zone Avoidance Performance of a Sample TCS.

This demonstration shows that 5-day look-ahead trajectories are sufficient to provide time for a 2 m/s trajectory control to avoid a region of this size (4° by 4°). NASA Balloon Program personnel have indicated that 1° by 1° avoidance zones for Rio de Janeiro and Johannesburg are probably sufficient for safety considerations.

### 5.7.2. Polar Atmospheric Chemistry

### 5.7.3. Target Overflight

Another constellation objective that we studied is generically called target overflight. Targets may be moving or stationary. Targets may also be points or zones. Target overflight is important for those times when science observations are desired at a particular location. Examples include adaptive sampling of tropospheric conditions by dropsondes to enhance weather forecasting, hurricane overflight, monitoring of airborne pollution, monitoring of forest fires and volcano plumes, and monitoring of inland lakes and rivers.

The constellation objective for target overflight constellation management is “organize the resources in the network of balloons to maximize observing time over the target.” During Phase II, we studied several applications that utilize target overflight objectives. Those applications are discussed below.

#### *5.7.3.1. Hurricane Monitoring*

One attractive science option for the StratCon concept is hurricane monitoring. The simulations presented here provide a look at how the StratCon concept could be used for hurricane monitoring (See Section 3.2.6 and 4.5). Figure 5-38 is a frame from a representative hurricane intercept simulation.

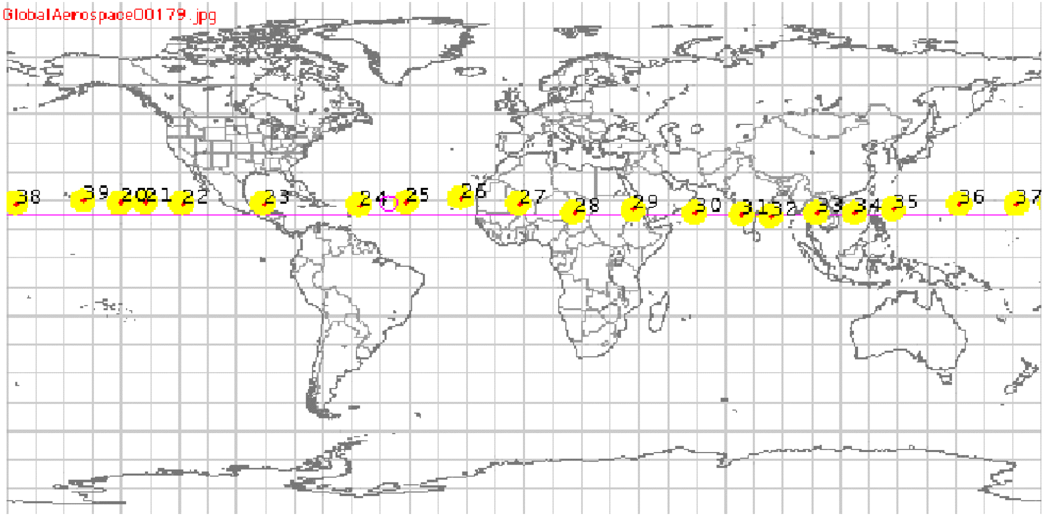


Figure 5-38. Hurricane Intercept Simulation

##### 5.7.3.1.1. Hurricane Alberto

The following figure shows ground tracks for all the tropical storms and hurricanes in the 2000 North Atlantic hurricane season. The storms originate in the tropics, and several have their origins off the west coast of Africa. Perhaps the most interesting track, from a constellation management perspective, is that of Alberto, which has an interesting loop in the middle of the Atlantic Ocean. [Storm track images from http://weather.unisys.com/hurricane]

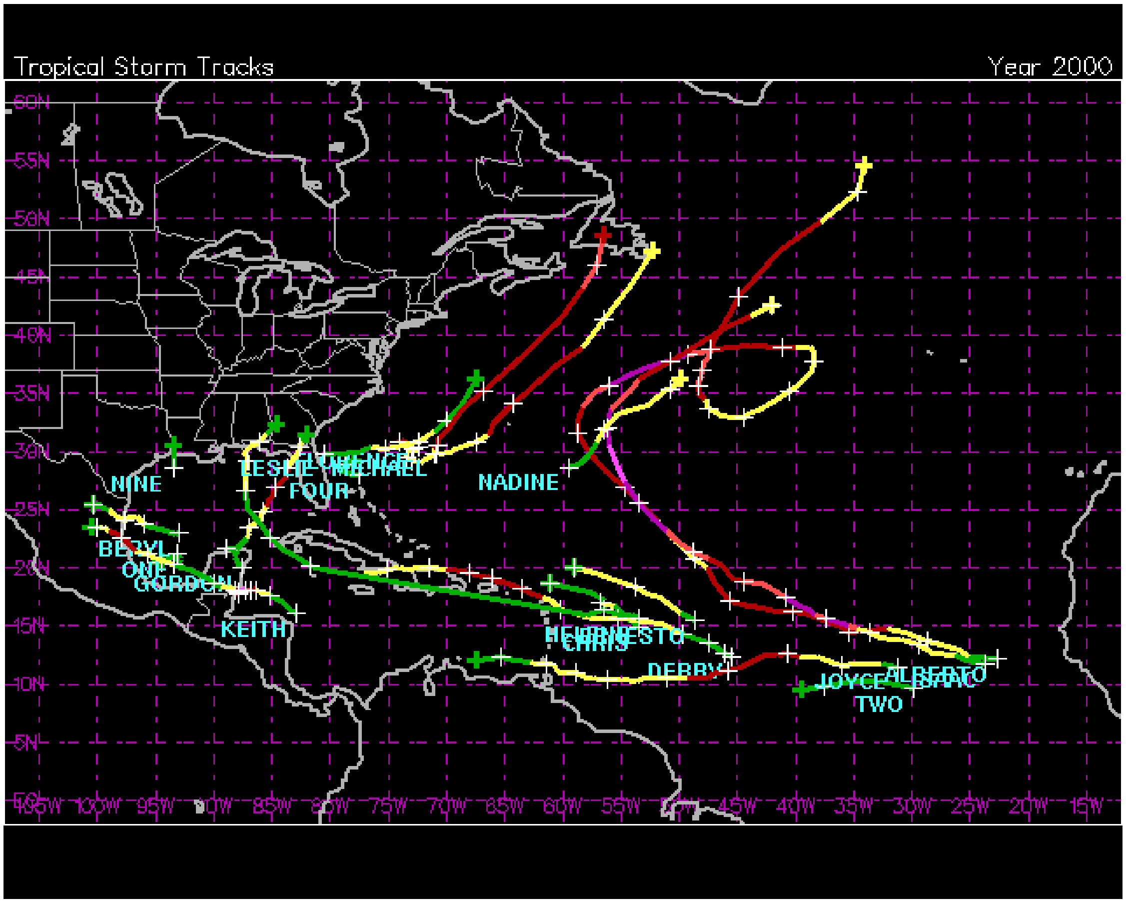


Figure 5-39. Hurricane and Tropical Storm Tracks in 2000.

The next figure shows Alberto's track. Hurricane Alberto was the first named storm, hurricane, and major hurricane of the 2000 Atlantic Hurricane Season. It caused some confusion in forecasting because water temperatures in much of the Tropical Atlantic remained in the upper 70s F, which is still below the essential threshold of 80 °F needed to support tropical development. So, the forecasting dilemma in terms of Alberto's intensity was understandable, and it continued throughout its storm life as the storm moved through the Central Atlantic. Alberto fluctuated between tropical storm and hurricane strength several times, and almost reached major hurricane status twice during its life. Alberto set a record for the longest-lasting hurricane or tropical storm in the month of August. It is the 3$^{rd}$ longest-lasting Atlantic storm on record. Here are some details about Alberto:

- Highest winds were recorded at 125 miles per hour.
- Highest wind gusts were recorded at over 145 miles per hour.
- Lowest barometric pressure recorded at the surface was 950 mbar (28.05 inches)
- Became a hurricane three times.
- No impact on any major land masses in the Atlantic Basin.
- No death or damage reported.

[Source: http://members.aol.com/windgusts/Alberto.html]

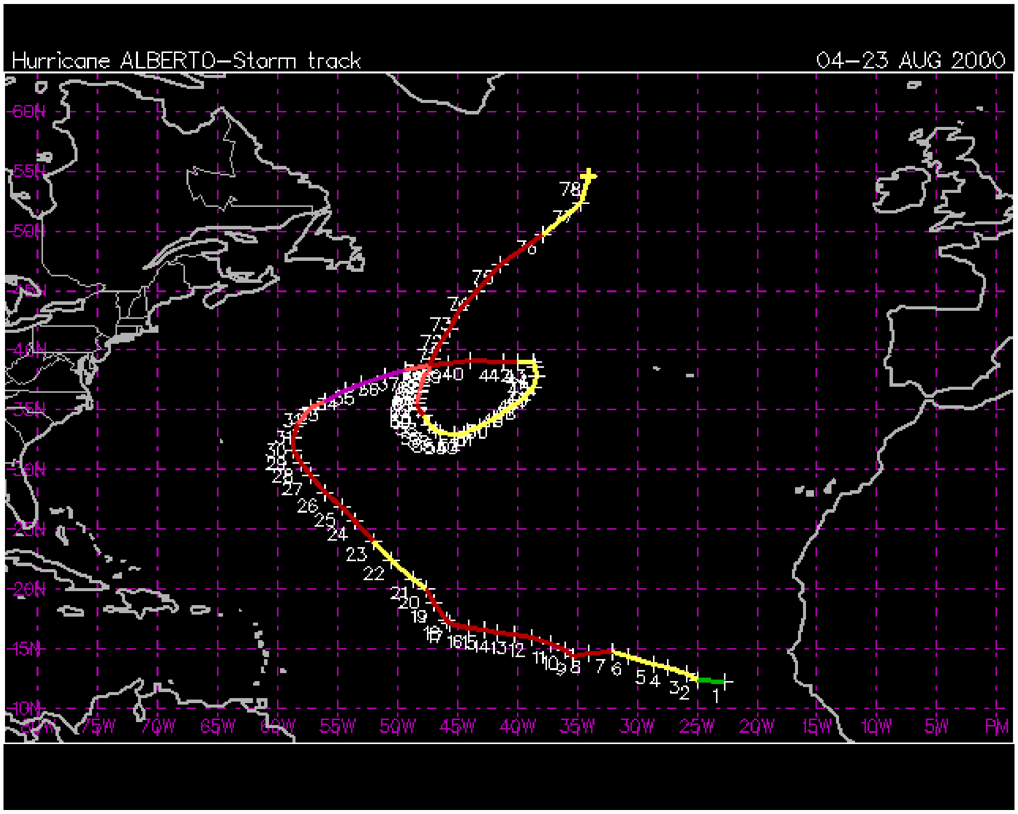


Figure 5-40. Hurricane Alberto Storm Track.

The next figures shows a satellite view of Alberto.

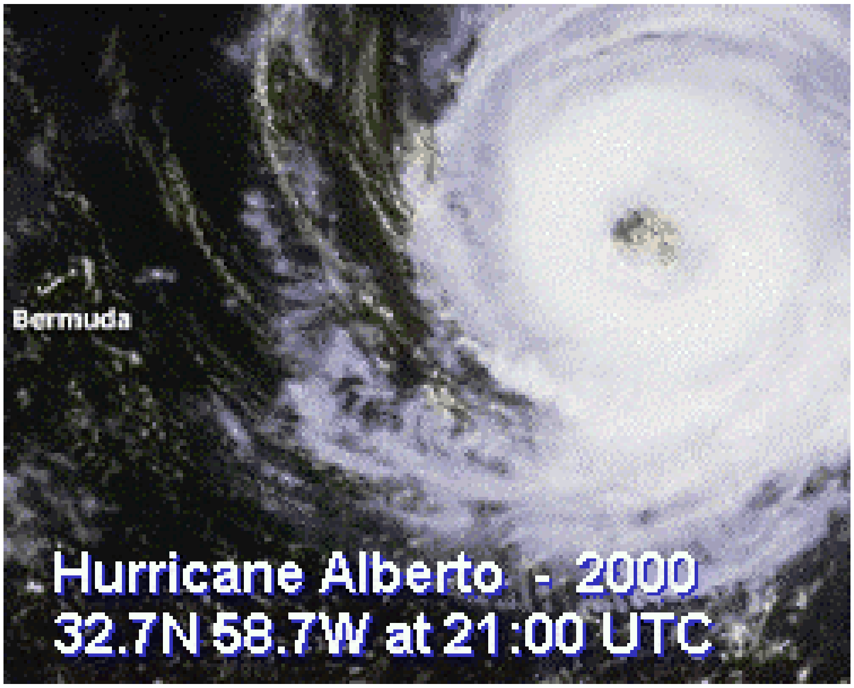


Figure 5-41. Hurricane Alberto Satellite Image.

#### 5.7.3.1.2. Controlled and Uncontrolled Balloon Trajectories

We began our investigations of using balloons to track Alberto by simulating the trajectory of a single balloon as it approaches the storm. To show the effect of a trajectory control system, we simulated balloon trajectories both with and without a TCS.

In the figures that follow, the blue trajectory is uncontrolled and floats with the winds at 35 km. The balloon represented by the red trajectory utilizes a first-generation StratoSail® TCS with approximately 2 m/s control authority. We use an aerodynamic model for the TCS. The aerodynamic model uses UKMO winds at both the balloon and the TCS to calculate the effect that the TCS will have on the trajectory of the balloon.

For this simulation, the objective is to overfly the hurricane. The strategy is to maintain the latitude of the hurricane, even as Alberto changes location during the simulation. There is no look-ahead capability for this simulation.

The figures below show several frames from a movie that shows the complete simulation. The hurricane is represented by a blue circle of 300 km radius. The balloon trajectory colors alternate between black and blue or red. Color changes occur every 24 hours, and a 1.5 day tail is shown for each trajectory. To view the entire QuickTime™ movie of this simulation, point a web browser at http://www.gaerospace.com/projects/StratoCon/hurracane_intercept.html. The simulation shows that trajectory control is important for hurricane tracking because it provides more options for starting positions from which a balloon could intercept a hurricane.

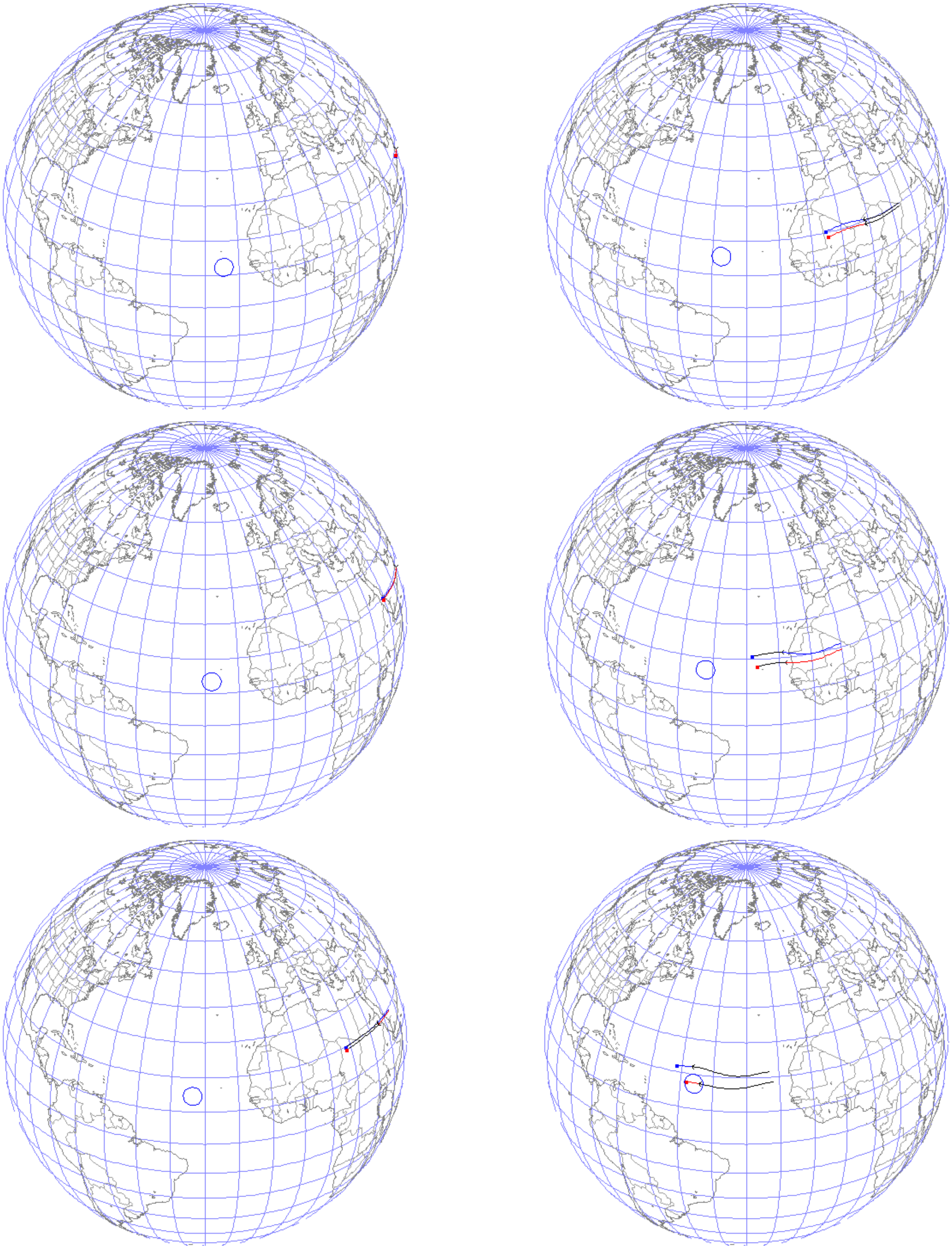


Figure 5-42. Effect of Trajectory Control on Balloon Trajectories for the Hurricane Intercept Mission.

### 5.7.3.1.3. String of Pearls

To track a hurricane and provide several repeated observations, it will be necessary to have a regional network of balloons at or near tropical latitudes. We simulated a network of 20 balloons with the constellation management objective of marshaling the resources of this network to provide as many hurricanes as possible. This type of regional network is called a "String of Pearls."

### 5.7.3.1.4. Overflight Frequency and Return Time

To evaluate the frequency of overflight of the hurricane, we calculated the time between overflight for balloons in the string of pearls using maximum zonal winds for hurricane season for several latitude bands of interest. The following graph shows the required number of balloons as a function of desired return time and latitude.

Note that these results are based on average winds. For maximum winds, the return time is minimized but dwell time is small. For minimum winds, the dwell time is large, but the return time is also large.

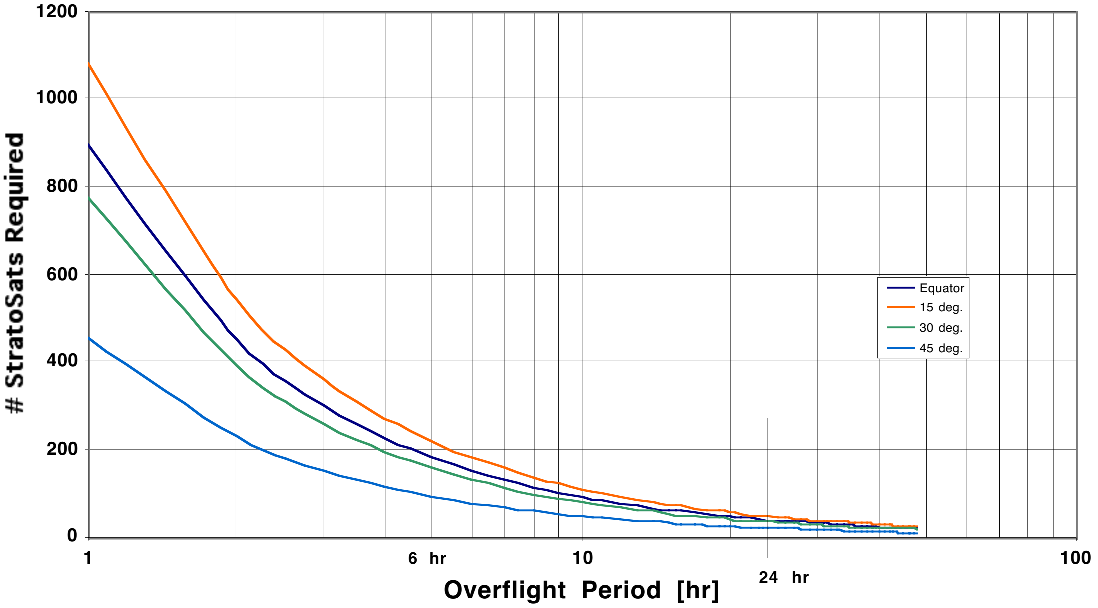


Figure 5-43. Number of Balloons Required for Desired Return Time.

### 5.7.3.1.5. Target Overflight Algorithm

For the String of Pearls simulation, we chose to use 20 balloons, which provides a return time of approximately 24 hours, depending on latitude.

The algorithm for the string of pearls simulations is as follows:

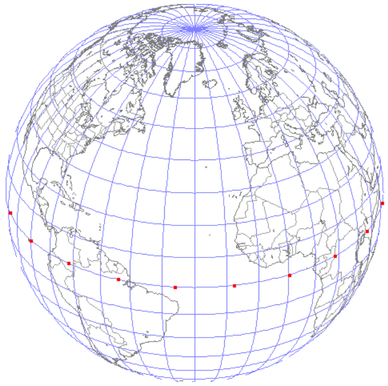
- For each balloon in the network, make a 3-day forecast of the balloon's trajectory.

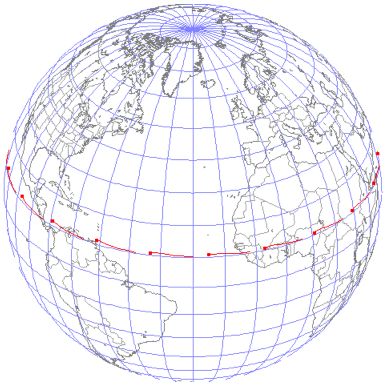
- If the balloon is >90° longitude away from the hurricane during the entire 3-day forecast period, command the balloon's TCS to achieve the current latitude of the hurricane.
- If the balloon is within 90° longitude of the hurricane at any time during the 3-day forecast, compare the forecasted balloon trajectory with the path of the hurricane. (For the simulations presented here, we used the actual path of the hurricane. However, one could also use a forecasted hurricane path.)
- If the balloon goes to the left of the hurricane at the point where the hurricane is closest to the balloon trajectory, command the TCS to push the balloon right.
- If the balloon goes to the right of the hurricane at the point where the hurricane is closest to the balloon trajectory, command the TCS to push the balloon left, using 1 m/s increments

For these simulations, we assumed that the TCS had 5 m/s control authority. And, we assumed 30 m/s easterly winds at the balloon altitude (35 km). The assumed winds are reasonable and based on observed data from the time of the hurricane. In fact, the uncontrolled balloon in Figure 5-42 (blue) was simulated using actual winds, and it shows predominantly easterly winds of about 30 m/s coupled with a zonal wave amplitude of about 1.5 m/s.

The following figures show eight frames from a movie of the simulation. The movie of the simulation can be found at http://www.gaerospace.com/projects/StratoCon/string_of_pearls.html.

The simulation begins with 20 balloons on the equator. Each balloon has a 0.5-day tail. The String of Pearls moves north to the location of tropical storm origin as the simulation begins. When Alberto forms, the balloons start tracking the storm. To the east of the storm, the balloons move northward or southward in anticipation of future storm motion. This simulation shows the feasibility of tracking a hurricane with a TCS with 5 m/s control authority.





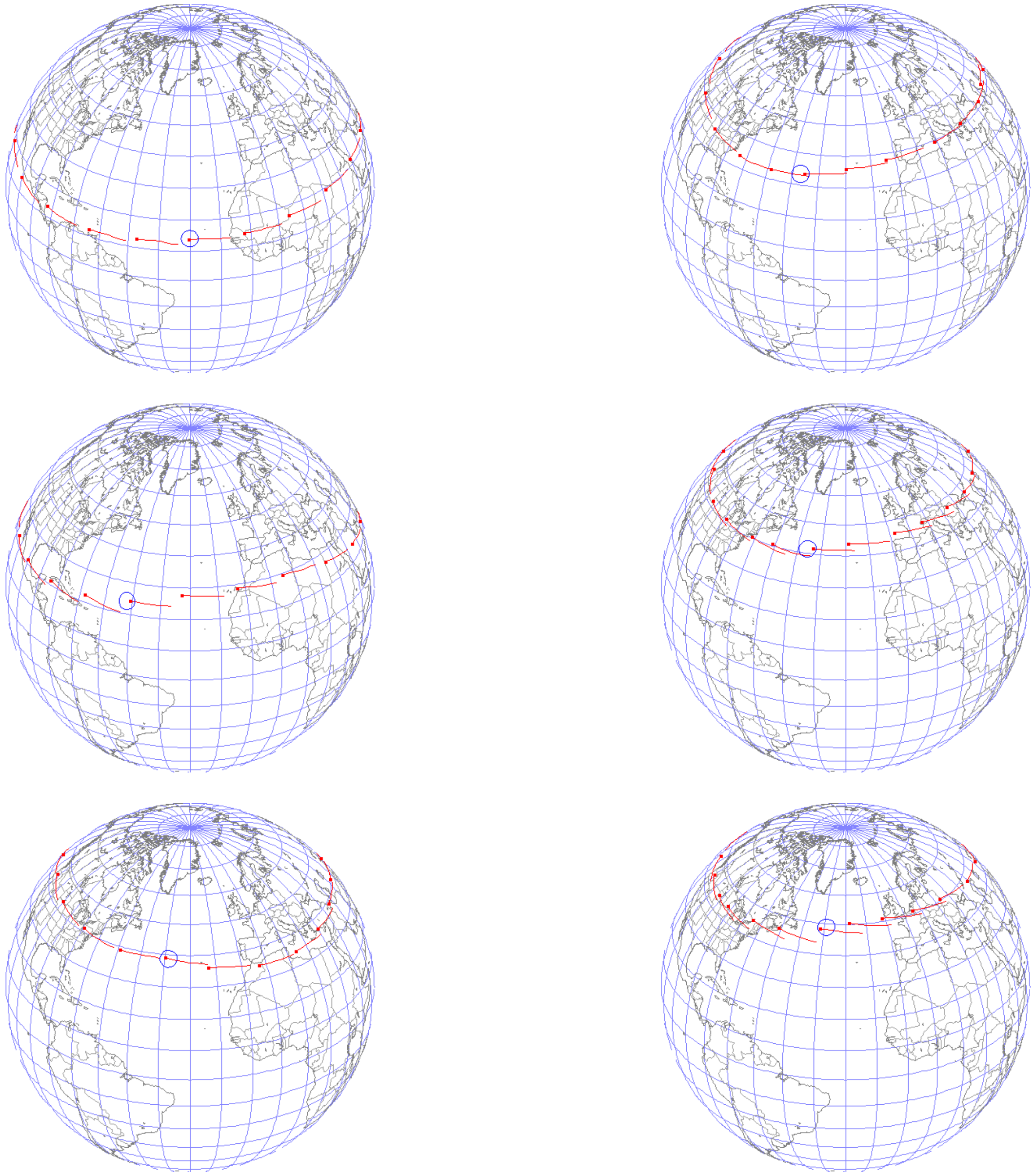


Figure 5-44. “String of Pearls” Hurricane Intercept Mission Simulation.

### *5.7.3.2. Demonstration Earth Radiation Budget Experiment (DERBE)*

During Phase II, we developed a simulation of a Demonstration Earth Radiation Budget Experiment (DERBE). The following figure shows the trajectory, and an animated movie of the flight can be viewed at http://www.gaerospace.com/projects/StratoCon/Derbe1.html.

The simulation shows a potential mission scenario for DERBE. In the scenario, a balloon carries radiometry instruments. Launch occurs at Palestine, Texas, the existing NASA Scientific Balloon Facility, thereby minimizing launch costs. A StratoSail® guides the balloon southward to 15 deg. North latitude. Later, the trajectory moves to 20 deg. North. The objective is to fly over the DOE's Atmospheric Radiation Measurement (ARM) Program's Cloud and Radiation Testbed

(CART) site in Oklahoma. For the simulation, launch occurs on 30 June 2000. The flight lasts 92 days and achieves four passes at 35 km over the ARM site. Stratospheric winds are provided by UKMO assimilations. Figure 5-45 shows the last frame of the simulation.

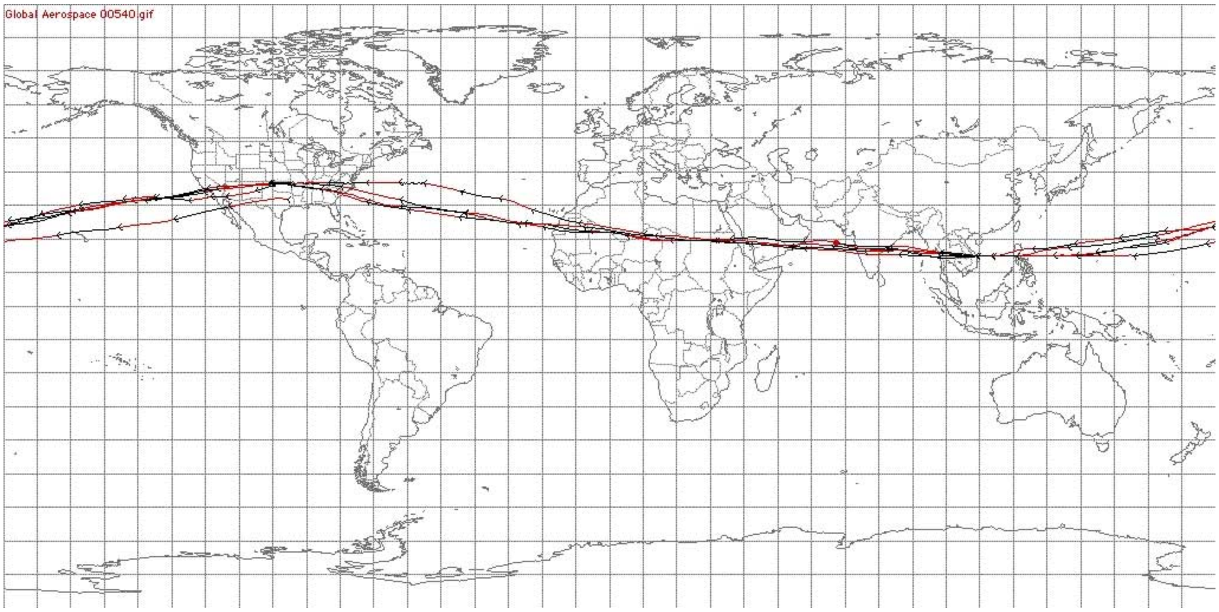


Figure 5-45. DERBE Trajectory Simulation.

### 5.7.4. Hemispheric Constellation

During Phase II, we successfully utilized artificial potentials to control constellations of hundreds of stratospheric balloons for simulated constellations. This is the first known application of Artificial Potential 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 5-46 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.

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. The artificial potential is given by the following equation

$$V_{ij} = \begin{cases} k\left(\ln\left(r_{ij}\right) + \left(\dfrac{d_0}{r_{ij}}\right)\right) & 0 < r_{ij} < d_1 \\ k\left(\ln\left(d_1\right) + \left(\dfrac{d_0}{d_1}\right)\right) & r_{ij} \geq d_1 \end{cases} \tag{6}$$

where

$V_{ij}$ = artificial potential between balloons i and j,
$k$ = 2.0 x $10^6$ $m^2/s$,
$d_0$ = 4.8 x $10^6$ m,
$d_1$ = 9.6 x $10^6$ m, and
$r_{ij}$ = vector from the ith balloon to the jth balloon.

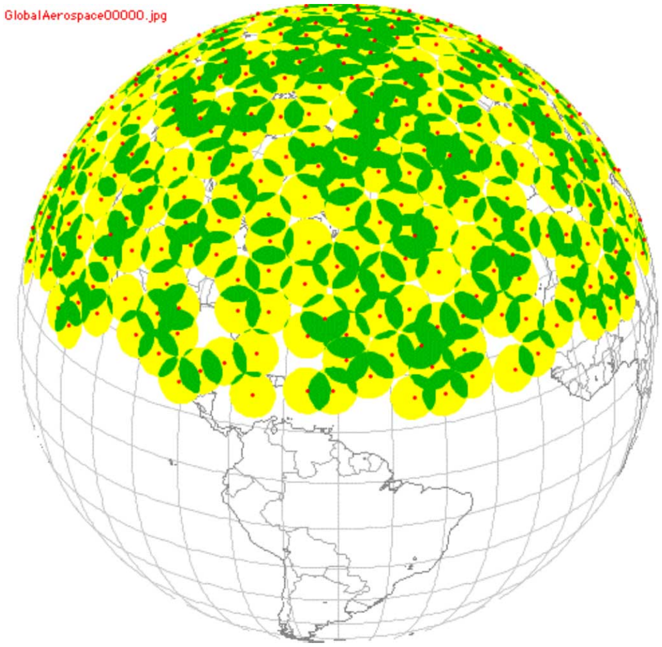


Figure 5-46. Northern Hemisphere Constellation of 383 Stratospheric Balloons.

The velocity influence of the j$^{th}$ balloon on the i$^{th}$ balloon is given by

$$\mathbf{u}_{ij} = \begin{cases} -\nabla V_{ij} & 0 < r < d_1 \\ 0 & r_{ij} \geq d_1 \end{cases}, \tag{7}$$

where

$\nabla V_{ij}$ = the gradient of V along the direction from i to j.

For each balloon, the desired total velocity is given by

$$\mathbf{u}_i = \mathbf{u}_{wind,i} + \sum_{j=1, j \neq i}^{j=n} \mathbf{u}_{ij}, \tag{8}$$

where

$\mathbf{u}_{wind,i}$ = wind vector at balloon i and

$n$ = total number of balloons in the network.

In cases where the desired velocity vector is not achievable by the TCS, we choose to preserve the lateral component of the desired velocity vector (up to the maximum lateral magnitude).

### *5.7.4.1. 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 the 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. The following figure 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.

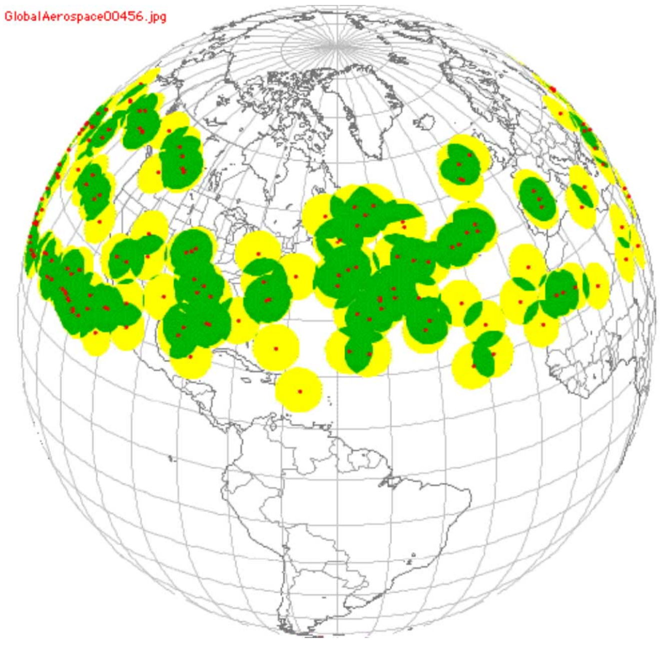


Figure 5-47. Constellation Without Trajectory Control.

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.

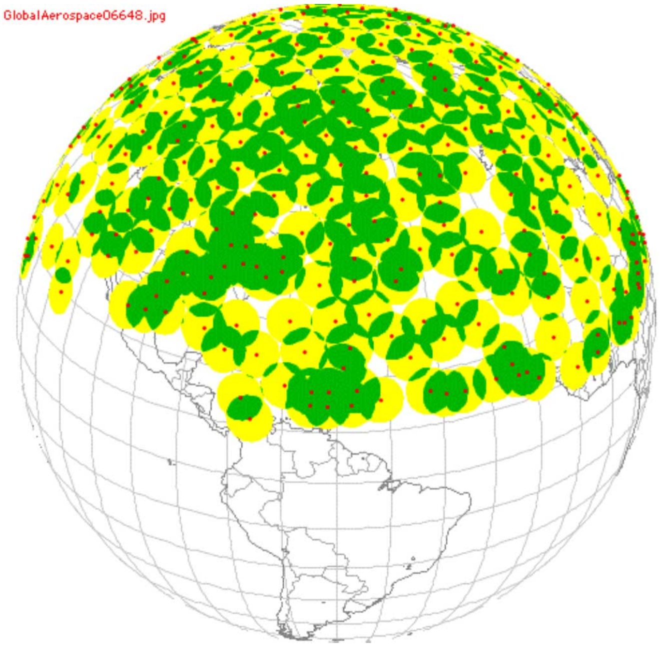


Figure 5-48. Constellation with AP Control (277 Days into the Simulation).

#### *5.7.4.2. 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. The following figure 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.

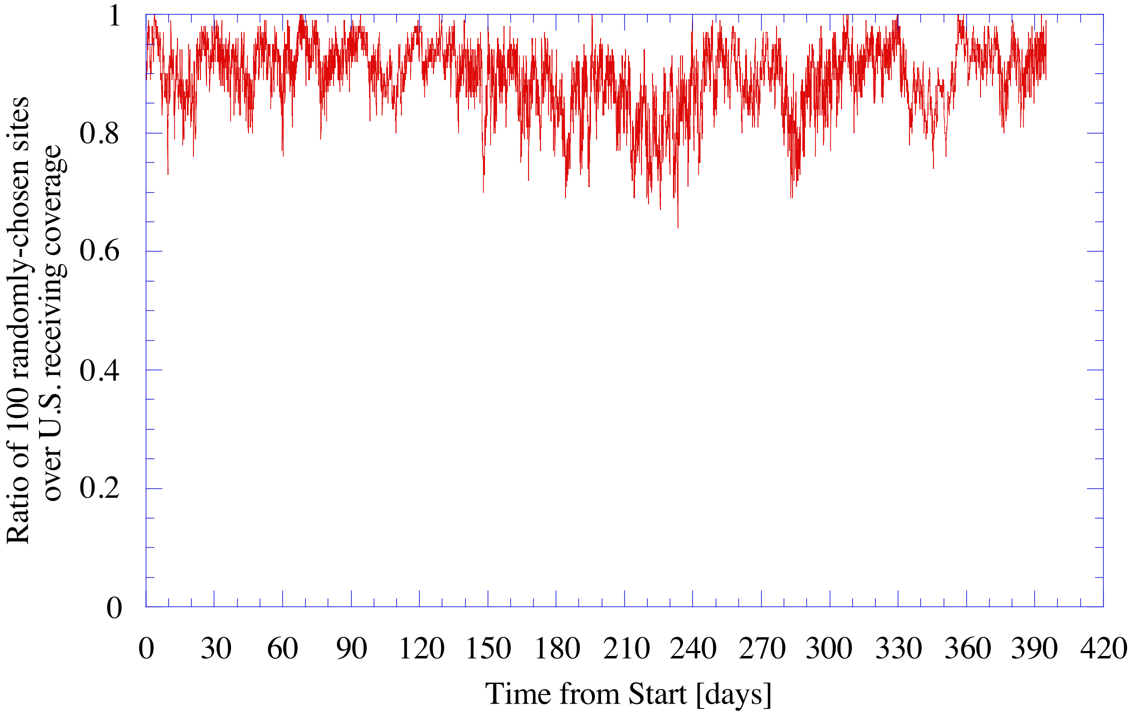


Figure 5-49. Coverage Ratio as a Function of Time (Controlled Constellation).

### *5.7.4.3. 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 the following graph 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.

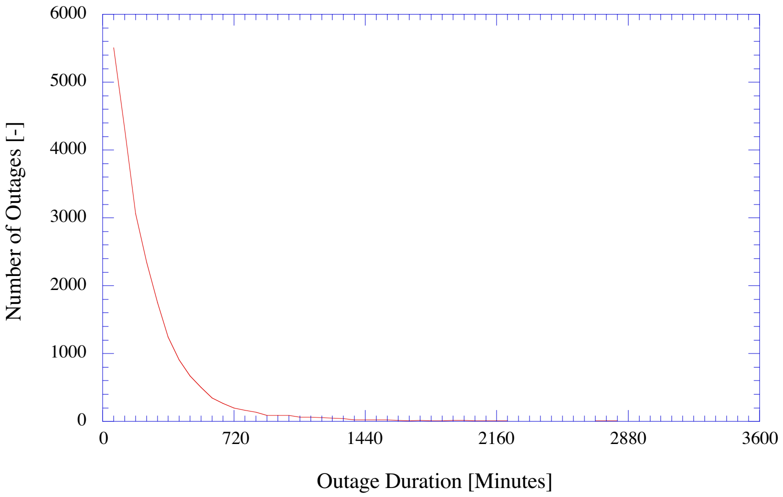


Figure 5-50. Outage Duration Distribution (Controlled Constellation).

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 larger tail toward longer recovery times.

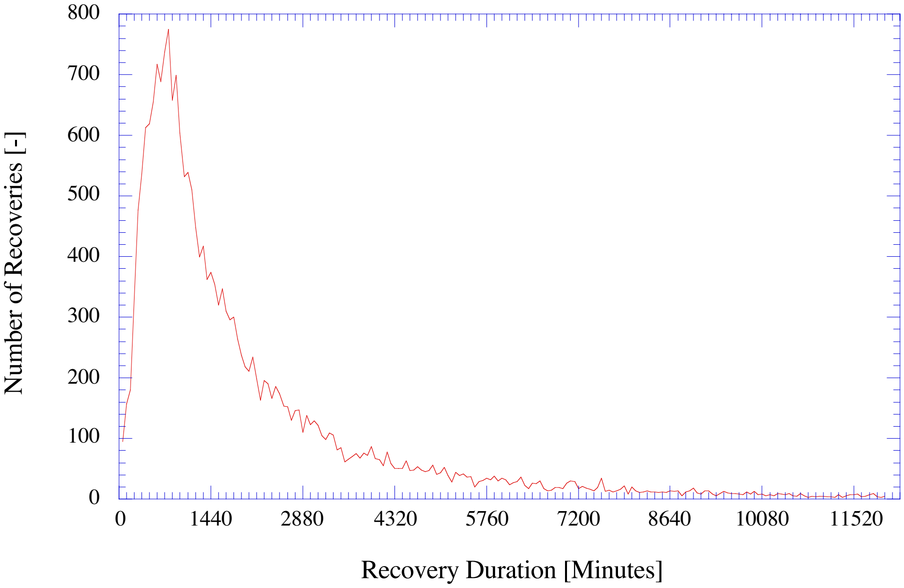


Figure 5-51. Recovery Duration Distribution (Controlled Constellation).

### 5.7.5. Adaptive Observation Systems

#### *5.7.5.1. THORpex Missions*

During Phase II, we developed simulations of balloon trajectories appropriate for data gathering for THORpex. THORpex is a loose acronym for The Hemispheric Observing system Research and Predictability Experiment. These simulations evaluated mission options for the application of stratospheric balloons to THORpex, including multiple dropsonde samples in regions of high sensitivity for 2- to 10-day weather forecasts in the western U.S. This region of high sensitivity is the Pacific Ocean in Northern Hemisphere winter. Note that this application is not typical for NASA's stratospheric scientific balloons that have always flown in the summer hemisphere.

To prepare for the simulations, we evaluated example wind fields from the time period of interest. The following figures show stratospheric winds from 1 January 2001. These figures demonstrate the existence of vortex features in the northern Pacific Ocean at both 35 km (balloon altitude) and 20 km (StratoSail® TCS altitude). This feature is not uncommon at this time of the year.

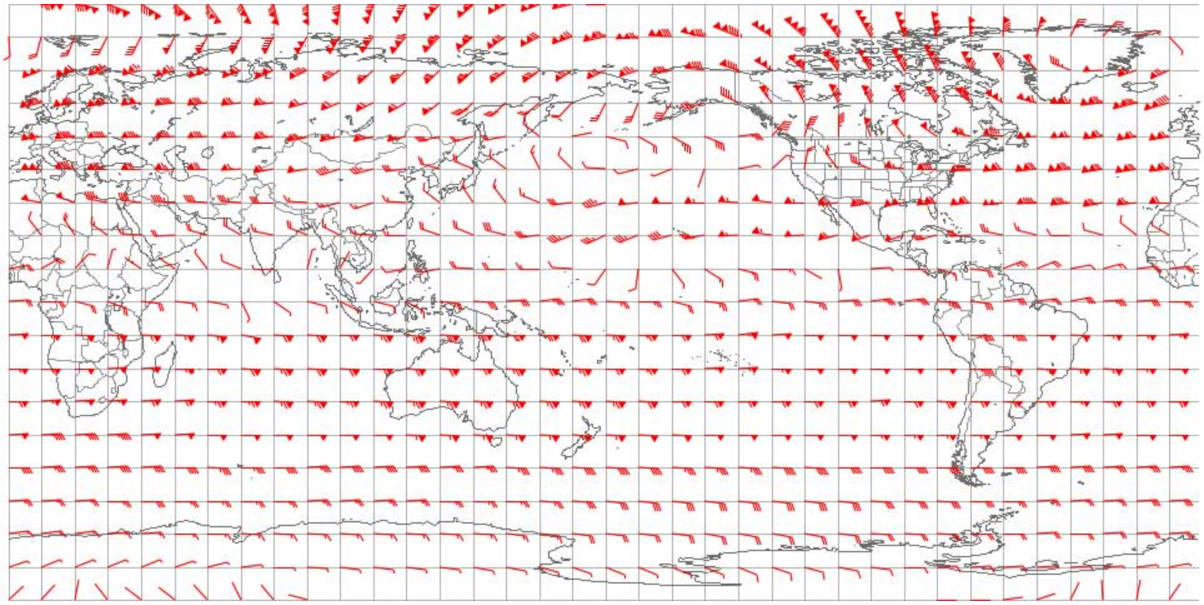


Figure 5-52. Stratospheric winds from 1 January 2001 at 35 km.

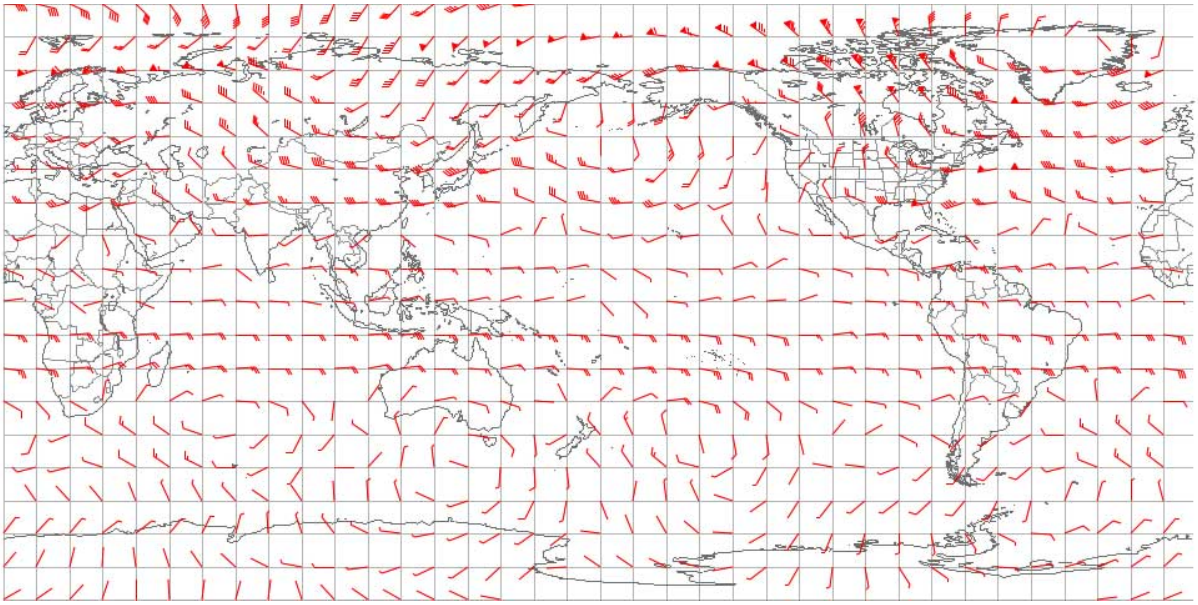


Figure 5-53. Stratospheric winds from 1 January 2001 at 20 km.

Initial balloon trajectory simulations showed that neither free floating balloons nor simple control strategies (such as maintaining a given latitude) provide desired trajectories due to the complexity of the stratospheric circulation patterns at mid latitudes in the winter. To illustrate these complexities, the following figure shows trajectories of three balloons that are launched from Tokyo, Japan on 1 January 2000. These are small balloons that float at 25 km while the StratoSail® TCS is at 18 km. The three balloons are commanded to maintain 45°, 35°, and 25° latitude with the intent of providing opportunities for radiosonde profiles in the Pacific Ocean. The figure illustrates the difficulties in obtaining profiles in those locations with these simple control strategies; the structure of the wind fields prevents radiosonde drops in the desired region, which is outlined in green.

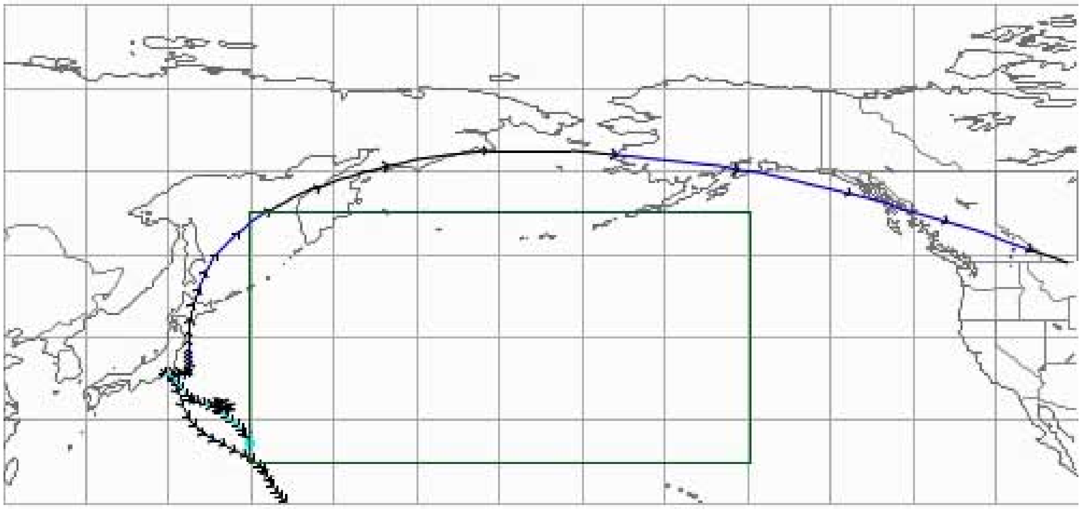


Figure 5-54. Balloon trajectories with simple trajectory control strategy.

Because these simple strategies resulted in minimal opportunities for data collection in the desired regions, we developed sophisticated control algorithms that respond to the structure of the wind fields to achieve measurement objectives.

Figure 5-55 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.

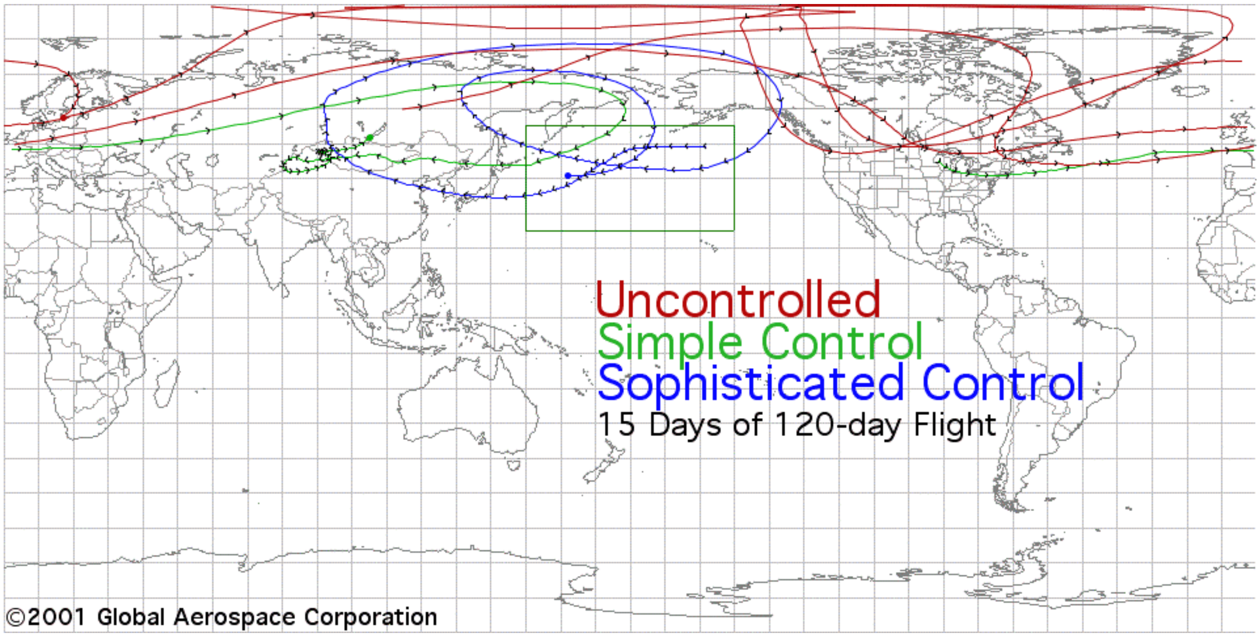


Figure 5-55. A 15-day Snapshot of an Example THORpex 120 day Targeting Test.

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 5-2 gives the number of sonde observations in the region of interest over the 120 days of simulation.

Table 5-2. Number of Observations "in the box" on Figure 5-55.

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

These simulations demonstrate the effectiveness of trajectory control capabilities for targeted balloon observations. They also show the potential for using information about the wind field to improve the quality and quantity of scientific observations. Such strategies are essential for adaptive observations.

### *5.7.5.2. THORpex Dropsonde Deployment Simulation*

In addition to studying single THORpex trajectories, we developed and utilized new techniques to display opportunities for dropsonde deployment in a potential future THOR*pex* deployment. The following figures show dropsonde opportunities in a region of high sensitivity for CONUS forecasts. These dropsonde opportunities are based on drops every hour or every 6 hours. Trajectories are taken from our existing simulation of 383 balloons in the northern hemisphere.

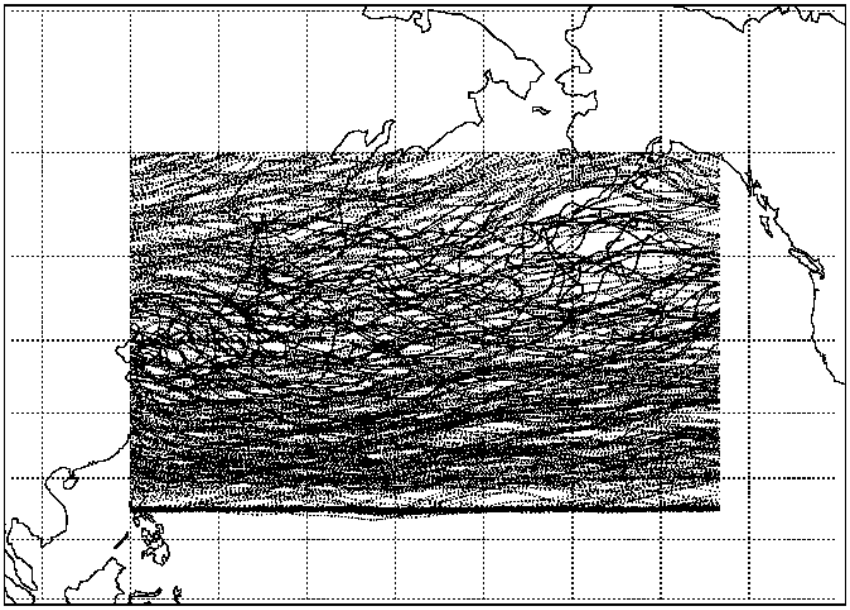


Figure 5-56. June Dropsonde Opportunities (1-hour Drop Intervals).

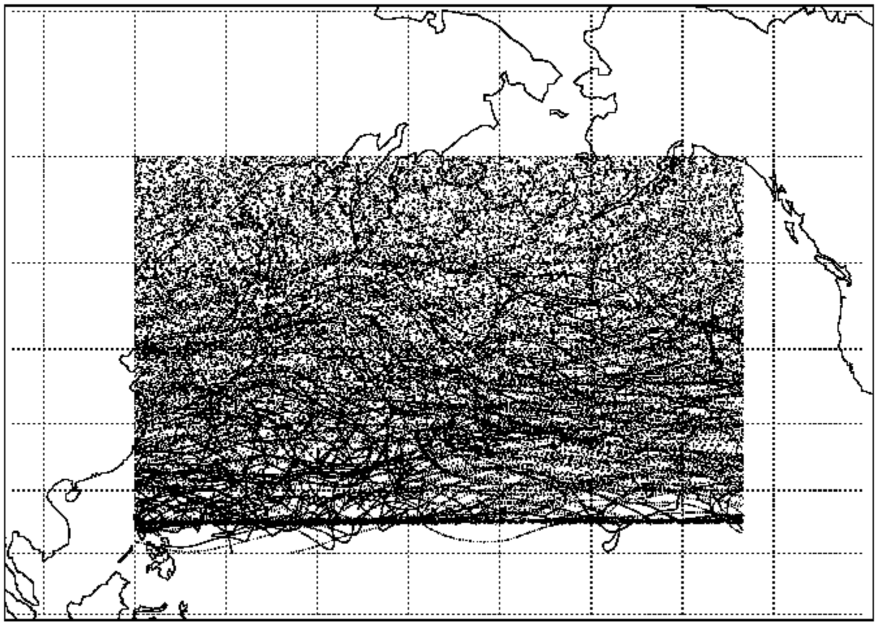


Figure 5-57. January Dropsonde Opportunities (1-hour Drop Intervals).

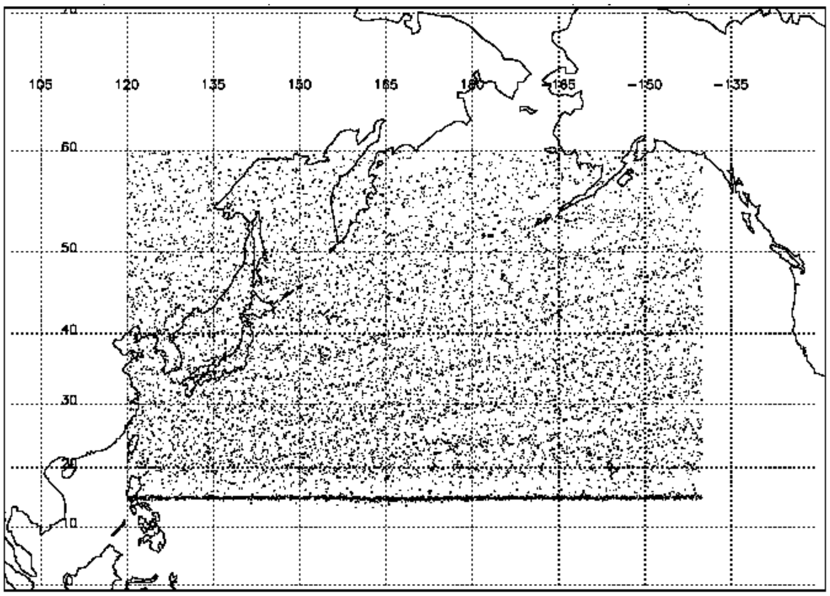


Figure 5-58. June Dropsonde Opportunities (6-hour Drop Intervals).

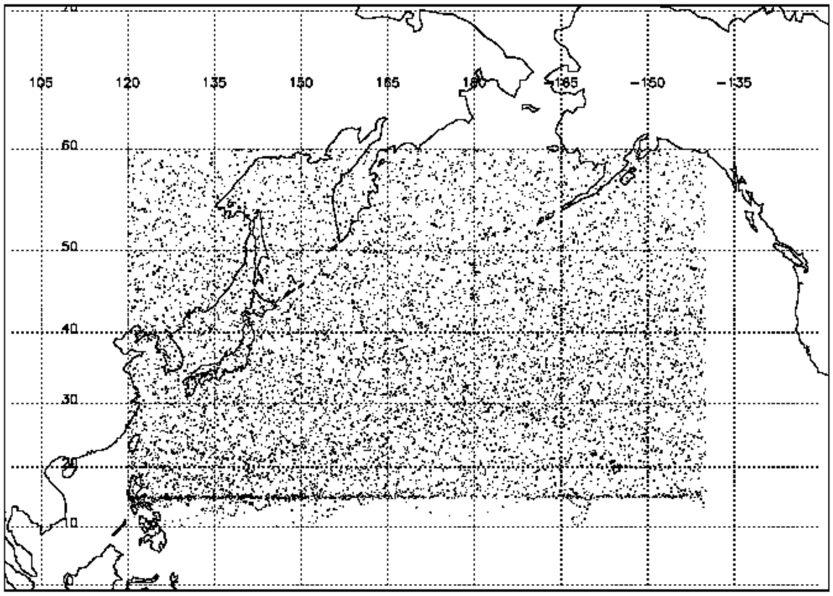


Figure 5-59. January Dropsonde Opportunities (6-hour Intervals).

It is interesting to note the relationship between coherence of the trajectories (whether or not individual trajectories are observable) and sampling interval. With a 6-hour sampling interval, there is no observable trajectory coherence, indicating that the dropsonde samples are essentially randomly distributed over a timescale of a month. However, at 1-hour sampling intervals, trajectory coherence is obvious in the June plot. The January plot at 6-hour sampling intervals shows coherence below 40° N latitude, but little coherence above 40°N latitude. This difference is caused by significantly higher wind velocity above 40 °N than below 40 °N.

### *5.7.5.3. Disaster Monitoring*

During Phase II, we built new software for simulations of constellations of StratoSat™ platforms responding to disasters. We developed a simulation that includes four disasters that are observed during the course of one year in preparation for participating in the upcoming Global Disaster Information Network (GDIN) meeting in Rome, Italy in June 2002. The disasters are listed in the table below.

Table 5-3. GDIN Simulation Parameters.

| **Disaster** | **Longitude [°]** | **Latitude [°]** | **Start Date** | **End Date** |
|---|---|---|---|---|
| Tsunami in Indonesia | 125 E | 5 S | 2000-02-01 | 2000-03-01 |
| Earthquake in Rift Valley | 33 E | 8 S | 2000-05-01 | 2000-06-01 |
| Typhoon in Bangladesh | 90 E | 23 N | 2000-08-01 | 2000-09-01 |
| Volcano in Congo | 29.3 E | 1.5 S | 2000-11-01 | 2000-12-01 |

The following figure shows a frame from the simulation during the Tsunami.

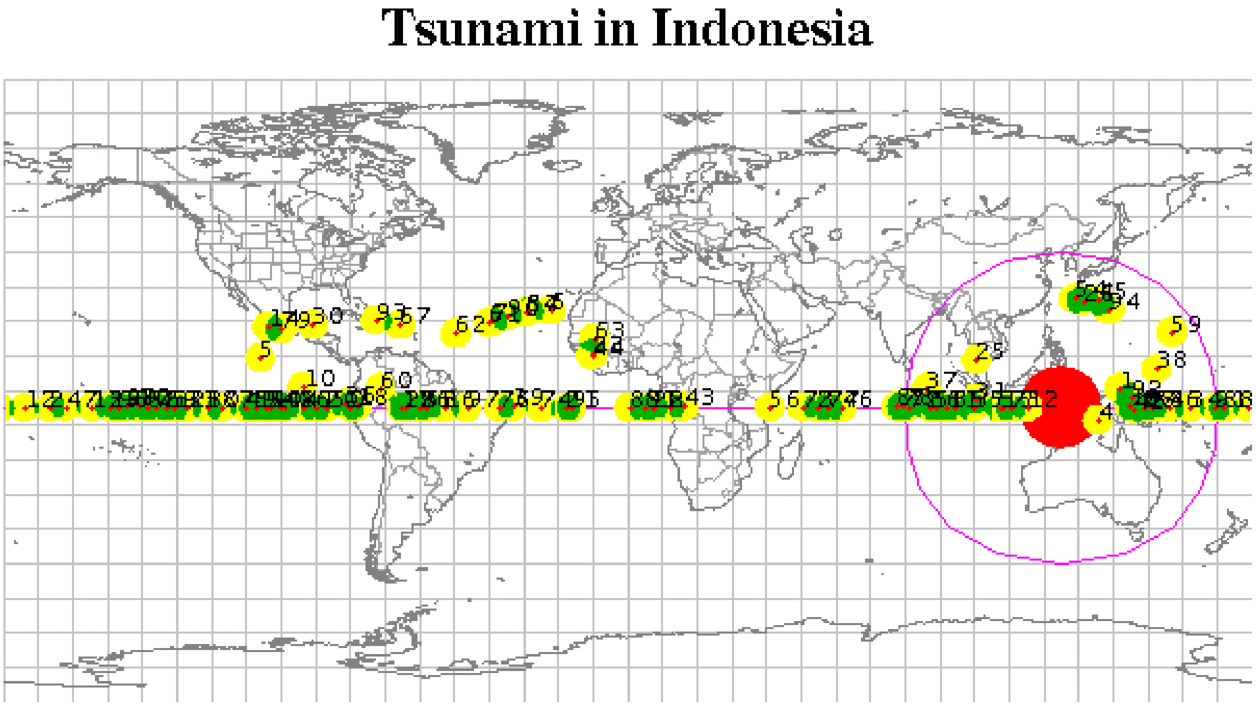


Figure 5-60. Tsunami Disaster in GDIN Simulation.

This simulation employs a constellation of 100 balloons that are nominally commanded to maintain a uniform distribution between 20 °N and 20 °S latitude. When a disaster occurs, the balloons are commanded to maintain the latitude of the disaster. In the case of the Tsunami shown above, 5 °S latitude is maintained.

Inside the large magenta circle, the StratoSat™ platforms are commanded toward the disaster location, so that they can overfly the disaster site to provide visual coverage of the site or to assist with communications at the site. After each disaster is completed, the balloons redistribute in the ±20° latitude band. The visual effect is very interesting: the constellation appears to pulse between the distributed and intensive observing states, depending on whether or not a disaster is happening.

The simulation is conducted using UKMO data for atmospheric conditions, and it employs balloons at 35-km altitude. Individual balloons reel up their trajectory control system if their desired direction of travel is within 45° of the direction of the wind at the balloon altitude. The trajectory control system is a simplified model of an advanced TCS that is essentially a double-size first-generation TCS attached to a 100-m diameter superpressure balloon. The StratoSat™ platform design employed in this StratCon activity utilizes smaller balloons with less cross-sectional area and less aerodynamic drag. Thus, the simulation performed here can be considered to be conservative in terms of the trajectory control authority available to any individual balloon.

This simulation accurately takes account of the bounded and underactuated nature of the StratoSail® TCS. There are limitations on the directions for the $\Delta V$ vector that can be obtained by this TCS. There are also limitations on the magnitude of the $\Delta V$ that can be generated by the TCS, and this magnitude is a function of the relative wind velocity at the wing. This simulation approximates both of these effects. The various disasters are implemented as targets that should be overflown in the simulation software. These targets are turned on and off at the appropriate times. When a disaster is happening, balloons that are moving toward the disaster and that are inside the large magenta circle use predictive, look-ahead trajectories to do their best to overfly the center of the disaster.

One of the key parameters for this application is the availability of a balloon over the disaster site. When balloons are available, they assist with observations and communications. The following graphs show the number of balloons that are capable of viewing the region of the simulated disasters. The first one shows balloons above Tsunami in the simulation. Except for the 20th day, more than one balloon of the network is available to view the disaster site at all times.

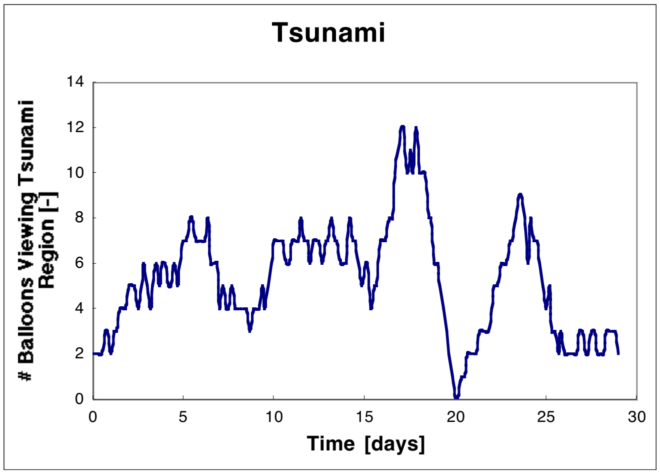


Figure 5-61. Balloons viewing the Tsunami site in the GDIN simulation.

Another disaster in the simulation is a volcano in the Congo. The following graph shows coverage of the volcano region.

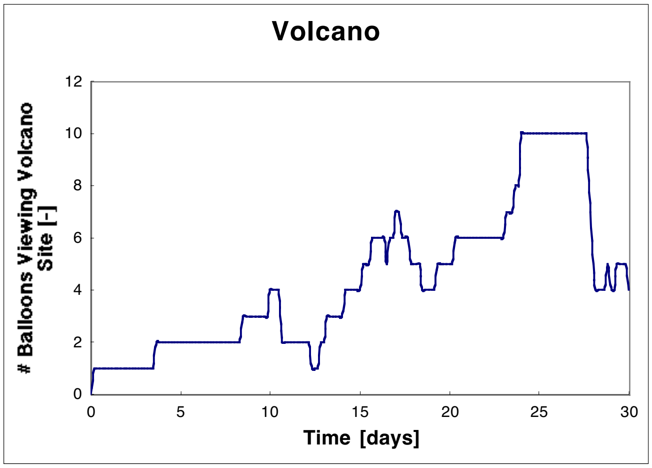


Figure 5-62. Balloons viewing the volcano site in the GDIN simulation.

For both of these disasters in this simulation, the balloon constellation provides excellent coverage and a desirable platform from which to monitor the event and provide communications support. This simulation demonstrates the effectiveness of trajectory control capabilities for targeted balloon observations at disaster sites. For more details and online movies of this simulation, see http://www.gaerospace.com/projects/StratoCon/global_disaster_info.html.

## 5.8. Summary of Constellation Management Work

In summary, we have made significant progress during Phase II on the Constellation Management task. We have studied several new applications and constellation objectives, including overflight avoidance, target overflight, and the hurricane intercept mission. We developed an advanced framework for performing and analyzing constellation management. And, in the process, we demonstrated the feasibility of using a constellation of stratospheric balloons to answer pressing scientific questions.

### 5.8.1. Firsts

During Phase II, we reached several milestones and achieved several "never-been-done-before" results.

#### *5.8.1.1. AP/WSB Research*

The Princeton work is exciting new research that has uncovered several new "firsts." To the best of our knowledge, the work reported here is the first use of gradients of artificial potentials to determine control actions in the presence of non-uniform external flow fields for multi-vehicle systems. This work also represents the first use of WSB theory for arbitrary force fields. Finally, this work represents the first demonstration of a non-space (i.e., atmospheric) application of WSB theory.

#### *5.8.1.2. Adaptive Observations for In-situ and Remote Observations*

To our knowledge, we completed, in Phase II, the first ever simulation of the use of stratospheric balloons to perform adaptive observations for in-situ and remote science. Our simulations of applications related to the Global Disaster Information Network (GDIN) use a sophisticated layering of time-dependent objectives that are adjusted in response to environmental conditions and scientific objectives. As discussed above, this adaptive capability is essential for the adaptive sampling and adaptive observation concepts being considered by NASA and NOAA.

Furthermore, the THORpex simulation demonstrated that utilization of information about the environment in which the balloons are floating can increase the number of useful observations by more than an order of magnitude. By adapting to the environment in which they are floating, the StratoSat™ platforms can significantly increase their science return.

### 5.8.2. Other Applications of Constellation Management

#### *5.8.2.1. NASA's Sensor Web*

Many organizations are now considering the use of "distributed systems" that provide more information than individual vehicles alone. NASA's sensor web concept is one such concept.

Dr. Heun attended the IEEE Geophysics And Remote Sensing Symposium in Toronto, Canada at which NASA personnel working on the sensor web concepts discussed progress and issues related to the sensor web concept. One key technology area for sensor web was decision-making for the coordination of sensor web assets. We demonstrated a type of that decision-making technology in Phase II. We believe that our work in this area would be potentially interesting to apply to the diverse assets (aircraft, satellites, surface sensors, and balloons) of NASA's sensor web concept.

#### *5.8.2.2. Adaptive Ocean Sampling*

Our Princeton collaborator, Dr. Naomi Leonard, is researching underwater formation flying using some of the same strategies discussed above, namely the method of Artificial Potentials.

Like stratospheric balloons, the buoyancy-driven underwater vehicles studied by Dr. Leonard have bounded and underactuated control systems. The similarities between the two applications indicate that the concepts developed here would be applicable to underwater sensing for the Navy and other organizations.

# 6. Trajectory Control System Modeling

This section describes the modeling of the advanced trajectory control system (ATCS). Several models were developed with different levels of fidelity for different purposes. These will be discussed below in separate subsections.

A conceptual drawing of an ATCS is shown in Figure 6-1. The ATCS includes the capability to vary both the roll angle and angle of attack to achieve higher levels of trajectory control and more trajectory control options in terms of direction.

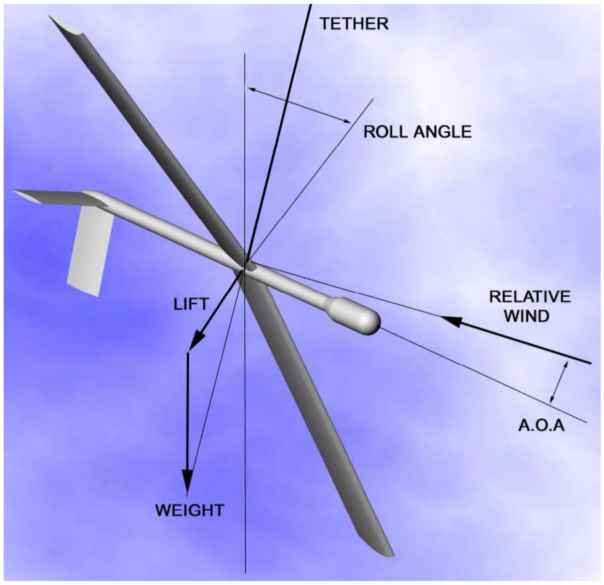


Figure 6-1. Advanced Trajectory Control System (ATCS).

Figure 6-2 shows a block diagram for ATCS model execution. The model will iterate to find a self-consistent solution in terms of TCS Wing Assembly altitude and tether angle.

## 6.1. Modeling Requirements

Although several model variants were implemented, they all basically met a similar set of modeling requirements (or subsets in some cases).

The modeling of the ATCS was implemented in MS Excel for simple investigations of various effects. For computing constellation behavior, JAVA was used. The underlying assumptions and requirements (inputs, outputs, formats, etc.) are listed below.

**Assumptions:**
- Dynamic equilibrium (i.e. quasi-steady-state)
- No altitude change caused by downward force of TWA
- Tether is a straight line
- Drag of tether equivalent to the drag on a length of tether equal to 20% of total length all operating at same conditions as the wing.

**Coordinate system:**

- The coordinate system for all variables passing across this interface is x in direction of wind, z upward, y to complete RH rule.

**Inputs:**

<u>Wing Design</u>

- Wing area
- Wing C_L (lift coefficient)
- Wing C_D (drag coefficient)

<u>Stabilizer Design</u>

- Stabilizer area
- Stabilizer aspect ratio
- Elevator lift curve

<u>Rudder Design</u>

- Rudder area
- Rudder aspect ratio
- Rudder lift curve

<u>TWA design</u>

- Separation distance between wing and elevator
- Separation distance between wing and rudder

<u>Tether Design</u>

- D (diameter)
- C_D
- Length
- Linear density

<u>Balloon Design</u>

- Area (horizontal projection)
- C_D

<u>Float Altitude</u>

- Balloon altitude

<u>Environment</u>

- Winds as a function of altitude
- Density as a function of altitude

<u>Operating condition</u>

- Roll Angle
- Angle of attack

**Outputs:**

- Absolute horizontal velocity of balloon/tether/wing system
- Wing altitude
- Fx, Fy, Fz: balloon forces
- Wing lift force magnitude
- Wing drag force magnitude
- Tether drag force magnitude
- Unit vector down tether

## 6.2. Model Architecture

Figure 6-2 shows a flow chart for ATCS model execution. The model iterates to find a self-consistent solution in terms of TCS Wing Assembly (TWA) altitude and tether angle. The important variables involved are also listed, indicating which are help constant during calculation, and which vary as the iteration proceeds.

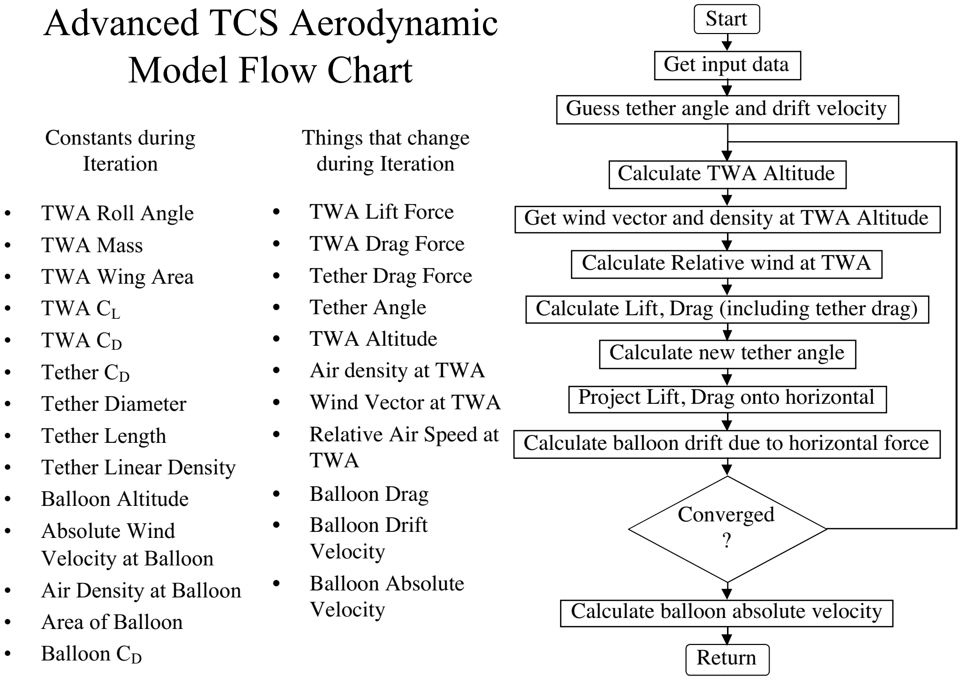


Figure 6-2. Block Diagram for ATCS Model Execution.

## 6.3. Single ATCS Model

The results of the constellation modeling were presented in its own major section (Section 5). However, some ad hoc models of a single Advanced TCS Wing Assembly (TWA) hanging from a tether were also used to investigate various operational aspects. These models were developed using Microsoft Excel. The results of these models will be discussed here.

### 6.3.1. Trajectory Control Performance in Different Wind Conditions

Figure 6-3 show the same set of results for four different wind differences between the altitude of the balloon and the altitude of the wing. Each plot basically shows the range of achievable operating points for the system in terms of relative velocity imparted to the balloon.

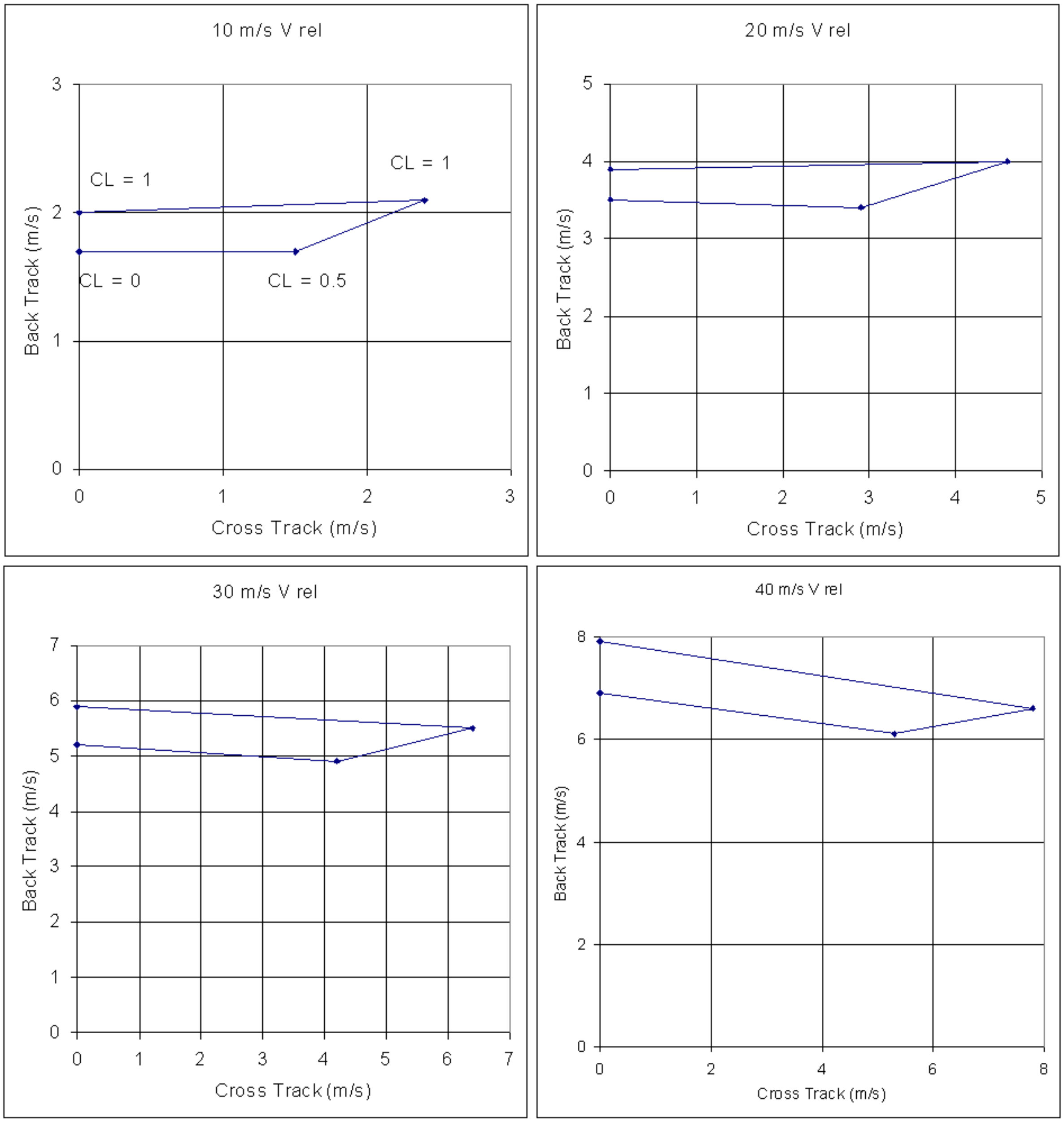


Figure 6-3. Trajectory Control Performance Envelopes in Different Wind Conditions

The roll angle of the wing can be controlled independently of the lift. Typically, we roll the wing to an angle that produces the maximum component of velocity lateral to the flight path of the balloon. When the wind is already carrying the balloon in the desired direction, no side force is required, and the roll angle can be set to zero. In that case, just the drag force (dominated by the tether) produces a component of velocity that simply slows down the balloon. At other times, an intermediate amount of sideways control is needed. In this case, the maximum lift coefficient (CL) can be reduced (by reducing the angle of attack). Alternatively, the roll angle can be reduced so the lift acts more downward and less to the side.

The effect on the balloon trajectory is indicated by the cross track velocity and back track velocity. The cross-track velocity is the component of balloon drift perpendicular to the wind at the balloon. This is the more useful component for trajectory control. The back track velocity is the component opposing the wind at the balloon. Because the winds are almost always stronger at the balloon altitude than at the wing, the drag on the wing and tether act to slow down the drift of the balloon, causing a back track velocity. If the winds were stronger at the wing (highly unlikely) then the drag on the wing and tether would speed up the balloon and the "back track" velocity would become negative.

On each of the graphs, there are four points. These are labeled only for one case (wind difference of 10 m/s). The two points on the ordinate each correspond to a roll angle of zero (so there is no cross track velocity). One is operated with maximum lift coefficient (~1.0) and the other at an angle of attack producing zero lift. It can be seen that the zero lift cases produced a somewhat smaller back track velocity because the drag is reduced, but the tether drag still produces an appreciable retardation of the balloon speed. For most cases, this component of drift velocity is not very important. It is conceivable that one might use this effect to adjust the time of arrival over a particular spot, but the range of control is not terribly large compared with the typical winds at the balloon altitude (on the order of 50 m/s).

The other two points on the graphs correspond to operating at lift coefficients of 0.5 and 1.0, but with the roll angle set to produce the maximum cross track velocity component. In the heavier wind conditions, rolling the wing to the side causes the wing to climb into less dense air, so the drag on the system decreases somewhat even though the side force increases. This is why the back track velocity decreases off to the side in these plots.

### 6.3.2. Optimum Roll Angle

When the wind difference between the balloon altitude and the wing altitude is small, then the maximum lift force that can be generated will be much less than the weight of the TCS Wing Assembly (TWA). In this case, the maximum side force is realized when the wing is rolled 90° so the lift force is directed to the side. This was the assumed condition when the first generation system was developed. The advanced TCS includes the ability to control the roll angle of the TWA independently of the lift coefficient. For a particular set of winds, a particular roll angle will produce the maximum sideways component of balloon drift velocity (cross track velocity). Actually, the parameter that one usually would want to maximize is the angle of the balloons trajectory compared to the wind direction. The optimum condition is then one with just a little more drag, which will slow the system down a little more, allowing the sideways component longer time to act to produce a sideways displacement of the trajectory. However, there is very little difference between the two operating conditions, so this is largely academic. The plot shown in Figure 6-4 shows the roll angle to produce the maximum trajectory angle of the balloon. This curve is not completely universal. It varies somewhat in its details based on the winds at different altitudes, and on the details of the design of the TWA and the balloon, but the general shape is always as shown. For this particular plot, the wind conditions and design of the TWA and balloon were kept fixed and the weight of the TWA was varied arbitrarily to change the Lift to Weight ratio. This was merely a convenient way to generate the plot for illustrative purposes. As the lift increases (or the weight decreases) the wing must be rolled less so the lift acts more downward and less to the side. If it is allowed to remain acting sideways, it causes the TWA to swing up into less dense air and the wind difference also reduces, so the TWA is less effective. If the TWA is rolled more horizontally, then the lift force is directed downward and less to the side, so again the useful sideways component is reduced. There is an optimum operating point for each L/W, and that is what is plotted.

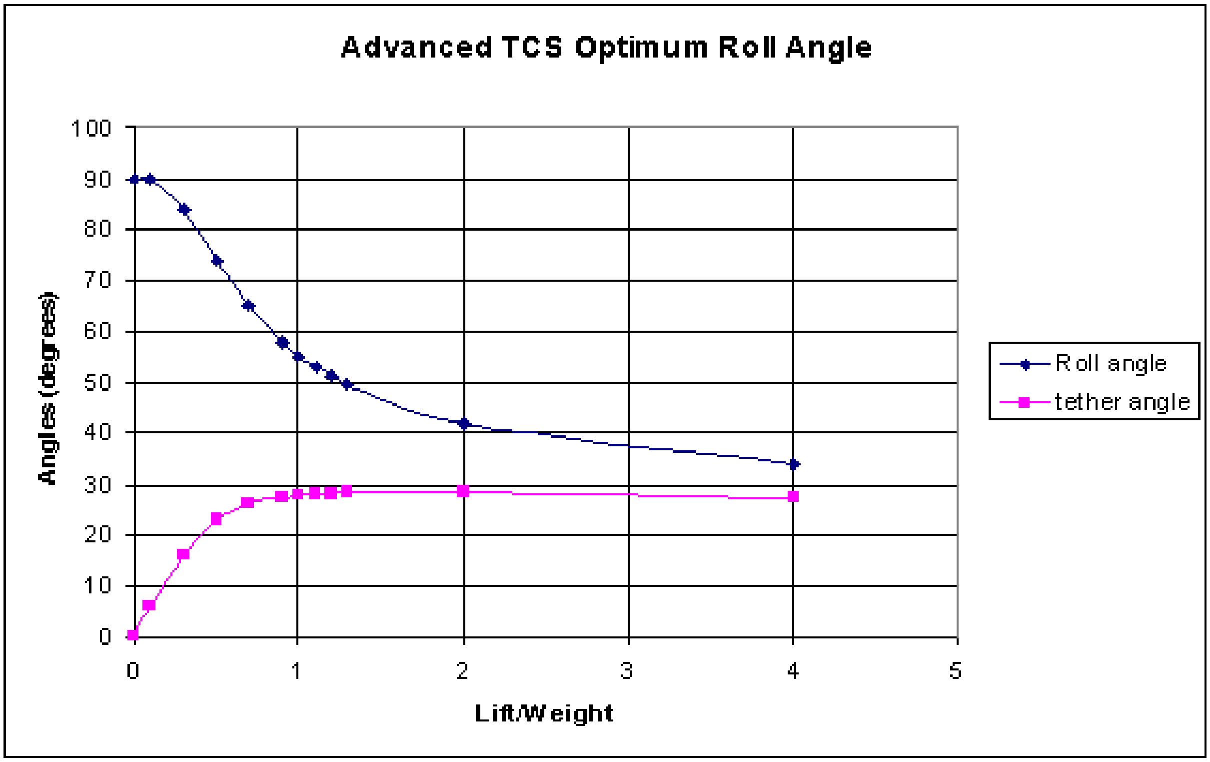


Figure 6-4. Optimum Roll Angle

The figure also shows the angle of the tether from vertical. When the lift is very small compared with the weight, it cannot move the wing very far sideways. As the lift increases, the wing swings more to the side and the tether angle increases. As the lift increases beyond L/W ~ 1, the optimum operating point for the wing results in the tether angle remaining almost constant. One can calculate the optimum roll angle when the TWA has zero mass (infinite L/W). At this hypothetical operating point, the roll angle is about 28.2° and so is the tether angle from vertical.

### 6.3.3. Sensitivity of Optimum Roll Angle

In the previous section, the optimum roll angle was presented. One might wonder how sensitive the actual performance is to the roll angle. This will give an indication of how well one might need to measure the angle, and how precisely the roll angle must be controlled. In this section, we investigate this aspect.

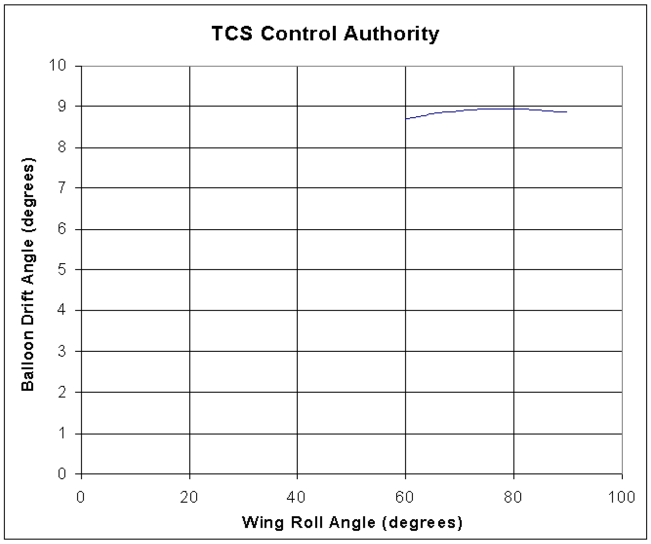


Figure 6-5. Roll Angle Sensitivity with L/W = 0.5

The trajectory control performance is shown as a function of wing roll angle in Figure 6-5 for a case with L/W = 0.5. The maximum performance is realized at a roll angle of 78°. However, it can be seen that the performance does not degrade significantly if the roll angle varies several degrees.

A similar plot is shown in Figure 6-6 with L/W = 2.0. In this case, the optimum roll angle is 49.5°, but again, the performance is not terribly sensitive to variations in roll angle of a few degrees.

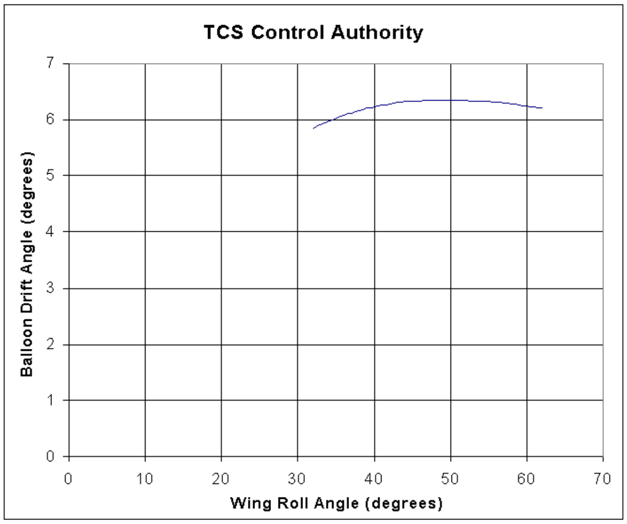


Figure 6-6. Roll Angle Sensitivity with L/W = 2.0

# 7. Flight Termination

## 7.1. Introduction

In the development of the DERBE proof-of-concept mission we recognized the importance in dealing with safety since much of the flight of the system would occur over high density population zones. The two issues are the density of population under possible flight paths and how that might translate to high Casualty Estimates (CE), and the technologies that must be developed to provide safe termination of payloads to the ground. Here safety refers to people and property on the ground and to the payload itself. The technologies that are needed include guided payload delivery systems, balloon trajectory prediction and control, and reliable after landing payload release systems.

## 7.2. Population Density Maps

Figure 7-1 is a population density map of North America (See http://www.ciesin.org/datasets/gpw/globldem.doc.html). The colors denote population density where the light tan represents 0-4 people per square kilometer and the darkest purple represents 367 to 28,895 people per square kilometer. Figure 7-2 displays an enlargement of the same data with features noted such as the location of the Oklahoma ARM site, major cities, current balloon launch sites, and possible low population density corridors for approaching and departing the OK ARM site. In the study we did for DERBE we assumed a flight in the summer hence the general east-to-west flight path.

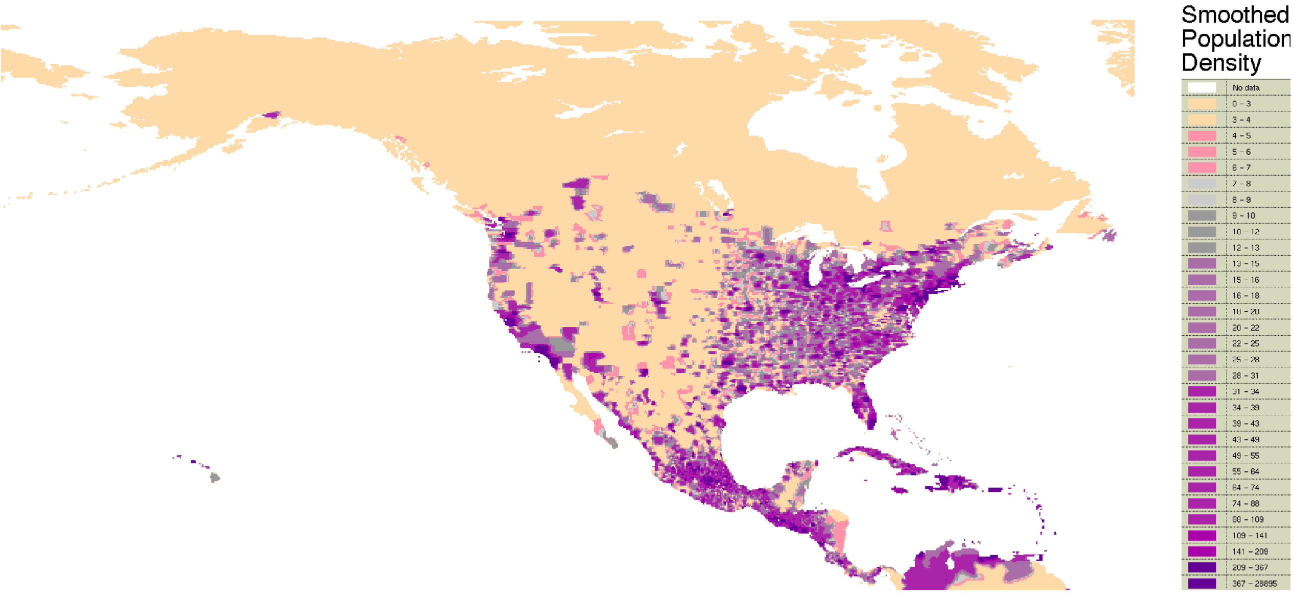


Figure 7-1. Population Density Map of North and Central America

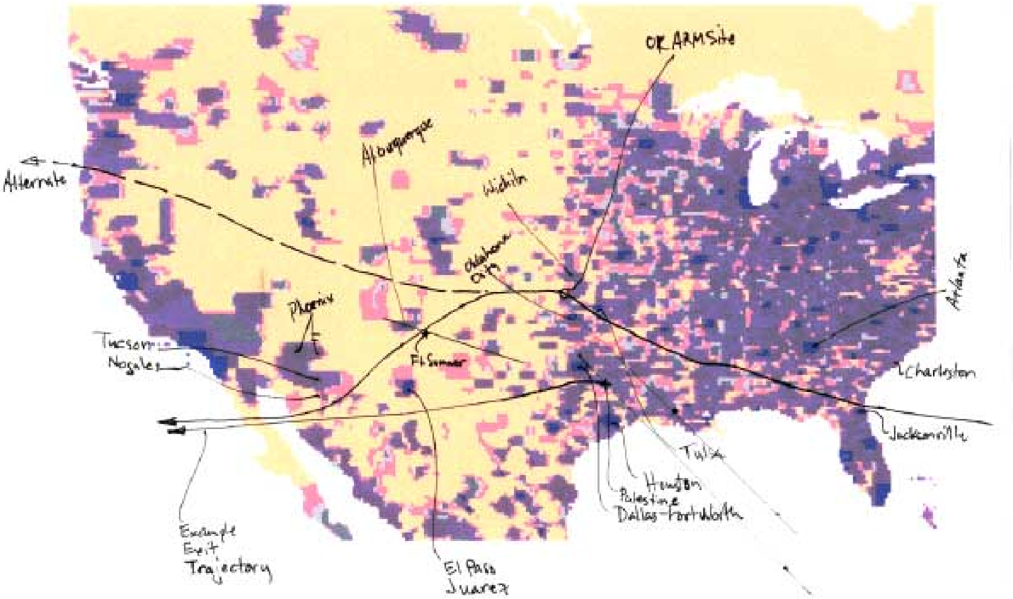


Figure 7-2. DERBE Flight Corridors

In examining these data, it became very clear that for flight over population zones that trajectory control is required in order to fly minimum population density corridors. Second, it will be important to have robust termination systems in the event of catastrophic failures to enable the safe recovery of payloads and balloon envelopes on the ground without significant risk of injury to people (Casualty Estimate, CE $<10^{-6}$) or damage to property. If such systems are not developed, it is unlikely significant payloads will be allowed to over fly such population zones.

## 7.3. Guided Payload Delivery

We investigated options for advanced safety systems for StratoSat™ platforms. Safety of people and property on the ground is a primary requirement of the StratoSat™ system concept. A key element of safety is guided payload recovery.

### 7.3.1. Orion

IST Aerospace developed the ORION™ Navigation Guidance and Control System (NGCS) for NASA's X-38 program and the French space agency's (CNES) balloon program. The ORION™ system is a version of the Guided Parafoil Airborne Delivery System (GPADS), being developed for the US Department of Defense. The ORION™ system is used to autonomously fly the parafoil to a landing site that has been loaded into the guidance software, turn into the wind, and flare, thus providing a slow speed, low impact landing on land. The French ORION™ system is capable of delivering 350-700-kg payloads to within 100 m of a pre-designated target. The ORION™ system could deliver the StratoSat™ platform payload to a safe landing site (airfield or unpopulated zone) after termination of the flight. To date NASA and the CNES have carried out several flight tests of the ORION™ system. The figure below shows ORION™ NGCS in operation guiding NASA's X-38 to a safe landing after deployment from an aircraft. In addition to this concept, we are exploring the possibility of using the advanced TCS as the recovery system instead of a parachute or parafoil. This would eliminate the need for one subsystem element.

Figure 7-3. ORION Guided Parafoil Airborne Delivery System (GPADS).

### 7.3.2. Sherpa

Another company is developing similar hardware that could be adapted to the balloon gondola termination problem. This company is called Mist Mobility Integrated System Technology Inc. (MMIST). MMIST is a Canadian developer of guided parachute delivery systems. One system developed by MMIST that could be relevant is the Sherpa system shown in Figure 7-4. The Sherpa system is a high glide ratio ram air parachute system that is capable of accurate delivery of payloads from altitude. The Sherpa control subsystem automatically guides the parachute using GPS. The Sherpa system is currently targeted at a variety of applications including disaster relief, search and rescue, and precision military airdrop.

Figure 7-4. Sherpa Ram Air Parachute Delivery System

### 7.3.3. ESA Parafoil Technology Demonstration Project

In the 1990s, ESA sponsored research into guided parafoil systems in the Parafoil Technology Demonstration (PTD) Project. This effort studied guided delivery systems for balloons, re-entry vehicles and sounding rockets for payloads up to 3200 kg. An autonomous guided flight test demonstrated delivery of a 2,000 kg payload to a target within 150 m diameter circle with landing speeds of <5 m/s and impact g-loads of <3.5 (See Petry, Günter, et. al., "Application of Parafoil Technology for Descent and Landing of Re-entry Vehicles," Atmospheric Reentry Symposium, Arcachon, France, April 1999).

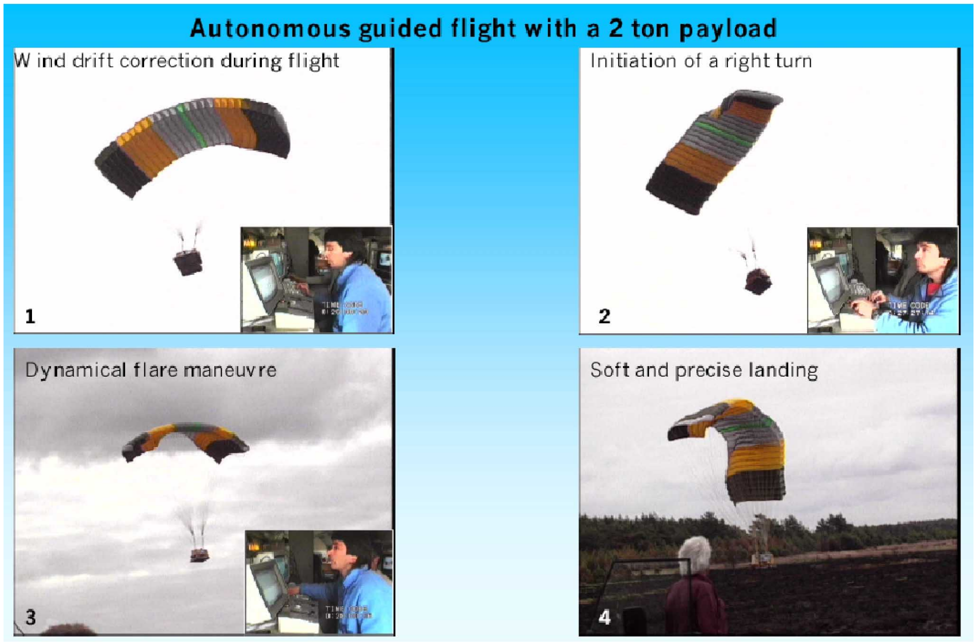


Figure 7-5. ESA Autonomous Parafoil Technology Demonstration Flight Test

# 8. International Airspace Overflight Issues

## 8.1. Introduction

As indicated earlier, the issues of international overflight of constellations of balloons should not be minimized. Both technical and political factors will determine the ultimate feasibility of this concept.

Today, permission to fly scientific research platforms, balloons and aircraft, over some nations is difficult and sometimes impossible to obtain. The reasons overflight is denied can range from safety and liability to national security issues. The overflight problem can be exacerbated if high-resolution, down-looking imaging is carried and/or if scientists from the country being over flown are not involved in the mission. Often, intensive international diplomacy is required to allow overflight. The list of countries that can make it difficult to allow overflight includes some of the more obvious States, but also frequently includes less obvious examples. The changing international political climate can heavily influence the authorization of overflight.

## 8.2. Definitions

These definitions are intended to provide a frame of reference to the discussion on international overflight. Because these definitions are not absolute, the topic of international overflight can be very challenging.

### 8.2.1. Delimitation

Delimitation refers to defining limits to something, e.g. airspace or outer space. In the past, delimitation of outer space has been a controversial problem. The upper boundary or highest extent in altitude of airspace would logically determine the lower boundary of outer space. However, as one will see later, the location of the upper boundary of airspace itself is controversial and ambiguous.

### 8.2.2. Demarcation

Demarcation refers to a proposed location that separates two or more regions of interest. There has been great interest in the last 50 years in defining the place where airspace ends and outer space begins. This place of separation has been referred to as a demarcation. Current US policy is to avoid demarcations, such as between airspace and outer space, wherever possible.

### 8.2.3. Extension of Sovereignty

Extension of sovereignty is when sovereignty is extended outward beyond State borders or upward from the surface of the State. For example, most States extend sovereignty outward from their shores by 12 miles. Some States extend partial sovereignty outward as far as hundreds of miles in the case of fishing rights. At the start of the space age, some States attempted to extend their sovereignty to outer space, even to the stars, but there were immediate problems with this extension because the Earth rotates and thus various celestial bodies would always be passing into and out of various States' sovereignty. Today it is generally agreed that State sovereignty does not extend into outer space. However, there is no agreed altitude at which outer space is defined to begin. A corollary is that there is no agreed altitude at which airspace ends.

### 8.2.4. Earth's Atmosphere

The Earth's atmosphere is a gaseous mass surrounding the Earth or the zone of the Earth in which air exists. Where the atmosphere ends is not so easy to define. For example, some scientists consider the zone of the atmosphere to extend outward from the Earth by thousands of miles due to the tenuous gas in low Earth orbit. In fact, there is really no such thing as a pure vacuum in space since there are molecules of hydrogen gas almost everywhere in space. Hence, the altitude where airspace ends and outer space begins cannot be defined, just as where there is no agreement as to where the atmosphere ends.

### 8.2.5. Outer Space

Outer space has been defined as the region beyond the Earth's atmosphere. Based on the section above, one can see that defining the start of outer space is not an easy task. Some have preferred a practical, functional definition of the start of outer space, i.e. the altitude in which an object can orbit the Earth, but even this altitude varies depending on the average density of the object.

### 8.2.6. Airspace

Again, some have preferred a practical, functional definition of the start of Airspace, i.e. the altitude in which an aircraft can fly, but even this altitude varies depending on vehicle. Most air breathing aircraft cannot fly much above about 22 km, however vehicles carrying there own oxidizers or rocket planes can fly to 50 km or higher, e.g. X-15. Controlled airspace, as defined by the US Federal Aviation Administration (FAA) is up to 18 km (~60,000 ft). Up to this altitude aircraft are required to carry certain equipment for navigation (transponders). Beyond controlled airspace, aircraft still must meet numerous regulations, primarily regarding flight safety.

### 8.2.7. Common law

Common law refers to the body of law that results from custom and precedent and that is usually not codified.

### 8.2.8. Right of Innocent Passage

As abstracted from maritime law, this is a right that allows vehicles of all States to enjoy the right of innocent passage through a zone. Passage means traversing that zone without entering sovereign space. Passage is continuous and expeditious. Passage is innocent so long as it is not prejudicial to the peace, good order or security of the State over flown.

### 8.2.9. Principle of Free Overflight

Our definition of free overflight is having the right of innocent passage over international boundaries. During innocent passage of the stratosphere a platform would be able to navigate and carry out scientific research.

### 8.2.10. Air Defense Zones

Air defense zones are extensions of sovereignty surrounding a State that have certain limitations and/or restrictions of use by commercial or military aircraft of other States.

### 8.2.11. Principle of "if no objection"

If there is no objection by a State of the passage of a vehicle (of another State) through regions of actual or potential sovereignty, then future passage can occur by exercise of common law. The best example of this principle occurred at the beginning of the Space Age. When the USSR and US began flying satellites in outer space there were no objections by the US of flights of USSR satellites over US territory nor did the USSR raise objections to US satellites over their territory. Since serious objections were not raised at the time, the territory above States in the region of outer space was deemed free for all States to pass.

## 8.3. Pathways to International Overflight

A number of pathways to global overflight of balloon constellations exist including (1) the exercise of the principle of free overflight of the stratosphere, (2) incorporation of constellation systems into the Basic Systems framework of the World Meteorological Organization (WMO), (3) expansion of the Treaty on Open Skies (TOS), or (4) a new treaty based on the free use of the stratosphere for scientific purposes or the need to monitor the troposphere for worldwide pollution control compliance.

### 8.3.1. Exercise Principle of Free Overflight

A rationale for the free overflight of the stratosphere is that (1) sufficient ambiguity exists as to the limits of airspace and, hence, of a State's sovereignty, (2) no treaty or agreement exists that unambiguously regulates or controls flight above 18 km altitude, (3) as with outer space, few States, if any, have special national interests in the stratosphere or the means to exercise control over activities within the stratosphere. The lack of clear definition and demarcation of airspace provides an opportunity for the free use of the stratosphere provided this use is in a manner that satisfies existing rules of law and such operation does not compromise national interests of the overflown State. Operating in the stratosphere under a principle of free overflight would provide an opportunity to deal with each issue as it arises, in a similar fashion as navigation on the high seas and outer space has developed. In this way, a common law of the stratosphere would be allowed to develop.

At this time there is no established definition of the height at which airspace ends and outer space begins. This ambiguity raises the opportunity for future international agreements to address the peaceful scientific uses of region between airspace and outer space. States do not object to overflight of satellites orbiting in outer space. Is there an altitude above which a balloon can fly without there being an issue of passage through sovereign airspace? In the discussion of the international overflight through airspace and outer space that has occurred over the last 50 years, the arguments for determining limits can be placed into certain categories. These are shown below:

Prescriptions of Air Conventions

Physical Characteristics of Airspace and Outer Space

Nature of the Flight Systems

Effective Power of a State to Exercise Control

Arbitrary Altitude Limits

Functional Criteria

The various air conventions (Paris, 1919; Chicago, 1944) do not offer much guidance in the question of international overflight of very high altitude stratospheric balloons. The main reason for this is that there is no accepted definition of airspace or outer space. It may be that at the time of these conventions flight into the upper reaches of the atmosphere and outer space had not been contemplated. In the past there have been proposals for interpreting these conventions by defining the limits to airspace, and hence to space. However they have all failed because of the Earth community interest in outer space operations. At this time there is reluctance by States to establish limits not because of the concern about where airspace ends so much as where outer space begins, i.e. States do not want to be limited in the location of their outer space activities.

Many commentators on this topic have attempted to establish boundaries to airspace and outer space based on characteristics. Some have tried to limit airspace due to physical factors such as the height of various layers of atmosphere or the number of molecules of air at a particular altitude. Even the seemingly simple question of where the Earth's atmosphere ends has received answers ranging from 10 to 60,000 miles in altitude over the years.

Some have suggested that the nature of the flight systems themselves should delimit airspace. For example, it has been suggested that airspace goes up to an altitude at which that normal aircraft fly, or to the altitude at which an object can orbit the Earth without expenditure of propulsive energy, or an altitude where levels of gravitational acceleration and the competing strength of aerodynamic and centrifugal forces (the "von Karman" line). Because the nature of flight systems continues to change with advancing technology and because one can always discover a ambiguity or contradiction, and because the community of airspace and outer space users have resisted delimiting spaces, such proposals for boundaries have not been accepted.

When States began flying satellites over other States it was pretty clear that even if there had been objections there was very little that any State could do about overflights. In essence these satellites were out of effective control of all States. Some have suggested that boundaries of airspace should be set at an altitude where this effective control ends. Before the US U-2 reconnaissance aircraft was shot down, the USSR was well aware of the frequent overflights and but did not object to them. The lack of objection was no doubt related to their sense of impotence in doing anything about the overflights. When they were able to shoot a U-2 down, because it flew at a lower than normal altitude, they exercised their national sovereignty over that level of airspace over the USSR. Today, the US and Russia have the capability to exercise control from the ground to the altitude of orbiting satellites. Many other States have the capability to exercise control, by force of arms, at altitudes up to the lower stratosphere. However, few States probably have the capability to exercise effective control at 35-km altitude. It has been argued that no State today has the capability to destroy a stratospheric balloon at such altitudes, but that the technology exists if a State were so inclined to develop the capability. An additional consideration is that if stratospheric balloons were to be shot down by objecting States, the liability for injury to persons and property could shift to the aggressor.

In 1956, the US, in concert with the UK, Norway, Brazil, Japan, Turkey and Panama, began launching "meteorological" balloons over the USSR and China. Some 4000 balloons were launched carrying meteorological instruments and radios but also cameras. Some were designed to fly at 9.1 km [30,000 ft] and others launched from Norway toward the USSR carried 182-kg [400-lbs.] payloads to 24.3-27.4 km [80-90 kft]. As expected several balloons landed before transiting Eastern Europe, Soviet or Chinese airspace. Protests by Eastern Europe were made to the International Civil Aviation Organization (ICAO) that these balloon flights were an invasion of sovereignty. The reasons given for the objections were that the flights menaced the safety of people and the security of air transport and were being used for espionage. After the revelation that the US and others were carrying out these flights, the US stopped all flights. As Secretary of State Dulles said, cessation was not on the basis that the US did not have a right to fly such balloons, but because "it was a matter of decent and friendly relations" between nations. In fact, the US probably stopped these flights because the USSR threatened to reciprocate. This is a clear example of the fact that then as now there are considerable questions of the rights of States to over fly other States from the stratosphere.

Some people have suggested that instead of a futile search for arbitrary limits, one should instead look at each individual case and all its relevant factors. In fact, this is what was proposed under the discussion of potential new treaties. In this manner overflight may become acceptable if it is recognized that such overflight is in a State's best interests. One needs to recognize that there are limits to extension of territorial sovereignty and that practical international necessities will lead to definitions in the future in the same way as Maritime Law has evolved. Freedom of the seas came about because it was in everyone's best interests and it was difficult for any nation to exercise effective control far from its shores.

### 8.3.2. Capitalize on World Meteorological Organization (WMO) Cooperation

The WMO is an intergovernmental organization with a membership of 185 member states and territories. As stated in its Fifth Long-term Plan 2000-2009, the "*WMO coordinates the international cooperation needed to develop and improve the provision of meteorological, hydrological and related services worldwide. . . . Set up in 1950, it became the specialized agency of the United Nations for meteorology (weather and climate), operational hydrology and related sciences in 1951. It is the United Nations (UN) system's authoritative voice on the state* *and behavior of the Earth's atmosphere, its interaction with the oceans, the climate it produces and the resulting distribution of water resources*." As a body, the WMO determines (through its member states and usually unanimously) the appropriate measurement requirements and systems capabilities for worldwide meteorological observations.

WMO interests goes far beyond meteorology. The WMO carries out a number of programs including the World Weather Watch, the World Climate Program, the Atmospheric Research and Environment Program, the Applications of Meteorology Program, the Hydrology and Water Resources Program, and others. Included in the World Climate Program (WCP) are World Climate Data and Monitoring Program; the World Climate Applications and Services Program; the World Climate Impact Assessment and Response Strategies Program; and the World Climate Research Program. The WCP supports the Global Climate Observing System (GCOS), encompassing all components of the climate system, atmosphere, biosphere, cryosphere and oceans.

The WMO is a hierarchical organization that receives its strength from many levels of teams of people in all member States. The World Meteorological Congress, which is the supreme body of WMO, meets every four years. It determines policies, approves the program and budget and adopts regulations. The Executive Council is composed of thirty-six members, including the President and three Vice-Presidents. It meets at least every year to prepare studies and recommendations for Congress, to supervise the implementation of Congress resolutions and regulations and to advise Members on technical matters. Members are grouped in six regional associations (Africa, Asia, South America, North and Central America, South-West Pacific and Europe). Each of them meets every four years to coordinate meteorological and operational hydrological activities within their Region and to examine questions referred to them by the Council. WMO has eight technical commissions responsible for aeronautical meteorology; agricultural meteorology; atmospheric sciences; basic systems; climatology; hydrology; instruments and methods of observation; and marine meteorology. Each of them meets every four years.

A key technical commission, regarding the establishment of new observing techniques, is the Commission on Basic Systems (CBS). The CBS itself is comprised of several expert and implementation and coordination teams. The CBS teams are divided into Open Program Area Groups (OPAGs) for the Integrated Observing Systems (IOS), Information Systems and Services (ISS), Data Processing and Forecasting Systems (DPFS), and Public Weather Services (PWS). The organization of the CBS teams are shown in Figure 8-1.

One of the teams of interest to future global constellations is the OPAG on Integrated Observing Systems (IOS). The OPAG on IOS is divided into implementation/coordination, observational data requirements, satellite, and automatic station teams. Each of these teams meets about every two years to formulate the WMO program in the IOS area. New ideas, such as global constellations of balloon platforms, are formulated, discussed and analyzed at the lowest levels before they move upward through the WMO. Given past examples, it can take a decade or more after they are presented for new observing techniques to be accepted by the WMO. Once accepted, however, all member States support the new technique and provide infrastructure to implement, e.g. satellites, radiosondes, buoys, etc.

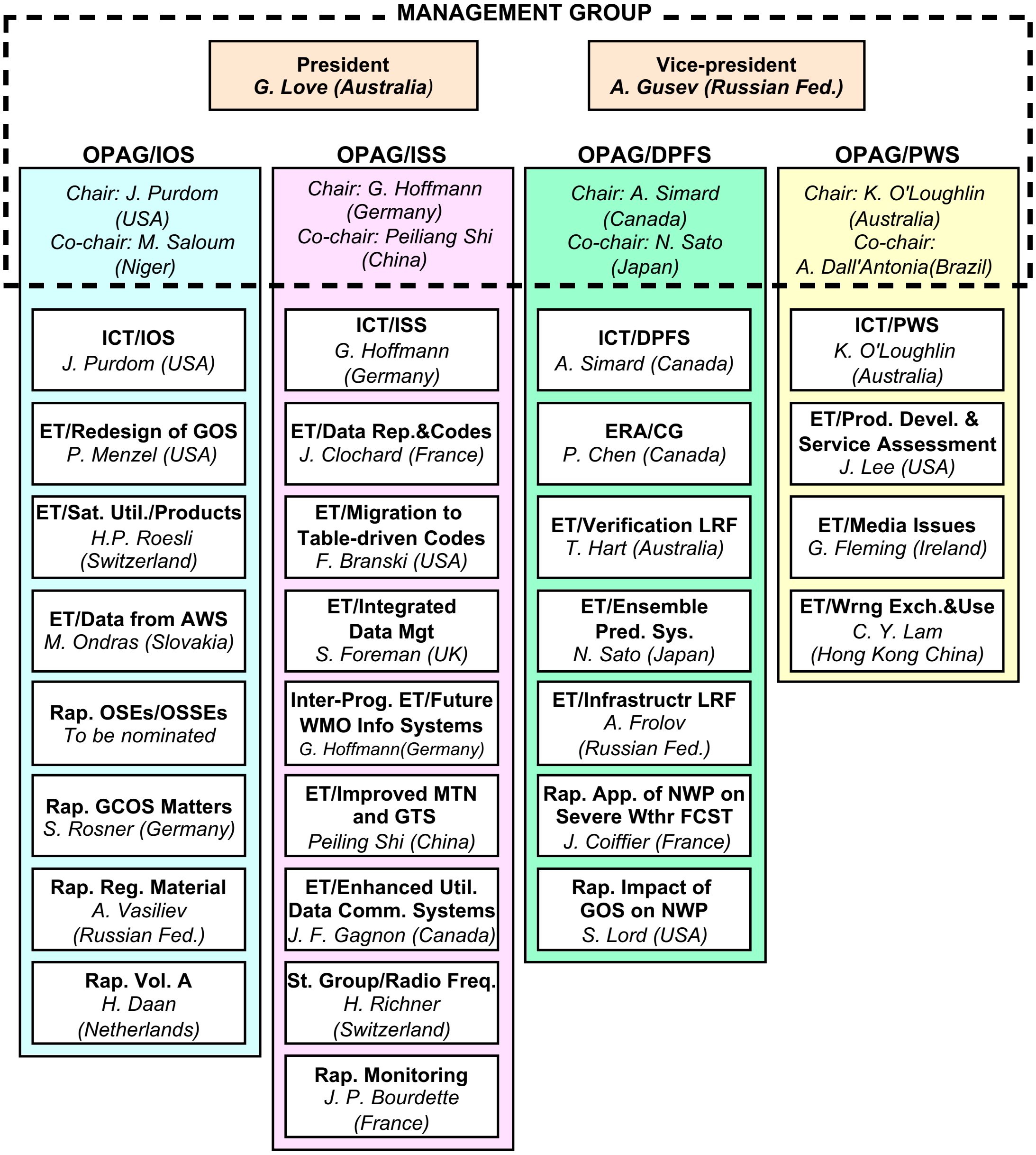


Figure 8-1. Organization of the WMO Commission on Basic Systems

If constellations of stratospheric balloon platforms were recognized as a cost effective means of satisfying the CBS requirements and as a result accepted by the WMO Council, such constellations would not require international treaties. All member states would be offered the opportunity of contributing balloons systems to the global network.

### 8.3.3. Expand Treaty on Open Skies

On March 24, 1992, 25 nations signed the Treaty on Open Skies (TOS) in Helsinki, Finland. When fully implemented, the treaty will establish a regime of unarmed military observation flights over the entire territory of its signatory nations. The TOS was originally negotiated between members of NATO and the former Warsaw Pact as a confidence building measure in arms control. The Treaty on Open Skies is a positive step toward building confidence and security in the arms control and verification process ongoing between signatory nations. The TOS gives one hope that in the future global stratospheric constellations of unarmed scientific platforms would be allowed to operate.

Some of the key statements in the TOS preamble are as follows:

1 *Recalling the commitments they have made in the Conference on Security and Co-operation in Europe to promoting greater openness and transparency in their military activities and to enhancing security by means of confidence- and security-building measures,*

2 *Wishing to contribute to the further development and strengthening of peace, stability and co-operative security in that area by the creation of an Open Skies regime for aerial observation,*

3 *Recognizing the potential contribution which an aerial observation regime of this type could make to security and stability in other regions as well,*

4 *Noting the possibility of employing such a regime to improve openness and transparency, to facilitate the monitoring of compliance with existing or future arms control agreements and to strengthen the capacity for conflict prevention and crisis management in the framework of the Conference on Security and Co-operation in Europe and in other relevant international institutions,*

5 *Seeking to establish agreed procedures to provide for aerial observation of all the territories of States Parties, with the intent of observing a single State Party or groups of States Parties, on the basis of equity and effectiveness while maintaining flight safety*

The following states have signed the TOS: Belarus, Belgium, Bulgaria, Canada, the Czech Republic, Denmark, France, Georgia, Germany, Greece, Hungary, Iceland, Italy, Kyrgyzstan, Luxembourg, the Netherlands, Norway, Poland, Portugal, Romania, Russia, the Slovak Republic, Spain, Turkey, Ukraine, the United Kingdom and the United States. The TOS entered into force since it has been ratification by at least 20 nations.

The TOS is designed to enhance mutual understanding and confidence and gives all participating countries, regardless of size, a direct role in gathering information about military forces and activities of concern to them. This agreement responds to the desire of many European countries to find a means of building confidence, stability and predictability in the arms control and verification process.

The treaty is based on territorial openness, the use of airborne sensors and quotas of annual overflights that each signatory to the treaty is willing to accept. The treaty is flexible, allowing for decisions to improve sensors, adjust annual flight quotas and admit new participants.

All aircraft used in Open Skies are subjected to certification to ensure that sensors are approved and conform to the standards of the treaty. Aircraft may be equipped with panoramic, framing and video cameras, infrared line scanning systems that can operate at night and synthetic aperture radar that can operate day and night in any weather. These sensors must be commercially available to all signatories.

Each Open Skies participant has agreed to an annual quota of observation flights that it is willing to accept from other participating countries. Annual flight quotas assigned to each nation are based on several factors including geographic size, military and strategic importance and other political criteria. The United States and Russia/Belarus, as the largest participants, have accepted quotas of 42 annual observation flights each.

The Open Skies Treaty is a positive step toward building confidence and security in the arms control and verification process ongoing between signatory nations. The TOS provides hope that in the future global stratospheric constellations of unarmed scientific platforms would be allowed to operate. In fact, the preamble leaves open this possibility when it envisions, "*. . . the possible extension of the Open Skies regime into additional fields, such as the protection of the environment.*"

### 8.3.4. Seek New Treaties

There is interest in the international scientific ballooning community to establish new international agreements for the free use of the stratosphere by scientific balloon systems. This interest is independent of Global Aerospace Corporation's interest in the international overflight of constellations of balloons.

At the 33rd COSPAR Scientific Assembly in Warsaw, Poland in 2000, the Scientific Balloon Panel formulated a resolution to the COSPAR Executive Council requesting a task group be formed to study and report to the bureau on the technical aspects of overflight of scientific balloons (including altitudes, balloon sizes and payload masses, characteristics and features of payloads, and safety requirements) and possible international actions to enable the geographically-unrestrained and the peaceful free flight of such apparatus over all countries. This resolution was accepted as COSPAR Internal Decision No. 1/2000. This task group met at the COSPAR 2002 conference in Houston in November 2002 for initial discussions. It is hoped that this initiative will eventually result in a new agreement that perhaps could recognize the stratosphere as a special zone for scientific balloon and lighter-than-air (LTA) craft where they could fly without overflight constraints provided they meet certain technical, legal and oversight requirements. Possible requirements are listed below:

Airworthiness certificates from appropriate organization, perhaps ICAO, indicating the craft meets equipment and safety requirements

A means of identification

Evidence of liability insurance

Payloads must not compromise any State's national security

Launch and payload oversight

Any nation free to operate stratospheric platforms if they meet all requirements

Finally, new diplomatic initiatives regarding the protection of the worldwide environment could instigate new international treaties for monitoring pollution. Such monitoring may require global constellations of stratospheric platforms, such as balloons, to make the measurements possible due to their proximity to the troposphere.

## 8.4. Bibliography

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# 9. StratCon Phase II Publications, Presentations, and Press Releases

During Phase II of the StratCon activity, GAC personnel were very active in terms of technical papers, presentations at conferences, and press releases. This section summarizes those activities.

## 9.1. Publications

Here is a list of publications for conferences and journals that were completed during Phase II.

M. K. Heun, K. T. Nock, A. A. Pankine, "Technology Requirements for Guided Stratospheric Balloons," Earth Science Technology Conference, June 2002

M. K. Heun, et. al., "Computer Simulations of Global Networks of Stratospheric Satellites," AMA Conference, January 2002.

A. A. Pankine, E. Weinstock, M. K. Heun, K. T. Nock, "*In Situ* Science from Global Networks of Stratospheric Satellites," AMA Conference, January 2002.

K. T. Nock, M. K. Heun*, and K. M. Aaron, "Stratospheric Balloon Constellations for Earth Science and Meteorology," AMA Conference, January 2001.

M. K. Heun, et. al., "Biological Analogs and Emergent Intelligence for Control of Stratospheric Balloon Constellations," First GSFC/JPL Workshop on Radical Agent Concepts (WRAC), January 2002 (originally scheduled for September 2001).

A. Pankine, K. Aaron, M. Heun, K. Nock, W. Wiscombe, B. Mahan and W. Su, "Stratospheric Satellites for Earth Science Applications," International Geoscience and Remote Sensing Symposium (IGARSS), June 2002.

W. Wiscombe and K. Nock, "Ultra-Long Duration Balloons for Earth Science Vision in the Post-2010 Era," Poster at International Geoscience and Remote Sensing Symposium (IGARSS), June 2002.

K. Nock, "Stratospheric Balloon Constellations for Earth Science and Meteorology," ***The Earth Observer***, Vol. 13 No. 1, p. 16, January/February 2001.

K. T. Nock, M. K. Heun, K. M. Aaron, "Global Stratospheric Balloon Constellations," ***Adv. Space Res.***, Vol. 30, No. 5, pp 1233-1238, 2002.

K. T. Nock, M. K. Heun, K. M. Aaron, "Global Constellations of Stratospheric Satellites," 14th ESA Symposium on European Rocket and Balloon Programs, May 2001.

A. A. Pankine, M. K. Heun, K. T. Nock, K. M. Aaron, S. Schlaifer, "Stratospheric Satellites for Earth Science Applications," COSPAR Panel on Scientific Balloons, November 2002.

## 9.2. Presentations

Below is a list of presentations made to various groups during Phase II. We do not repeat the list the presentations made to the conferences for which papers were published above.

K. Nock, “Global Constellations of Stratospheric Scientific Platforms,” Presentation to NASA Institute for Advanced Concepts (NIAC) 2nd Annual Meeting, 6 June 2000.

M. Heun, “Global Aerospace Corporation Technologies and Activities for Stratospheric Science,” Presentation to the Harvard University Atmospheric Research Program, 12 October 2000.

M. Heun and K. Nock, A New Approach to Lagrangian Atmospheric Research,” Presentation to the Harvard University Atmospheric Research Program, 9 November 2000.

K. Nock, “Global Stratospheric Balloon Constellations,” Briefing to NASA HQ Code Y, 5 January 2001.

K. Nock, et. al., “Global Constellations of Stratospheric Scientific Platforms,” Presentations at NASA Institute for Advanced Concepts Site Visit, 8 February 2001.

K. Nock, “Global Constellations of Stratospheric Scientific Platforms,” Presentation to the Working Group on Space-Based Lidar Winds, Oxnard, CA, 9 February 2001.

K. Nock and M. Heun, “Continuous Global In-Situ Radiation Measurements from 35 km,” Briefing to Don Anderson, NASA HQ Code Y radiation science programs, 19 March 2001.

K. Nock, “Global Constellations of Stratospheric Satellites,” Briefing to George Komar, NASA Earth Science Technology Office, 10 May 2001.

K. Nock, “Global Constellations of Stratospheric Satellites, Presentation to NASA Institute for Advanced Concepts (NIAC) 3rd Annual Meeting: Visions of the Future in Aeronautics and Space, June 2001.

K. Baker, “Stratospheric Satellites for Disaster Monitoring,” Presentation to the Global Disaster Information Network (GDIN) Meeting, Rome, IT, June 2002.

K. Nock, “Global Constellations of Stratospheric Satellites for Earth Science, Meteorology and Disaster Management,” National Reconnaissance Office Technology Seminar, 25 September 2002.

## 9.3. Press Releases and Stratospheric Satellites in the Press

### 9.3.1. Press Releases

| | |
|---|---|
| 19 March 2001: | Global Aerospace Corporation Developing Concept for Global Constellations of Stratospheric Balloons. |
| 3 July 2002: | Stratospheric Satellites: New Technology for Monitoring Global Disasters |

### 9.3.2. Stratospheric Satellites on the Internet

The following URLs discuss the StratCon concept.

http://www.beyond2000.com/news/Jul_02/story_1366.html

http://www.gisdevelopment.net/updates/news/news_15july2002a.htm

http://www.globaltechnoscan.com/18thJuly-24thJuly02/stratosphere_sattelites.htm

http://www.spacehike.com/sat18.html

http://biz.yahoo.com/bw/020703/30230_1.html

http://www.spacedaily.com/news/ballon-01a.html

# 10. Summary

Global Aerospace Corporation has developed the concept for global constellations of stratospheric scientific platforms. This work has involved extensive development of Earth science applications in several disciplines including Earth radiation balance, atmospheric chemistry, geomagnetism, meteorology, and hazard detection and monitoring. We have identified and defined specific proof-of-concept missions for many science applications. We studied in detail the issues of controlling single balloons and managing networks and constellations of balloons, including options for obtaining global coverage, analysis of wind fields, and the identification of atmospheric flow features (i.e. vortices). Much of this constellation control work comprises "never-been-done-before" analyses and simulations that are interesting and exciting to watch. We have also developed new frameworks for constellation management including animal group behavior, artificial potentials, and weak stability boundary techniques. Many network simulations have been created including surface zone avoidance, polar atmospheric chemistry, overflight by single balloons and of networks of balloons over moving and stationary targets, and adaptive sampling with simple and sophisticated control algorithms. An advanced trajectory control system concept has been developed and modeled. Problems of flight termination over population zones have been addressed, and the required systems to mitigate safety issues have been researched. International overflight and airspace issues have been researched and pathways developed for global operation of stratospheric balloon platforms. We have had extensive interaction with program managers and scientists in government and academia as the concept has evolved. Our list of publications and presentations is evidence of a high level of interaction with other experts in the field. Finally, we have experienced a relatively high level of interest from the press for this concept.

As a result of the NIAC-funded study effort, NASA management is now taking very seriously the use of stratospheric platforms for helping to answer some of the key Earth science questions. In February 2002, NASA began funding a major study of revolutionary stratospheric platforms for carrying out important Earth science objectives. Global Aerospace Corporation continues to seek opportunities for follow on study efforts, prototype flights of instruments and StratoSat™ systems, and proof-of-concept experiments that will eventually help to make this concept a reality.

# Appendix 1: NRO Technology Seminar

NIAC
NASA Institute for Advanced Concepts

# Global Constellations of Stratospheric Satellites for Earth Science, Meteorology and Disaster Management

## Presentation to the NRO Technology Seminar

by

Kerry T. Nock, President
Global Aerospace Corporation
Altadena, CA
626-345-1200
http://www.gaerospace.com

September 25, 2002

Global Aerospace Corporation

# TOPICS

- Constellation Concept
- Earth Science, Meteorology and Disaster Management
- StratoSat™ Systems
- Constellation Control & Simulations
- International Overflight Issues
- Costs
- Other Applications
- Summary

# CONSTELLATIONS OF STRATOSPHERIC SATELLITES

# CONCEPT

- Tens to hundreds of small, long-life (3-10 years) stratospheric balloons or *StratoSat™ Platforms*
- Uniform global and regional constellations maintained by trajectory control systems (TCS)
- Flight altitudes of 35 km (above controlled airspace) achievable with advanced, lightweight, superpressure balloon technology

# BENEFITS

- Provide low-cost, continuous, simultaneous, global and regional earth observations
- Provides *in situ* and remote sensing from very low earth "orbit"

Global Aerospace Corporation

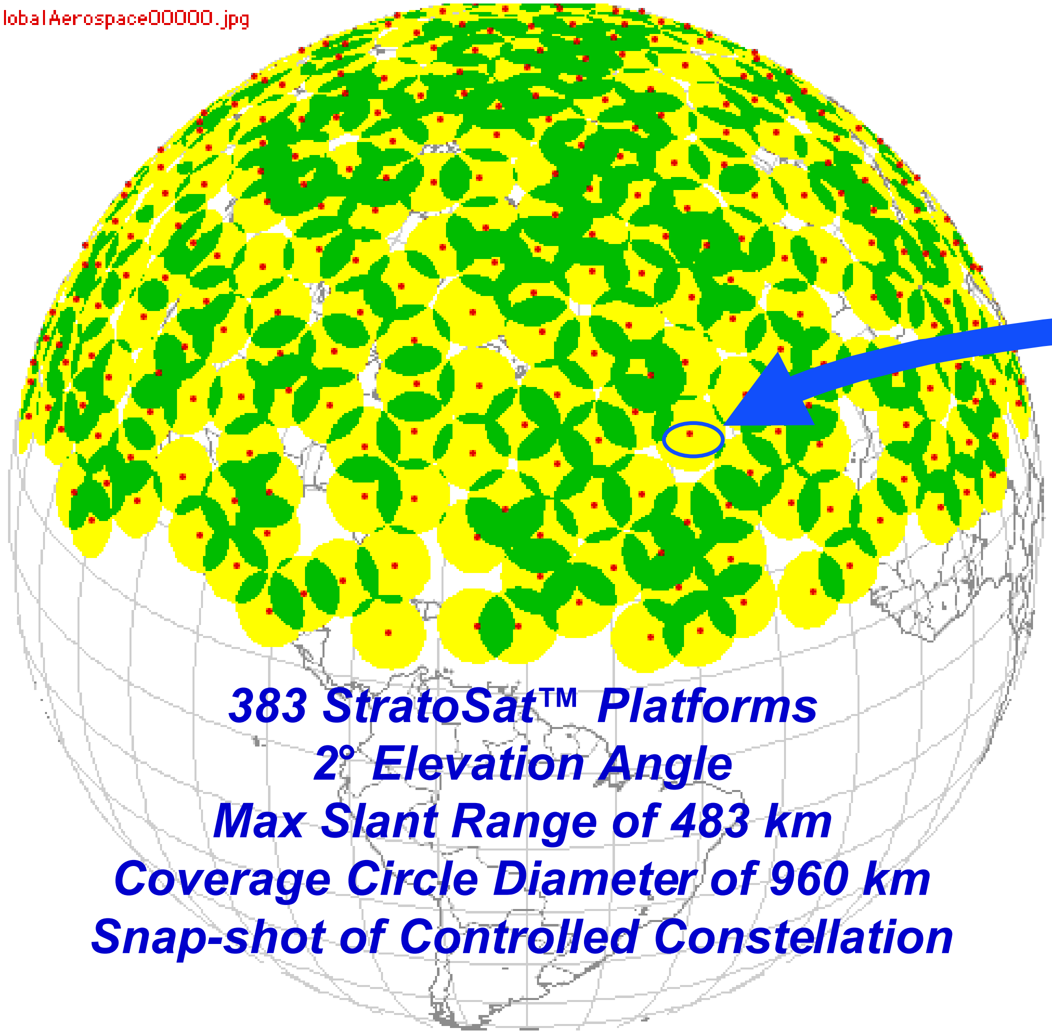
Global Constellations of Stratospheric Satellites

# CONCEPT SCHEMATIC

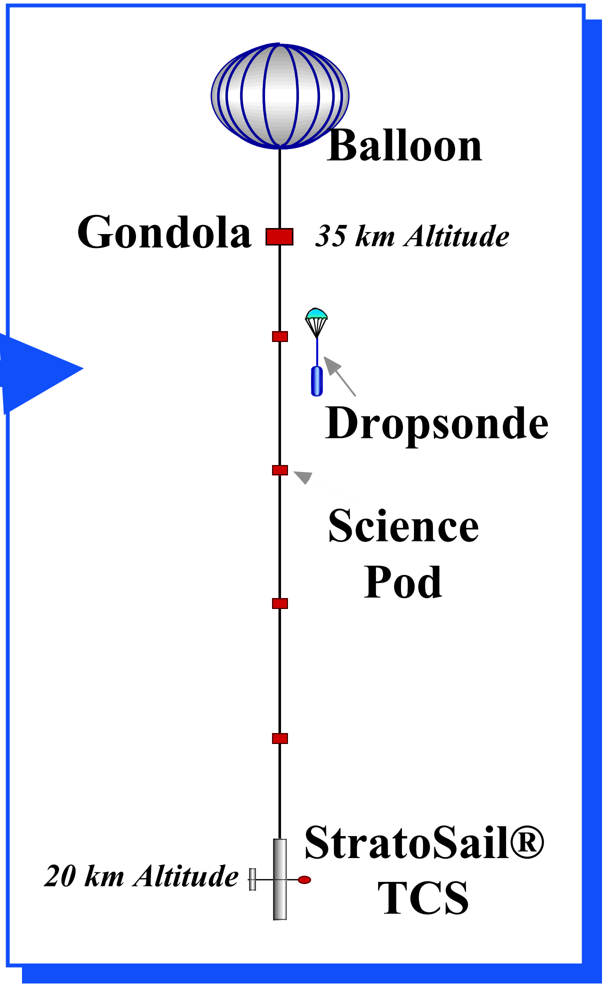
## Northern Hemisphere Constellation

## StratoSat™ System

GlobalAerospace00000.jpg



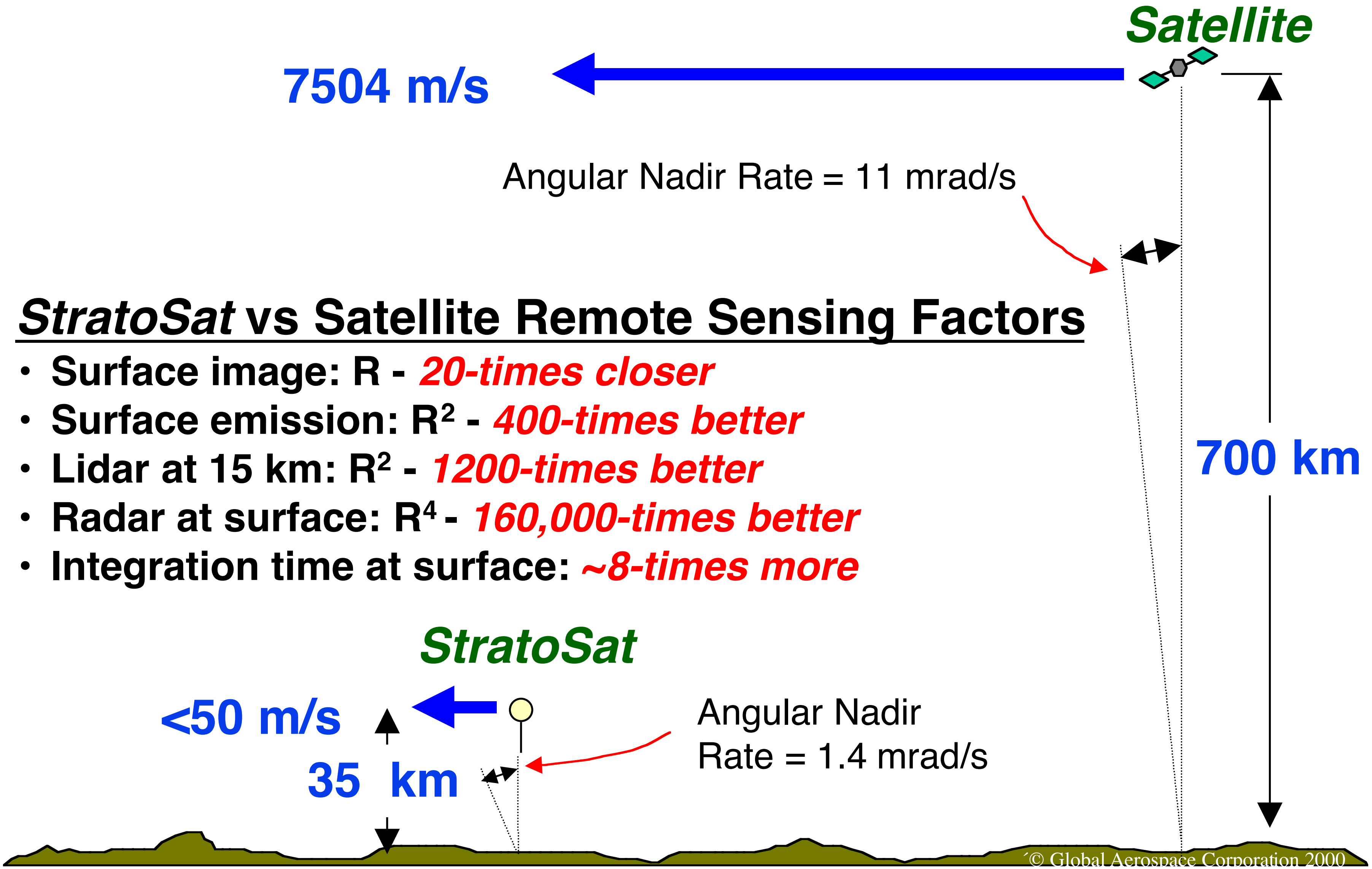
*383 StratoSat™ Platforms*
*2° Elevation Angle*
*Max Slant Range of 483 km*
*Coverage Circle Diameter of 960 km*
*Snap-shot of Controlled Constellation*



# BENEFITS OF GLOBAL STRATOSPHERIC PLATFORMS

- Good diurnal coverage of entire globe
- Low altitude observations that can improve resolution and/or signal-to-noise ratios of measurements
- Provide frequent to continuous measurements
- Long dwell time (hours-days) over science targets
- Targeted dropsonde package delivery opportunities
- Extended duration and low-cost potentially provide a cost-effective method for earth science and/or satellite calibration and validation

# REMOTE SENSING



## *StratoSat* vs Satellite Remote Sensing Factors

- **Surface image: R - *20-times closer***
- **Surface emission: R$^2$ - *400-times better***
- **Lidar at 15 km: R$^2$ - *1200-times better***
- **Radar at surface: R$^4$ - *160,000-times better***
- **Integration time at surface: *~8-times more***

# Applications

# PROMISING THEMES

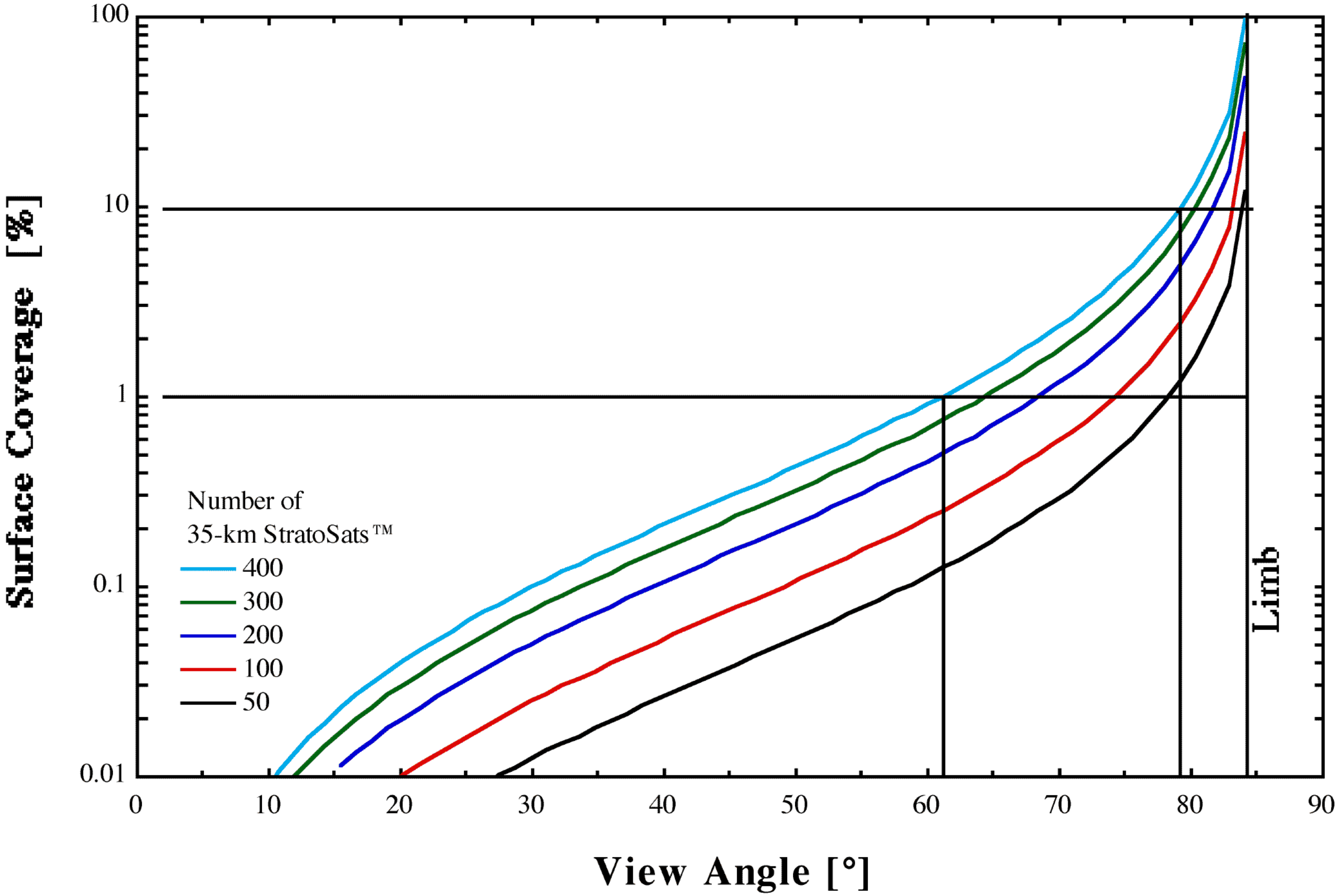
- **Earth science**
  - Climate change studies (global radiation balance, water vapor & circulation in tropics, and radiative studies
  - Atmospheric chemistry including ozone loss and distribution studies
  - Geomagnetism and the nature of crustal boundary
- **Meteorology**
  - Hurricane forecasting and tracking
  - Tropospheric winds
  - Adaptive sampling for forecasting weather from ocean basins & remote areas
- **Disaster management**
  - Hazard detection and monitoring
  - Global disaster information network (GDIN)

# EARTH RADIATION BALANCE (ERB)

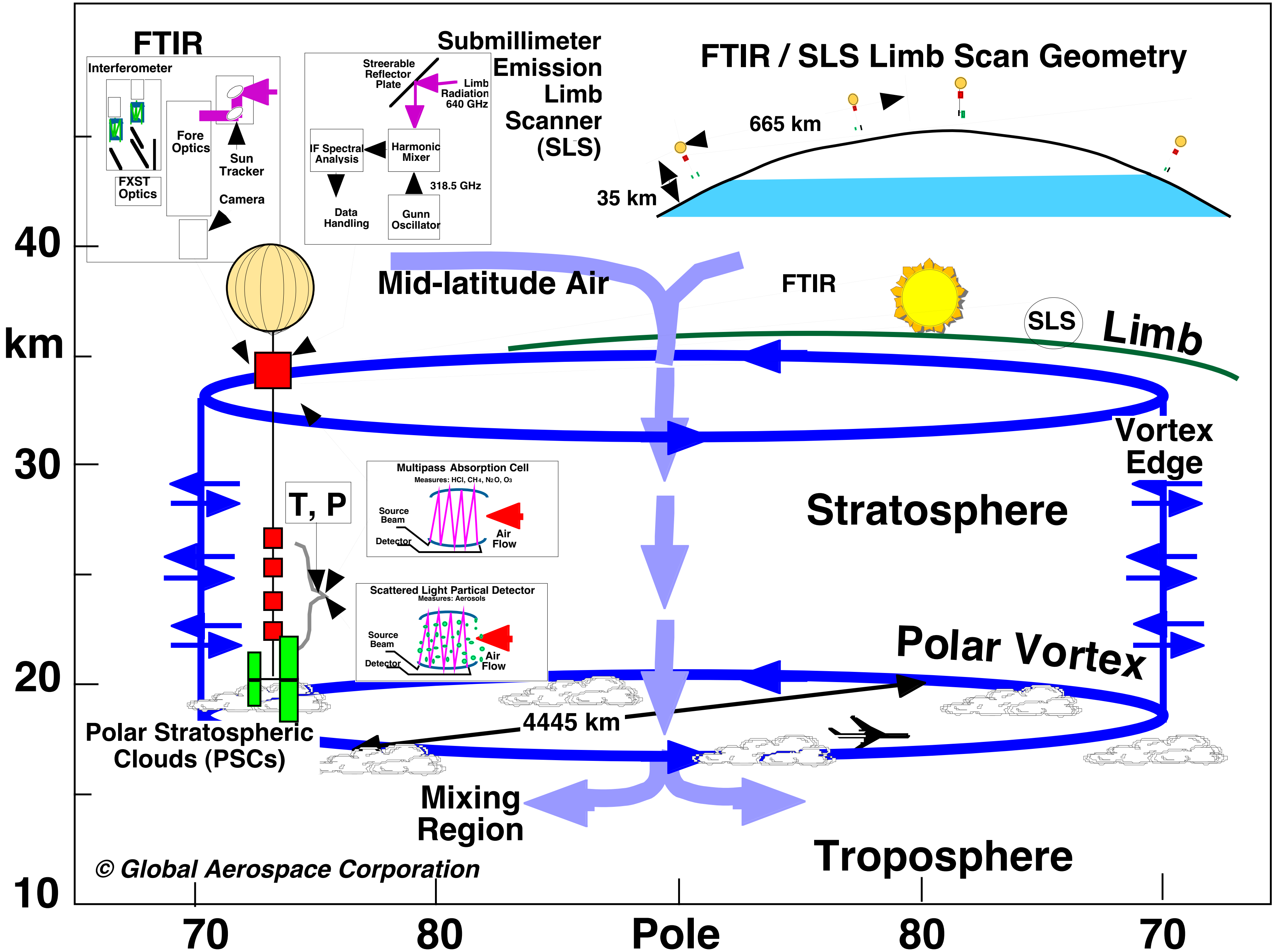
- Fluxes at TOA (Top Of Atmosphere) are primary drivers for climate
- Flux is a weighted integral of radiance over angle
- Space satellites measure radiance, not flux
- Thus, after 40 yr of retrieving these fluxes from single space satellites or small constellations, major uncertainties remain
- Dynamics of TOA flux (hourly and daily synoptic variation) are unknown
- 100 platforms around the globe could measure flux directly and provide dynamics that have never been seen

*Global Constellations of Stratospheric Satellites*

# ERB COVERAGE



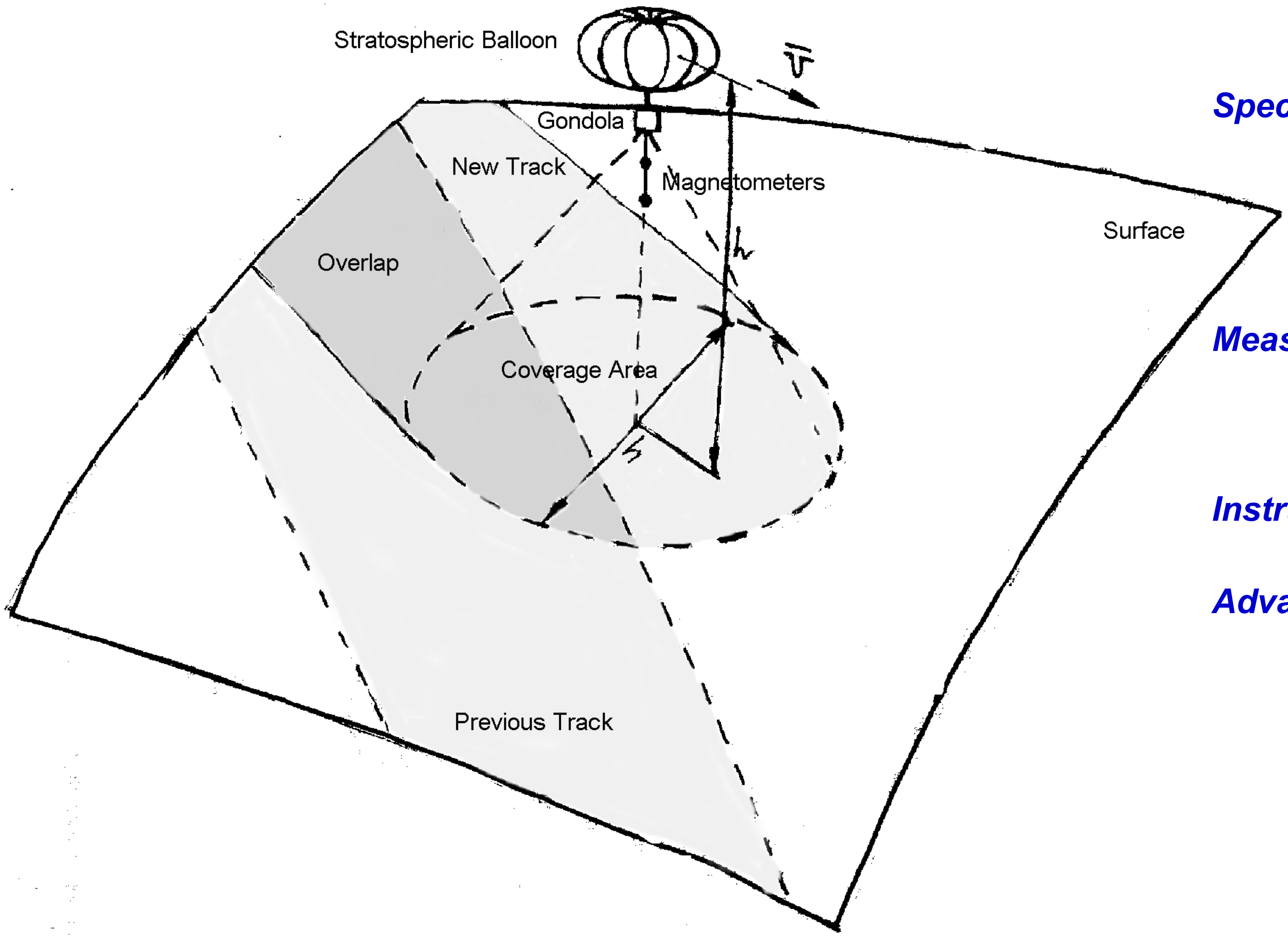
# OZONE STUDIES: POLAR OZONE LOSS



# GEOMAGNETIC FIELD MEASUREMENTS

- **Non-uniform distribution of existing, land-based observatories**
- **Stratospheric platforms could augment geomagnetic observatories and provide data over oceans**
- **Accurate data needed for aero-magnetic mineral and petroleum exploration**
- **Potential for gaining new understanding of Earth's crust**

# MAGNETIC FIELD EXPERIMENT



## *Specific Question*

What are the dynamics of the magnetic (and gravity) fields at regional geological scales, and what process drive the variations?

## *Measurements*

- Magnetic field gradient
- Close or overlapping trajectories add value

## *Instrument*

- Tethered magnetometers

## *Advantages*

- Cover oceans and remote areas
- Increased range
- Eliminate ionospheric noise

# HURRICANE PREDICTION

- **More accurate prediction of a hurricane track and its intensity can avoid economic disruption and save lives**
- **Current data sources include satellites, buoys, and crewed aircraft are limited in resolution, frequency and quality.**
- **More high quality, high resolution *in situ* data is needed**
- **For example, more accurate wind data is needed**
  - **The winds in the vicinity of the hurricane are important for predicting the hurricane's path**
  - **The winds and precipitation inside the hurricane are important to estimating its eventual intensity**

# EXAMPLE HURRICANE NETWORK

- **20 StratoSat™ Platforms, ~$5-10M**
- **Measurements**
  - **Dropsondes**
  - **Wind Lidar**
  - **Sea-state**
  - **Precipitation Radar**
  - **Imager**
- **Economics**
  - **Goal to reduce landfall uncertainty by 50%**
  - **Save ~$150M per landfall**

*Global Constellations of Stratospheric Satellites*

# DISASTER MANAGEMENT PROBLEMS & NEW TECHNOLOGY SOLUTIONS

| PROBLEM | SOLUTION |
|---|---|
| Space-based satellites cannot be positioned over target disaster areas | StratoSat™ Platforms include steering components to provide near constant coverage of disaster areas |
| Higher resolution than space-based data may be required for successful disaster monitoring | StratoSat™ Platforms based in the stratosphere can provide spatial resolution imagery 20 times higher than space-based satellite imagery, and improved remote sensing and in-situ data |
| Current observing systems (like satellites and aircraft) are expensive | A single StratoSat™ platform demonstration for GDIN will cost \$1.5-2M. A 100 balloon network is estimated to cost \$55-65M, including development |

# StratoSat™ Platform Systems

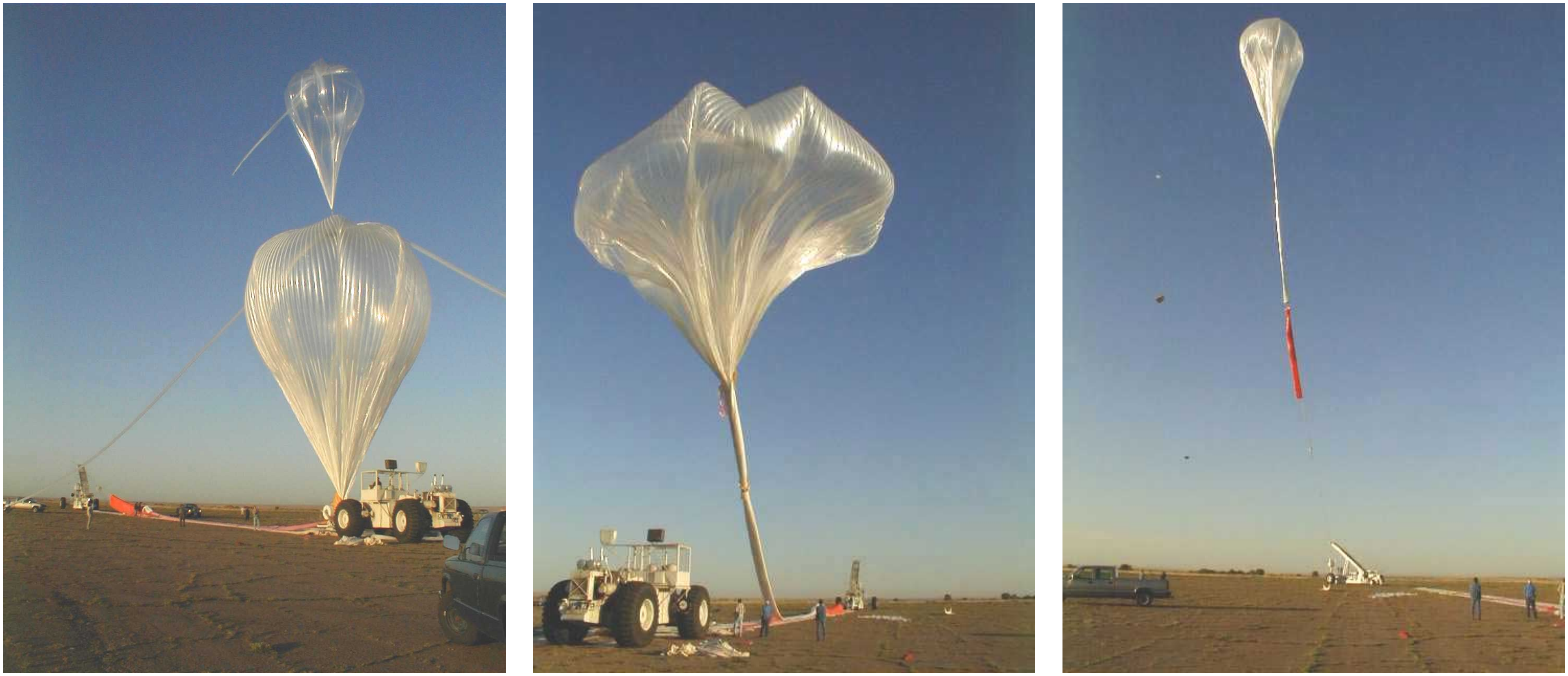
# Balloon Envelope

# NASA ULTRA LONG DURATION BALLOON (ULDB)

- Euler Elastica "Pumpkin" Envelope Design
- Lobbed Gores to Reduce Transverse Envelope Stress
- Very High Strength Zylon® Load-bearing Tendons Along Seams to Take Longitudinal Stress
- Advanced Lightweight, Medium Strength Films to Reduce Balloon Mass and Size
- Design goal of ~2,000 kg payloads

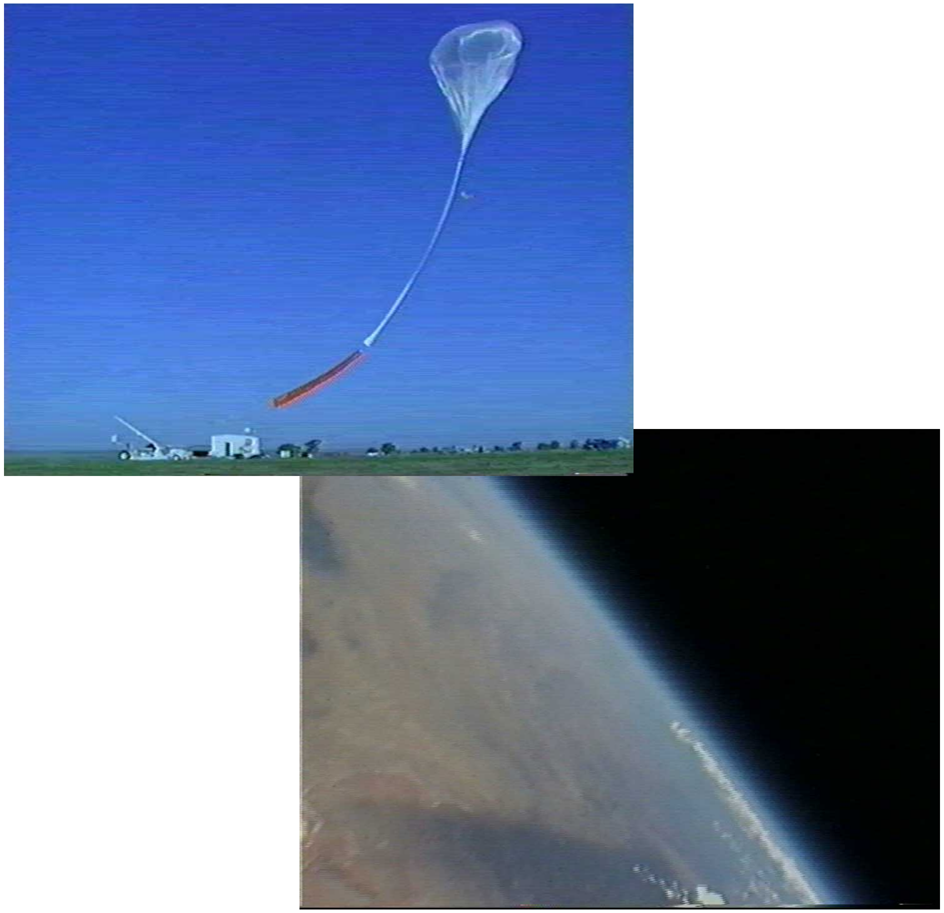
*NASA ULDB*
*Scale Model Tests*

# NASA ULDB FLIGHT TEST



# ULDB TEST FLIGHT VIDEO

- **June 2000 test video courtesy of NASA**
- **Sequence displayed:**
  - launch prep
  - Launch
  - Ascent
  - View of horizon from 85,000 ft
  - Planned termination viewed from inside balloon



# ADVANCED SMALL ULTRA LONG DURATION BALLOON (ULDB) DESIGN

- Euler Elastica Pumpkin Design
- Volume ~ 70,000 $m^3$
- Advanced Composite Film, 15 $g/m^2$
- 140 Gores ~1.3 m Wide
- 3-10 year life
- Balloon Mass ~ 250 kg
- Suspended Payload Mass ~ 220 kg

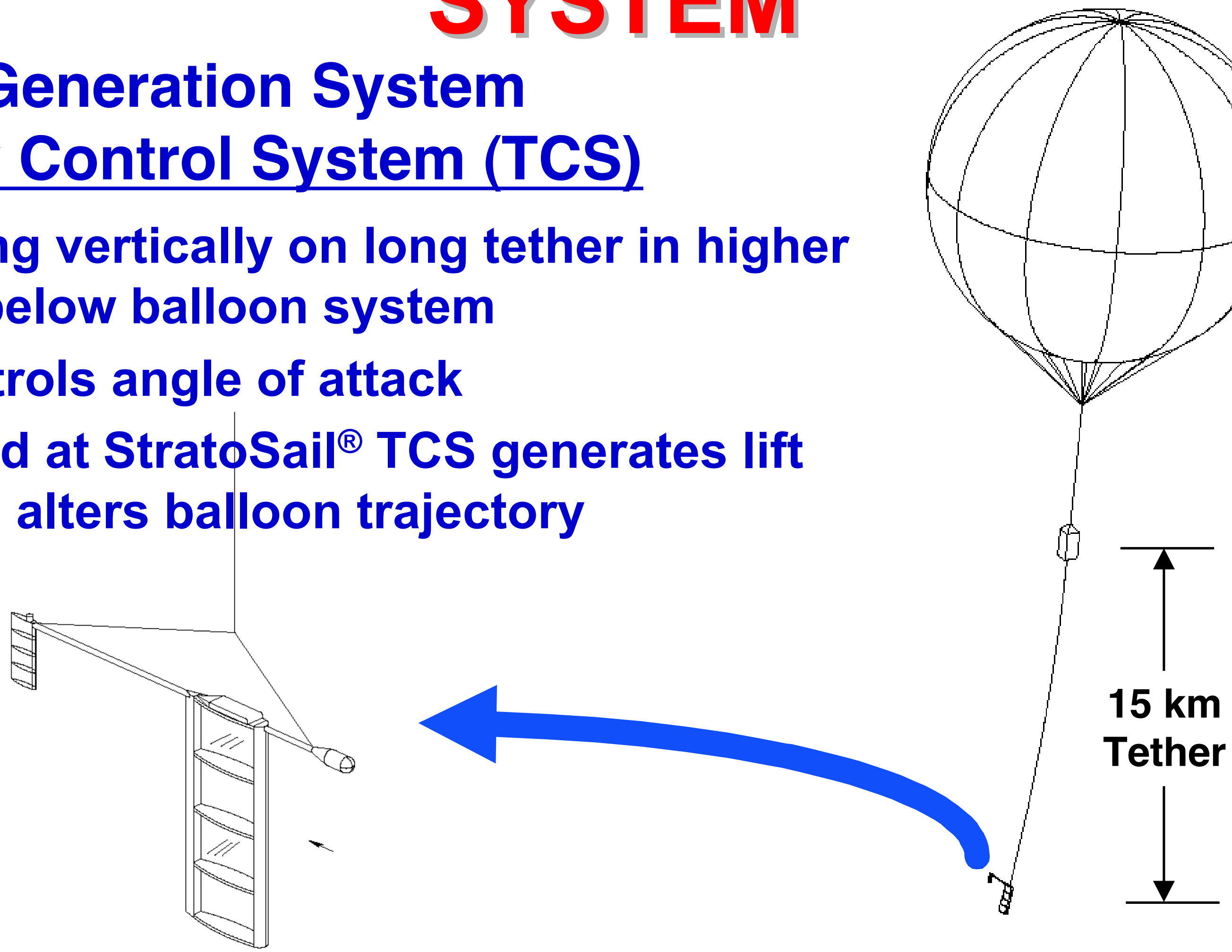
# Flight Path Control

# STRATOSAIL® BALLOON TRAJECTORY CONTROL SYSTEM

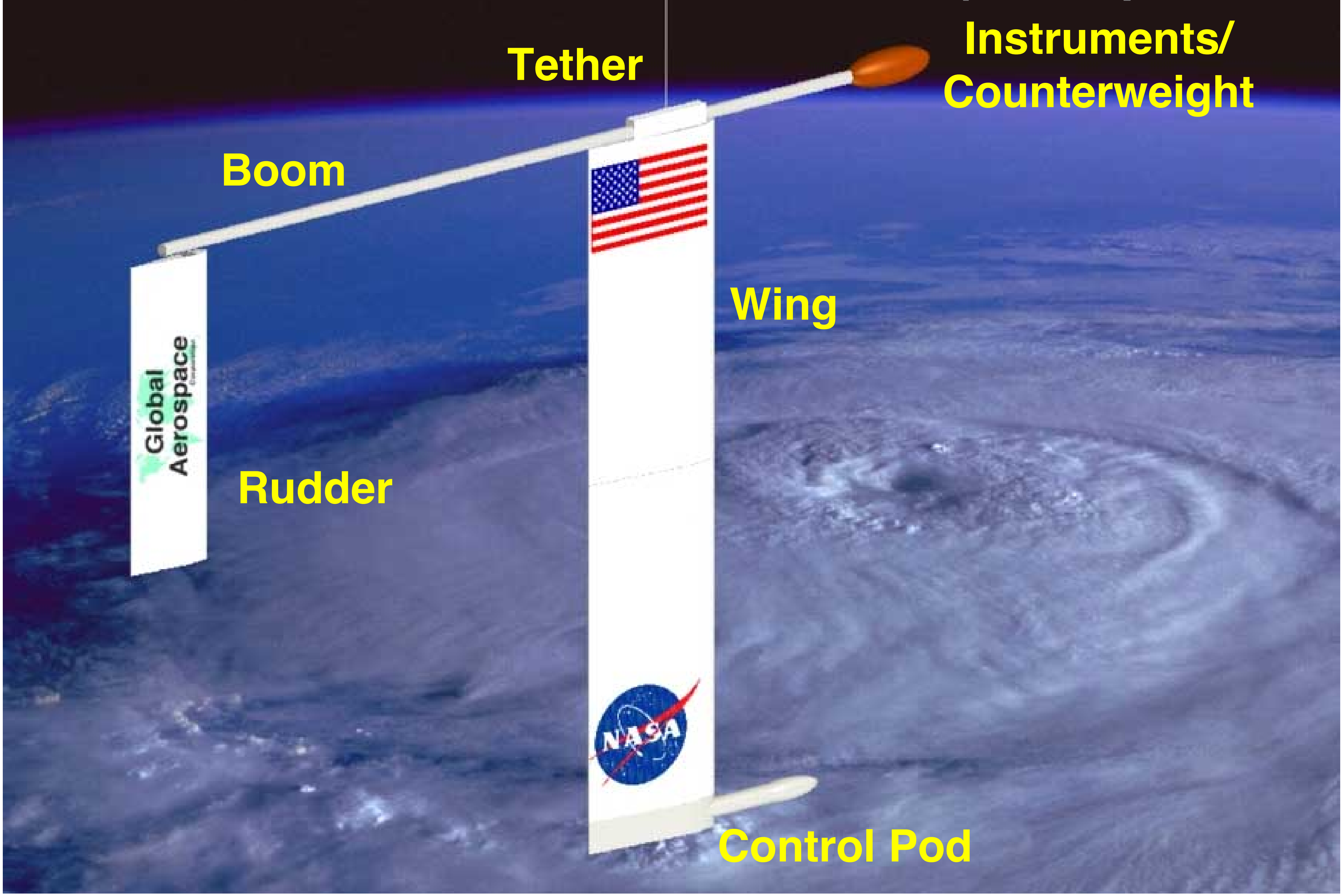
## First Generation System

## <u>Trajectory Control System (TCS)</u>

- **Wing hanging vertically on long tether in higher density air below balloon system**
- **Rudder controls angle of attack**
- **Relative wind at StratoSail® TCS generates lift force, which alters balloon trajectory**



# TCS WING ASSEMBLY (TWA)

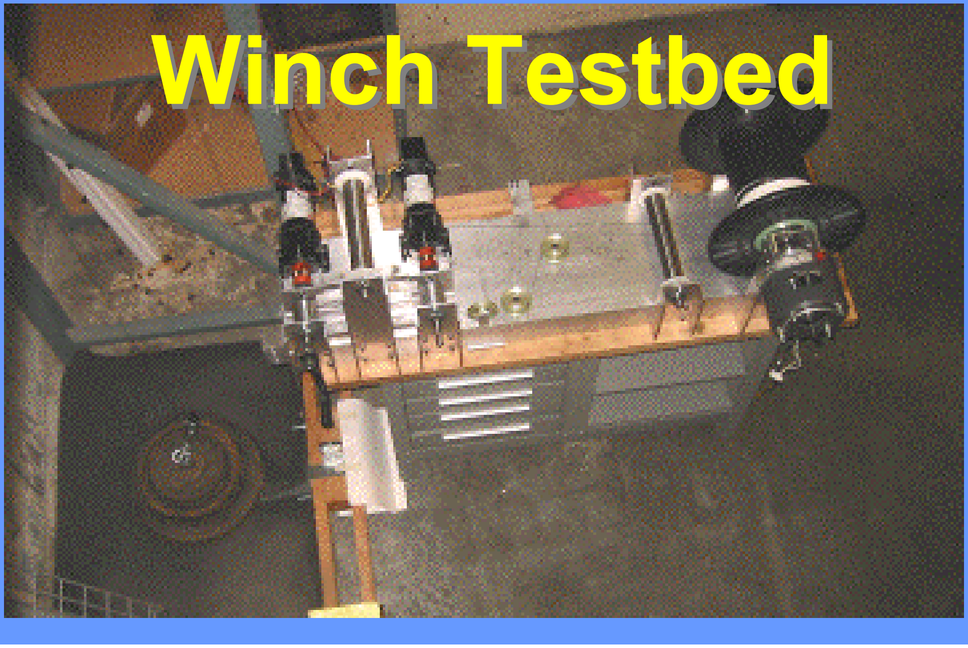


# BENEFITS OF TRAJECTORY CONTROL

- **Improved science return**
  - Access and maintain desired latitudes
  - Longer flight times
- **Enhanced safety and operations flexibility**
  - Launch opportunities less constrained with season
  - Avoid population centers to keep causality estimate (CE) low
  - Targeted landing sites
  - Greater landing site selection flexibility
  - Easier, more reliable payload recovery
- **Manage geopolitical overflight**
  - Avoid uncooperative countries
  - Reduce likelihood of premature cut-down
- **Avoid large weather systems**
- **Enable balloon formations and networks**

# STRATOSAIL® TCS ROLL OUT
## March 16, 2002

Wing Assembly

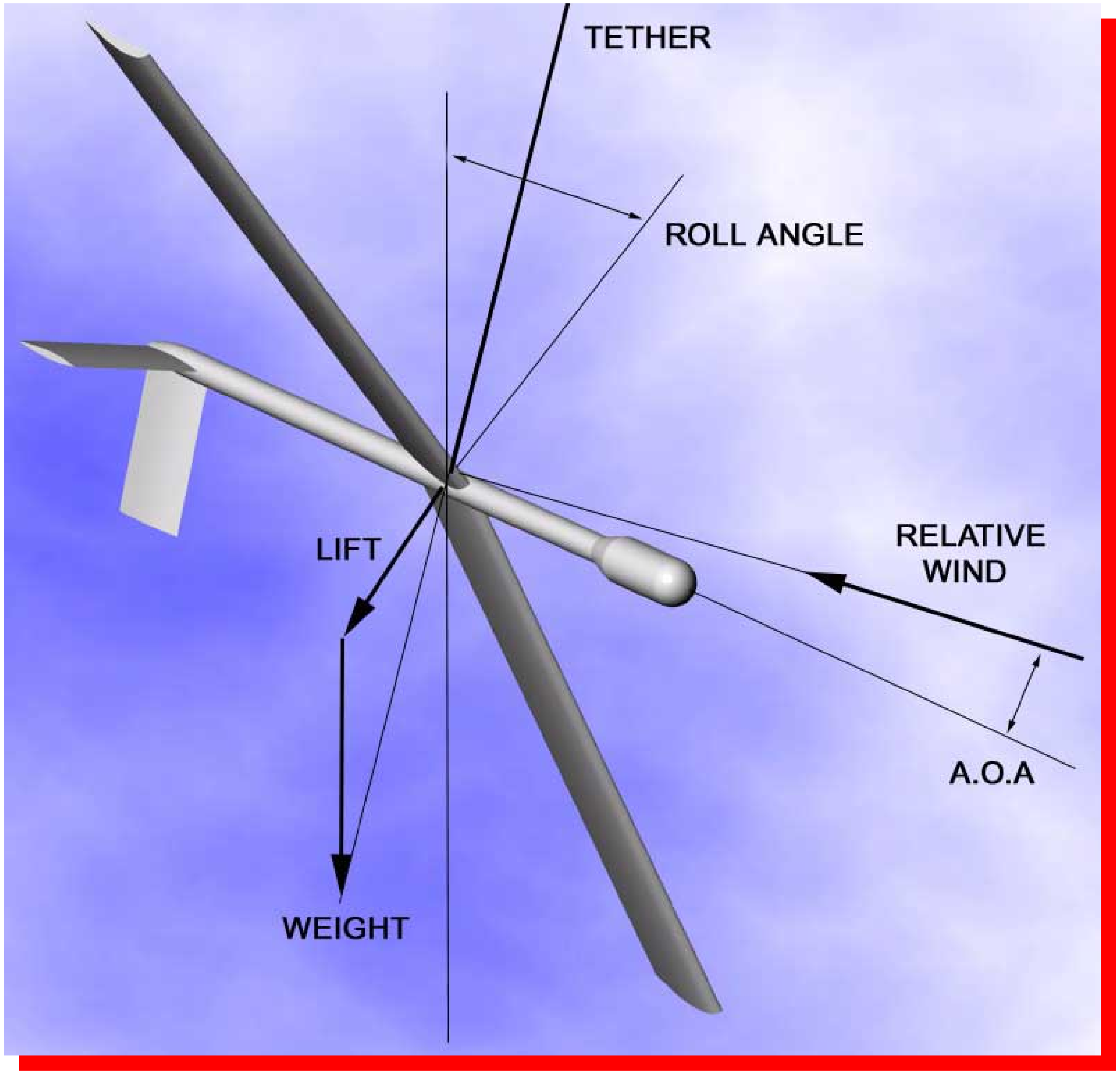


Winch Testbed

# ADVANCED TCS CONCEPT

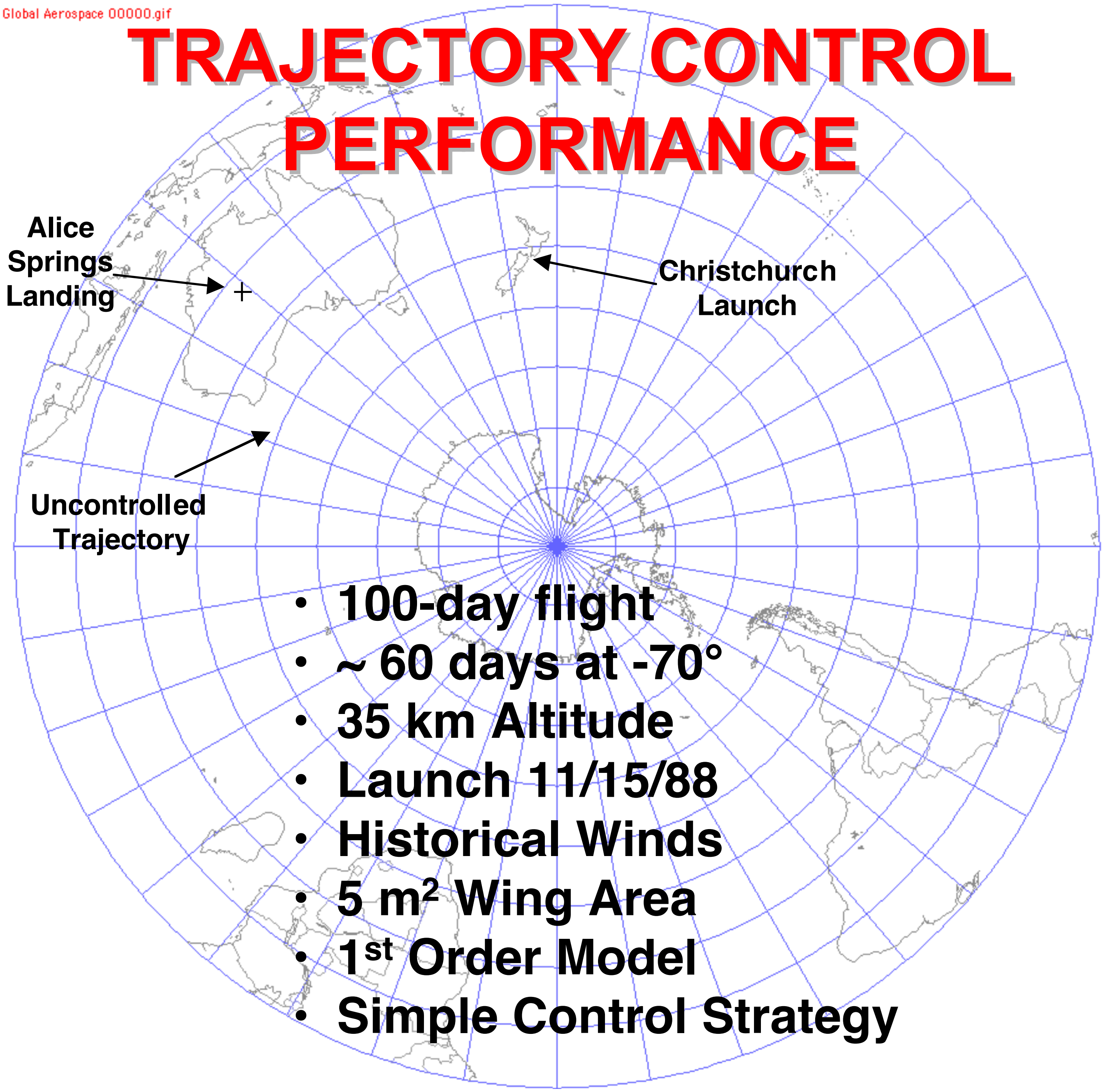
## Advanced StratoSail® TCS Design Features

- Lift force can be greater than weight
- Will stay down in denser air
- Less roll response in gusts
- Employs high lift cambered airfoil
- Greater operational flexibility
- Possible Dynamic Power Generation



# Stratospheric Satellite Flight Path Guidance, Formation Flying and Constellation Control

# TRAJECTORY CONTROL PERFORMANCE



Alice Springs Landing

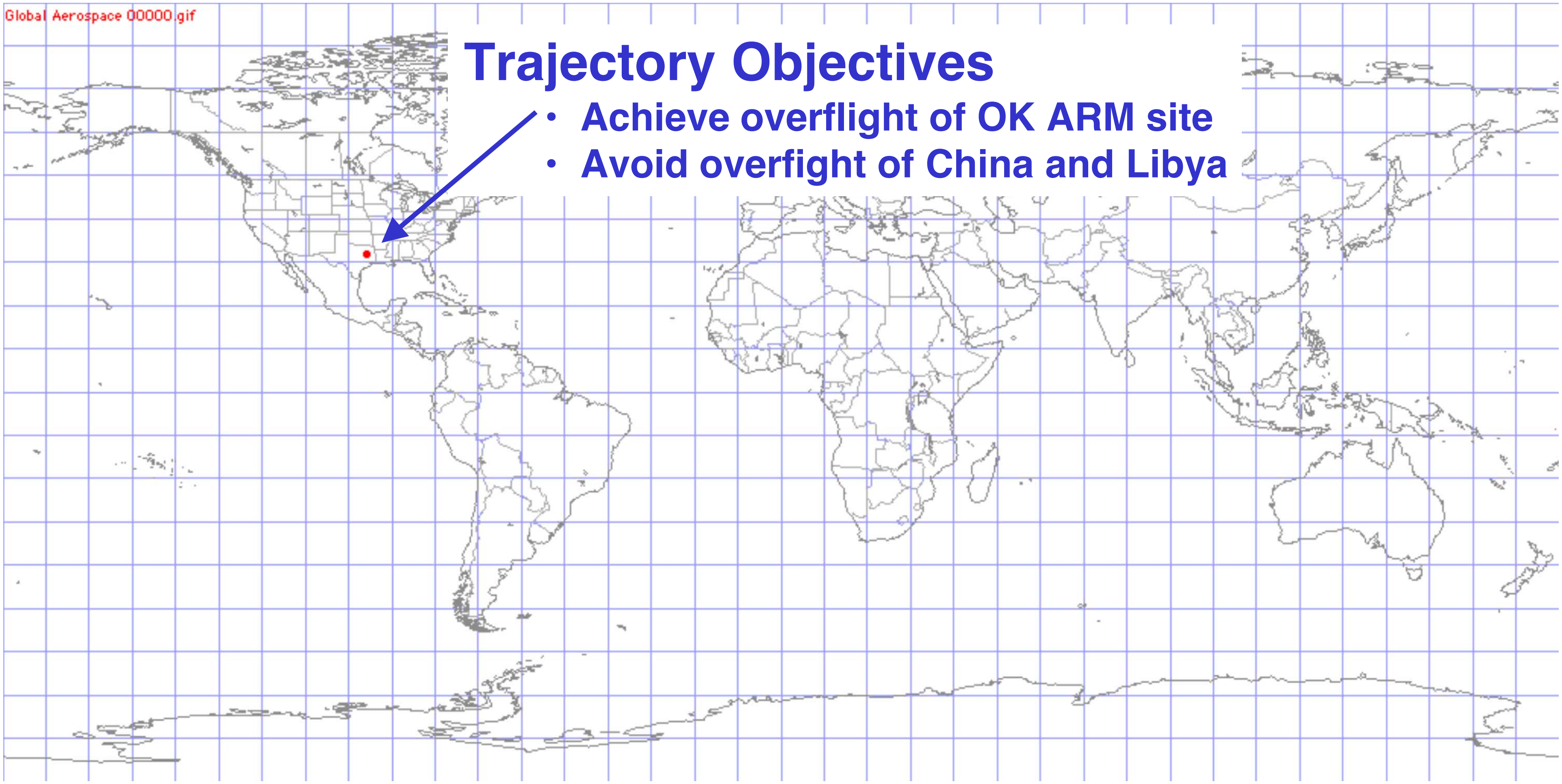
Christchurch Launch

Uncontrolled Trajectory

- 100-day flight
- ~ 60 days at -70°
- 35 km Altitude
- Launch 11/15/88
- Historical Winds
- 5 m$^2$ Wing Area
- 1st Order Model
- Simple Control Strategy

*Global Constellations of Stratospheric Satellites*

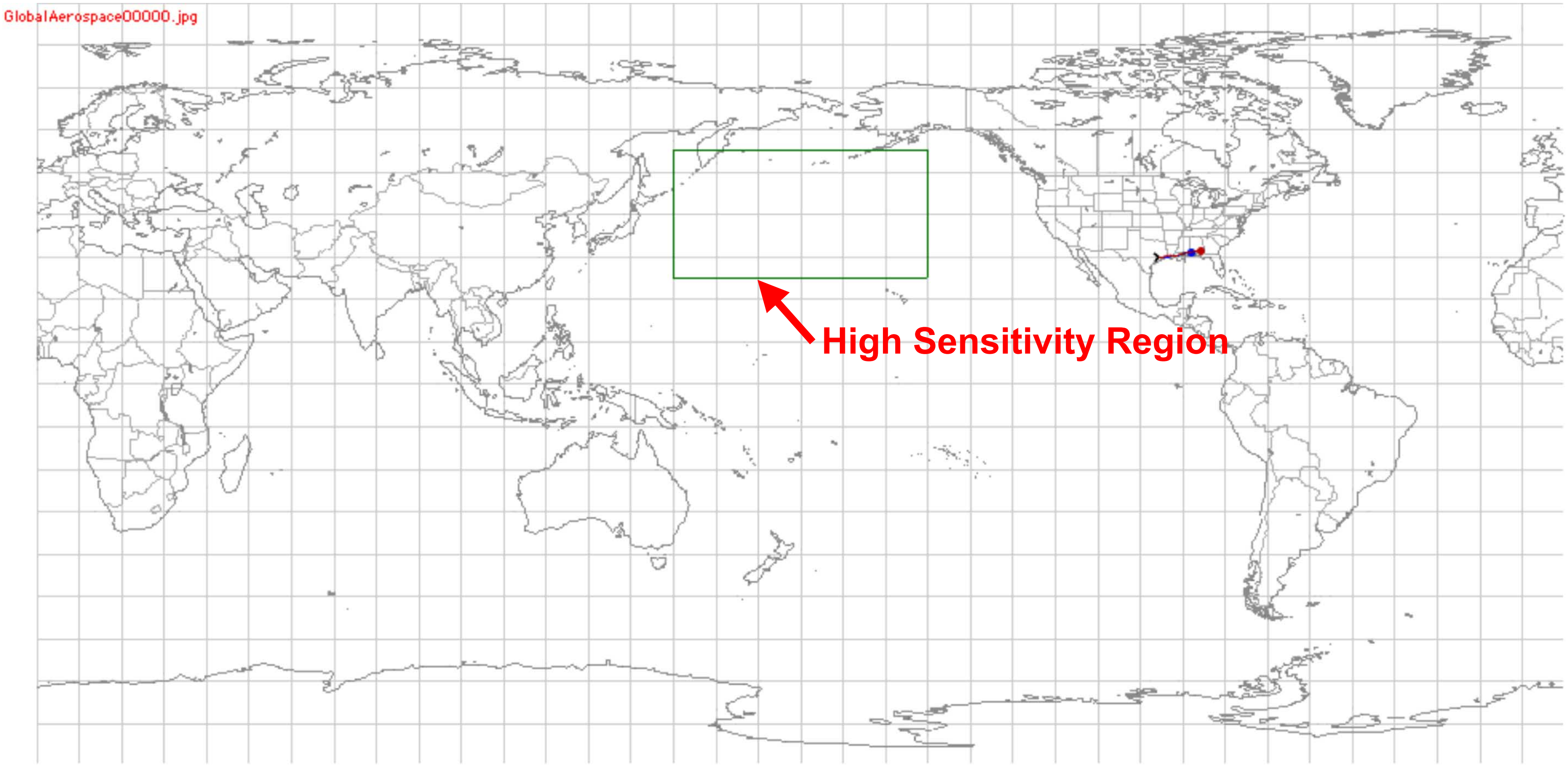
# STRATOSAT™ SYSTEM OVERFLIGHT SIMULATION



## Trajectory Objectives

- Achieve overflight of OK ARM site
- Avoid overfight of China and Libya

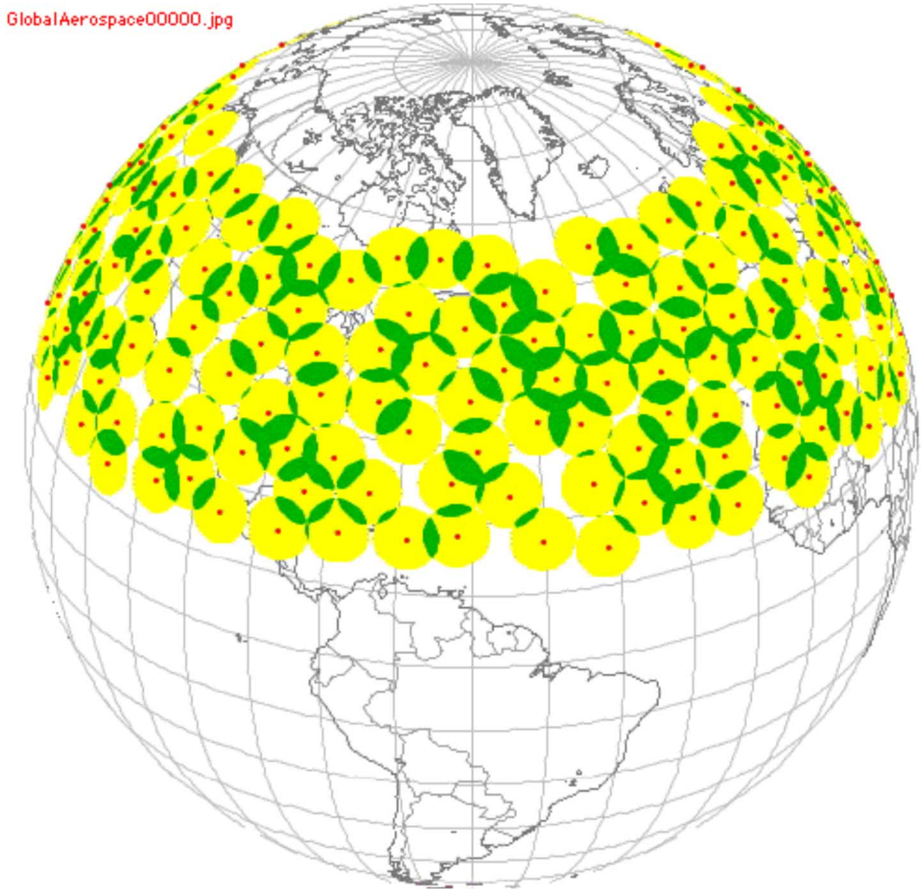
# ADAPTIVE SAMPLING EXAMPLE



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

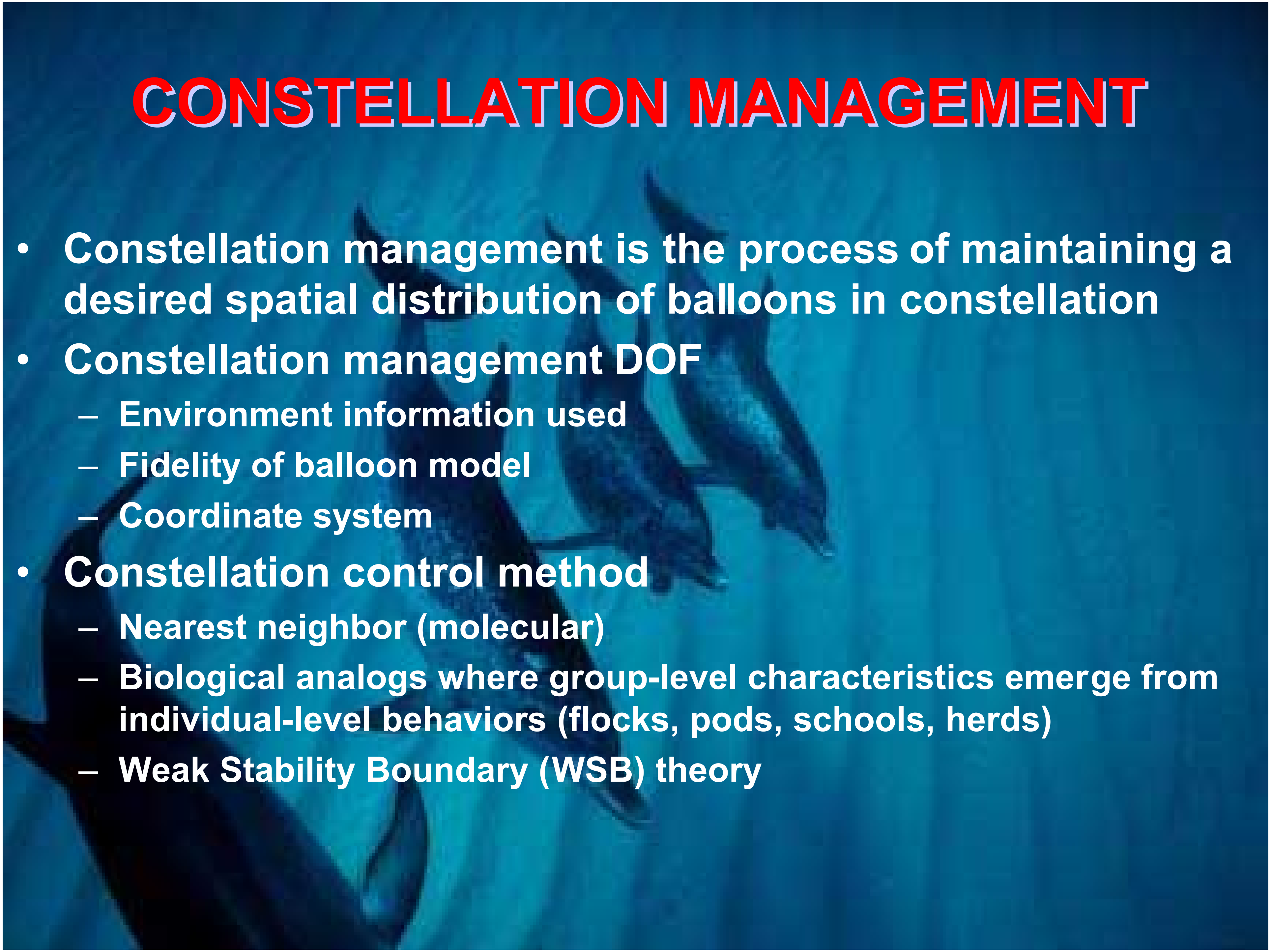
# THE NEED FOR GLOBAL CONSTELLATION MANAGEMENT

## Uncontrolled Constellation



- Constellation Assumptions
  - ~200 StratoSat platforms, >15° latitude <60°
  - Gondola altitude @ 35 ± 1 km
  - NO CONTROL
  - ~395 days (start 1 June 2000)
- Legend
  - Red - StratoSat platform locations
  - Yellow - 2° elevation
  - Green - overlaps
- 1 hr/frame, 48 frames/sec, 173,000x faster than reality
- UKMO weather data

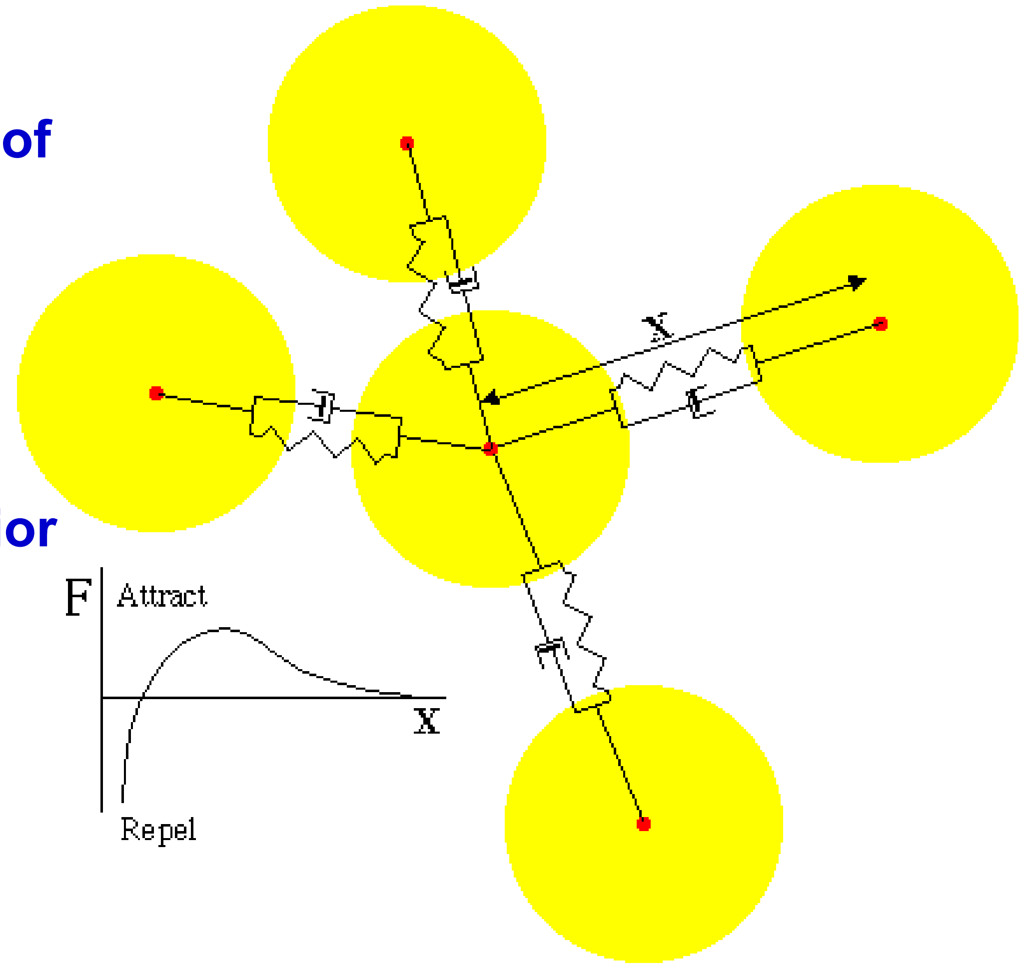
# CONSTELLATION MANAGEMENT



- Constellation management is the process of maintaining a desired spatial distribution of balloons in constellation
- Constellation management DOF
  - Environment information used
  - Fidelity of balloon model
  - Coordinate system
- Constellation control method
  - Nearest neighbor (molecular)
  - Biological analogs where group-level characteristics emerge from individual-level behaviors (flocks, pods, schools, herds)
  - Weak Stability Boundary (WSB) theory

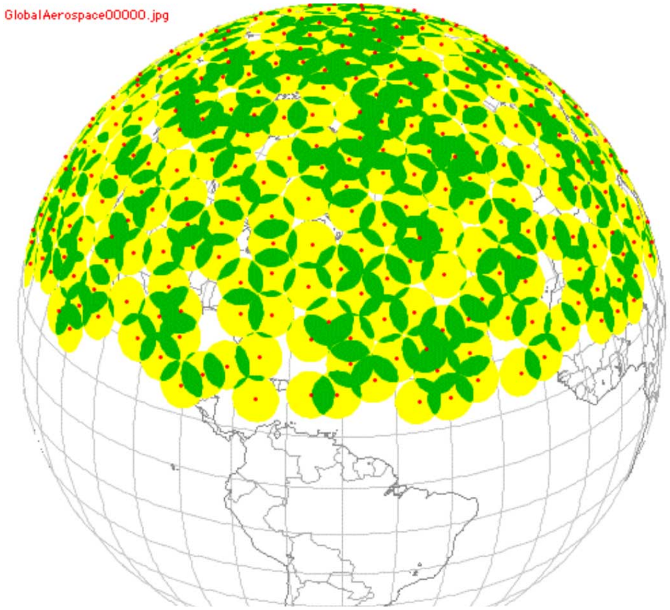
# ARTIFICIAL POTENTIALS (APs)

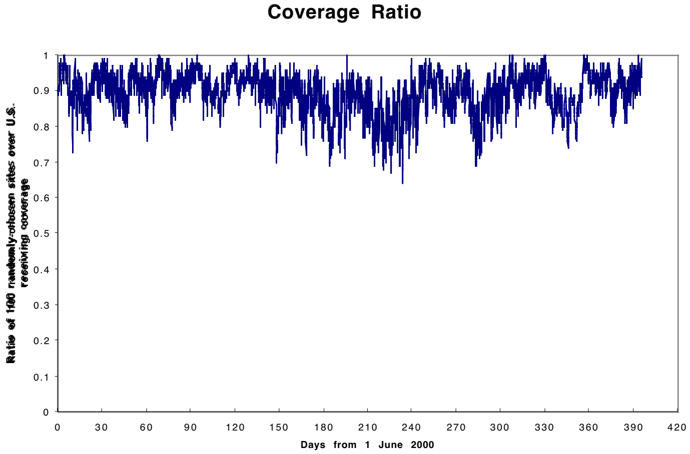
- **Control derived from a gradient of artificial potentials**
- **Model local "traffic rules"**
  - **Attraction**
  - **Repulsion**
- **Potentials and virtual members produce emergent group behavior**
  - **Manipulate group geometry**
  - **Direct group motion**
- **Useful for stability/robustness proofs**



# EXAMPLE HEMISPHERICAL CONSTELLATION MANAGEMENT

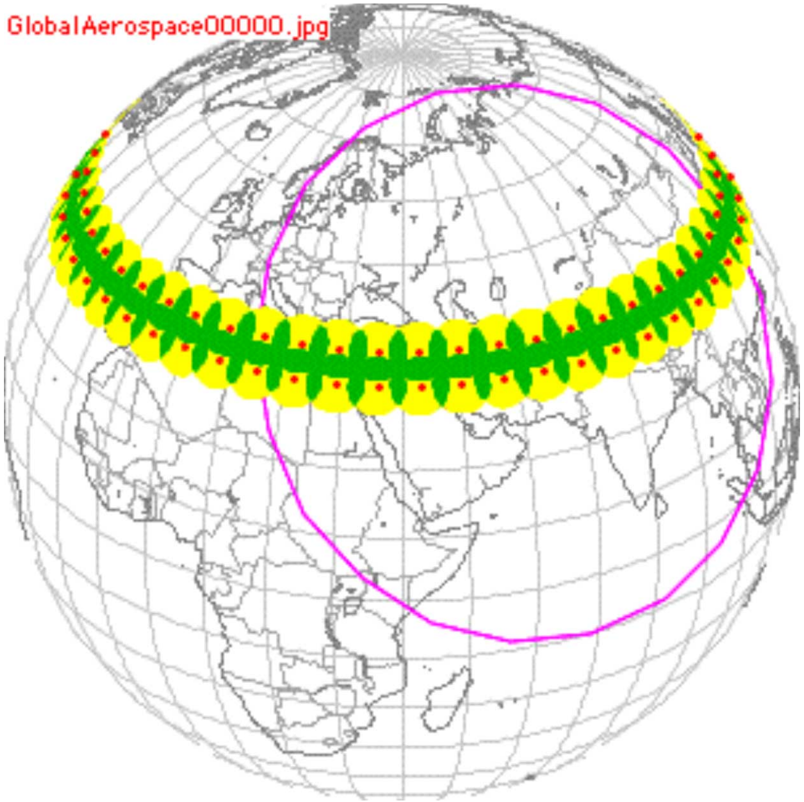
- **Constellation**
  - **383 StratoSat platforms, >15° latitude**
  - **Gondola altitude @ 35 ± 1 km**
  - **StratoSail® Trajectory Control System (TCS) @ 20 km altitude**
  - **Artificial Potentials control algorithm**
  - **~395 days (start 1 June 2000)**
- **Legend**
  - **Red - StratoSat platform locations**
  - **Yellow - 2° elevation**
  - **Green - overlaps**
- **1 hr/frame, 48 frames/sec, 173,000x faster than reality**
- **UKMO weather data**
- **Control Model**
  - **Bounded and under-actuated control system**
  - **$\Delta V$ proportional to relative wind velocity, $V_{rel}$, at 20 km**
  - **Feasible, limited control directions with respect to $V_{rel}$**



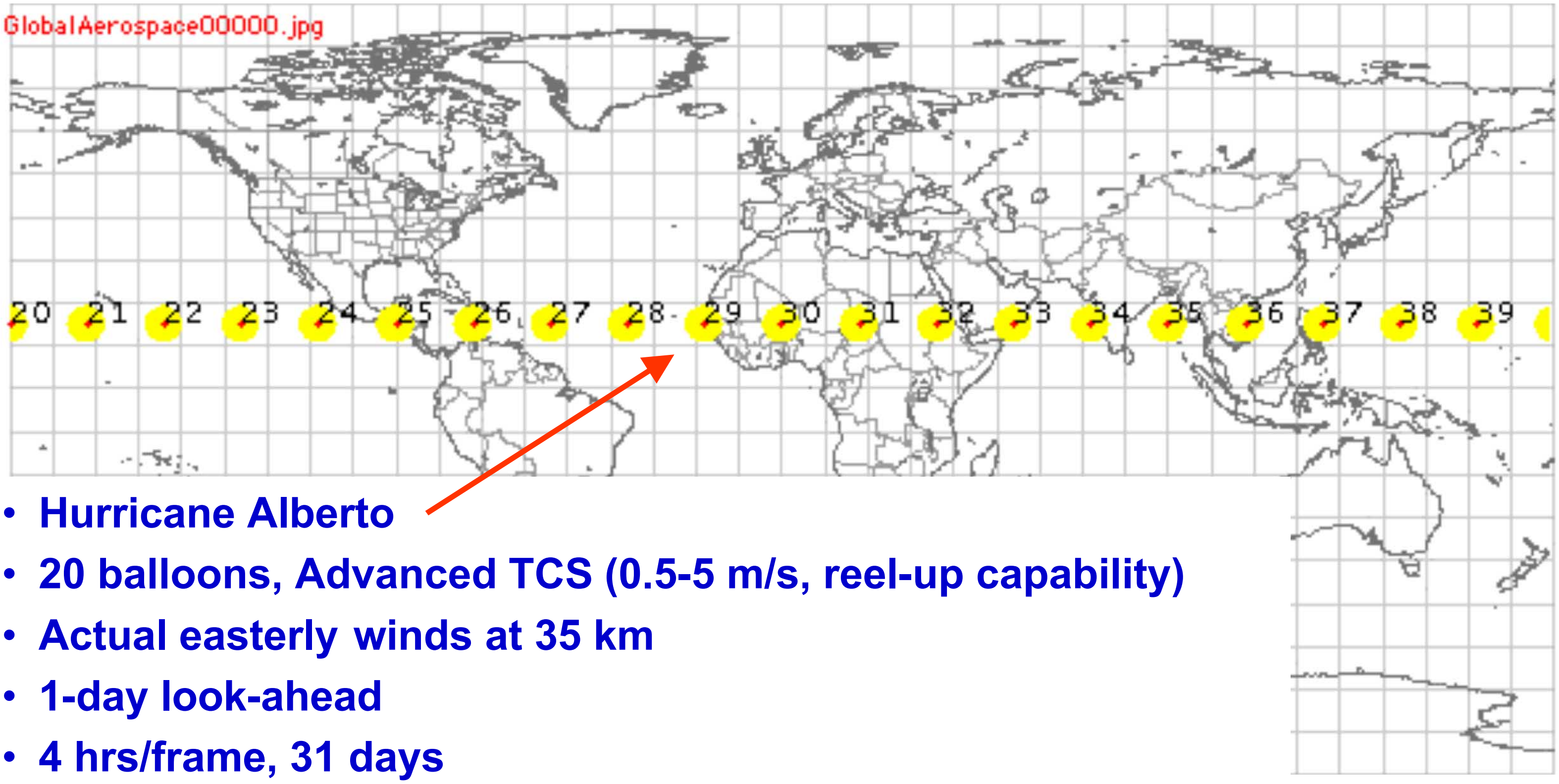


# SURFACE TARGET TRACKING

- **Constellation**
  - **100 StratoSat platforms, Overfly 34.5° N latitude and 69.2° E longitude**
  - **Gondola altitude @ 35 ± 1 km**
  - **StratoSail® Trajectory Control System (TCS) @ 20 km altitude**
  - **Multiple prioritized objectives: maintain latitude, equal spacing, overfly target**
  - **15 days (start 15 June 2000)**
- **Legend**
  - **Red - StratoSat platform locations**
  - **Yellow - 2° elevation**
  - **Green - overlaps**
- **4 hr/frame, 12 frames/sec, 173,000x faster than reality**
- **UKMO weather data**
- **TCS Model**
  - **Bounded and under-actuated control system**
  - **$\Delta V$ proportional to relative wind velocity, $V_{rel}$, at 20 km**
  - **Feasible, limited control directions with respect to $V_{rel}$**

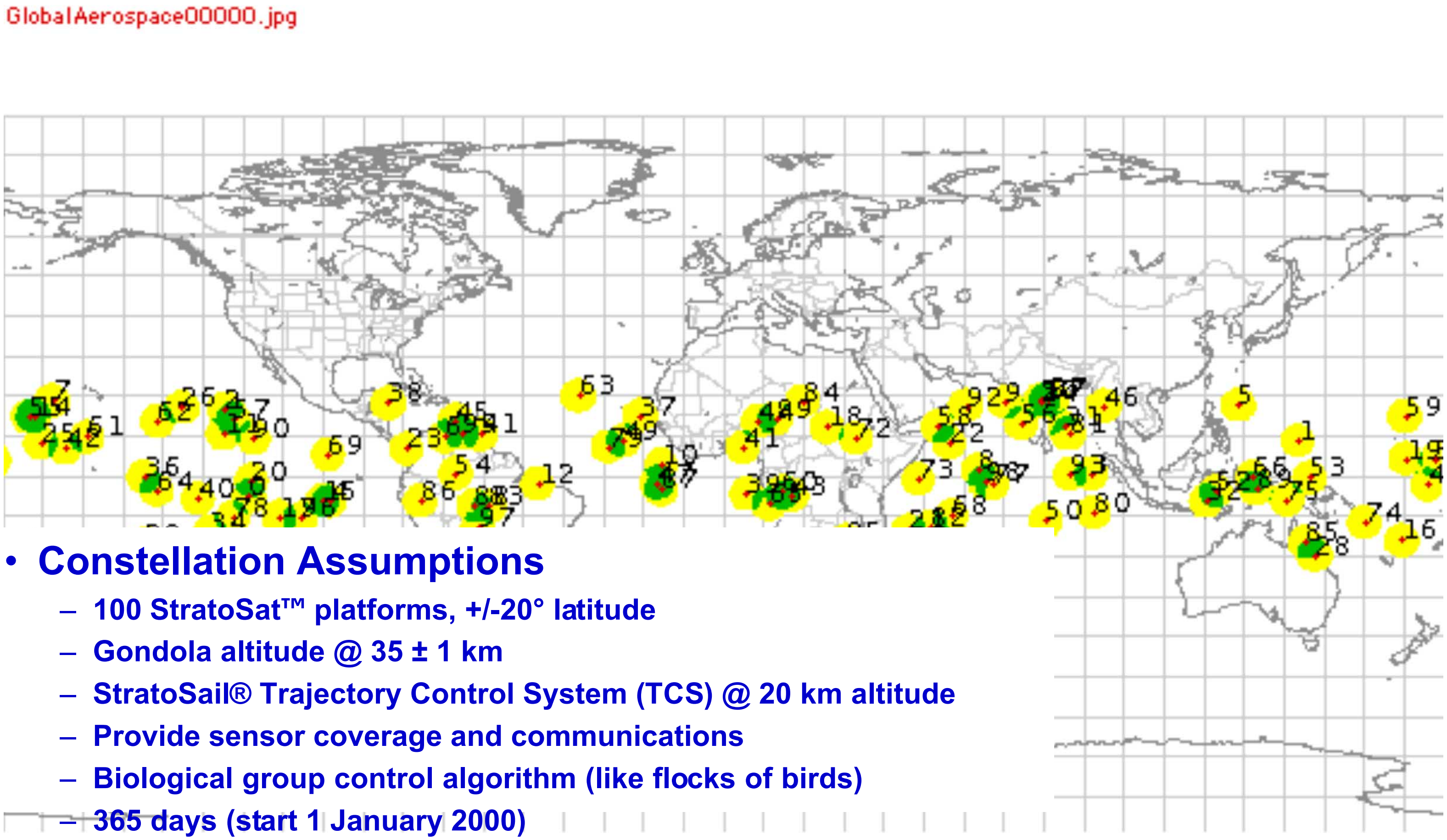


# HURRICANE TRACKING



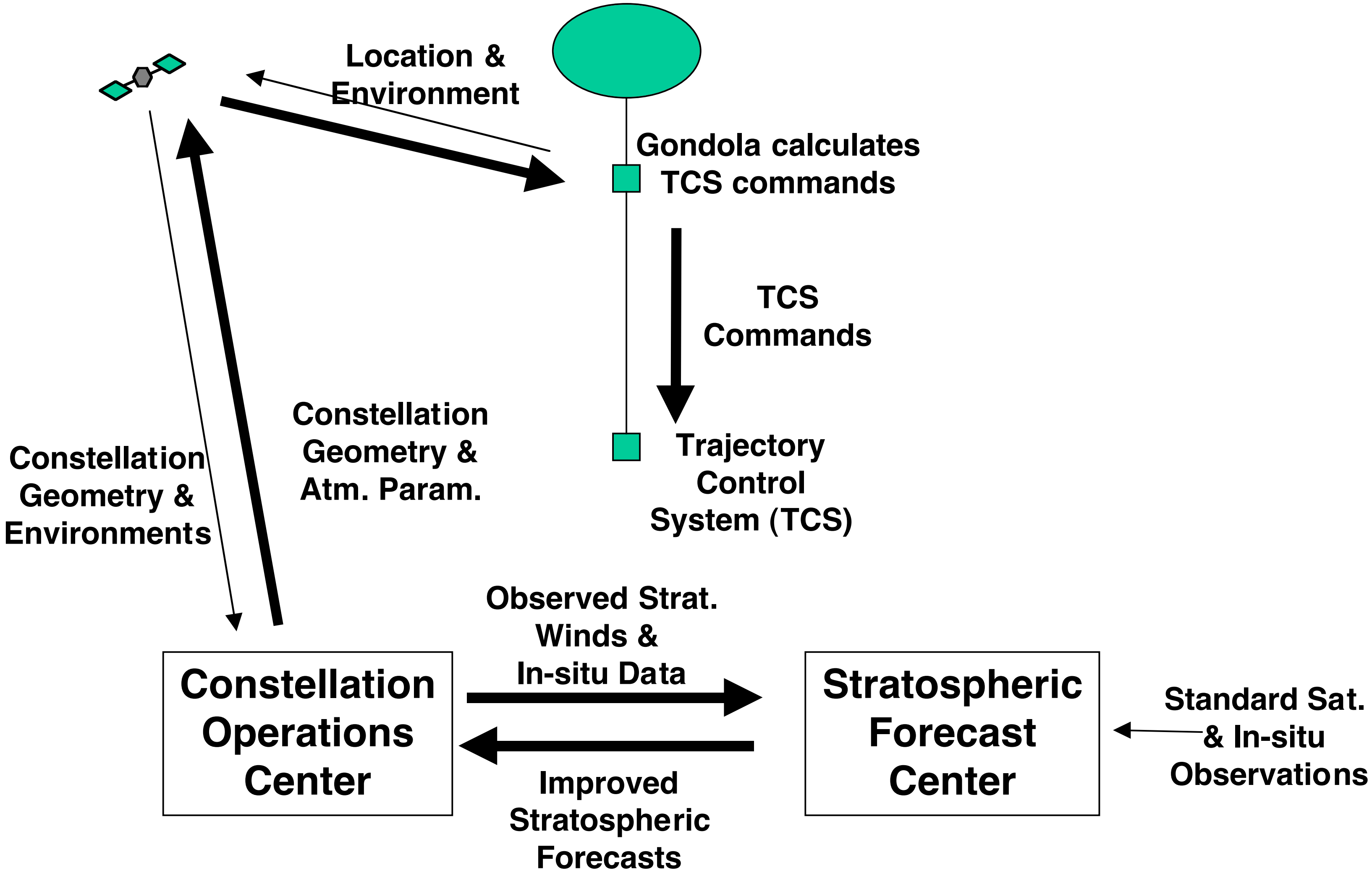
- **Hurricane Alberto**
- **20 balloons, Advanced TCS (0.5-5 m/s, reel-up capability)**
- **Actual easterly winds at 35 km**
- **1-day look-ahead**
- **4 hrs/frame, 31 days**
- **Latitude control strategy**
  - **>90° track lat**
  - **<90° aim eye**

# POSITIONING OVER DISASTER AREAS



- **Constellation Assumptions**
  - **100 StratoSat™ platforms, +/-20° latitude**
  - **Gondola altitude @ 35 ± 1 km**
  - **StratoSail® Trajectory Control System (TCS) @ 20 km altitude**
  - **Provide sensor coverage and communications**
  - **Biological group control algorithm (like flocks of birds)**
  - **365 days (start 1 January 2000)**

# CENTRALIZED STRATOSAT CONSTELLATION OPERATIONS



Location & Environment

Gondola calculates TCS commands

TCS Commands

Trajectory Control System (TCS)

Constellation Geometry & Environments

Constellation Geometry & Atm. Param.

Observed Strat. Winds & In-situ Data

Improved Stratospheric Forecasts

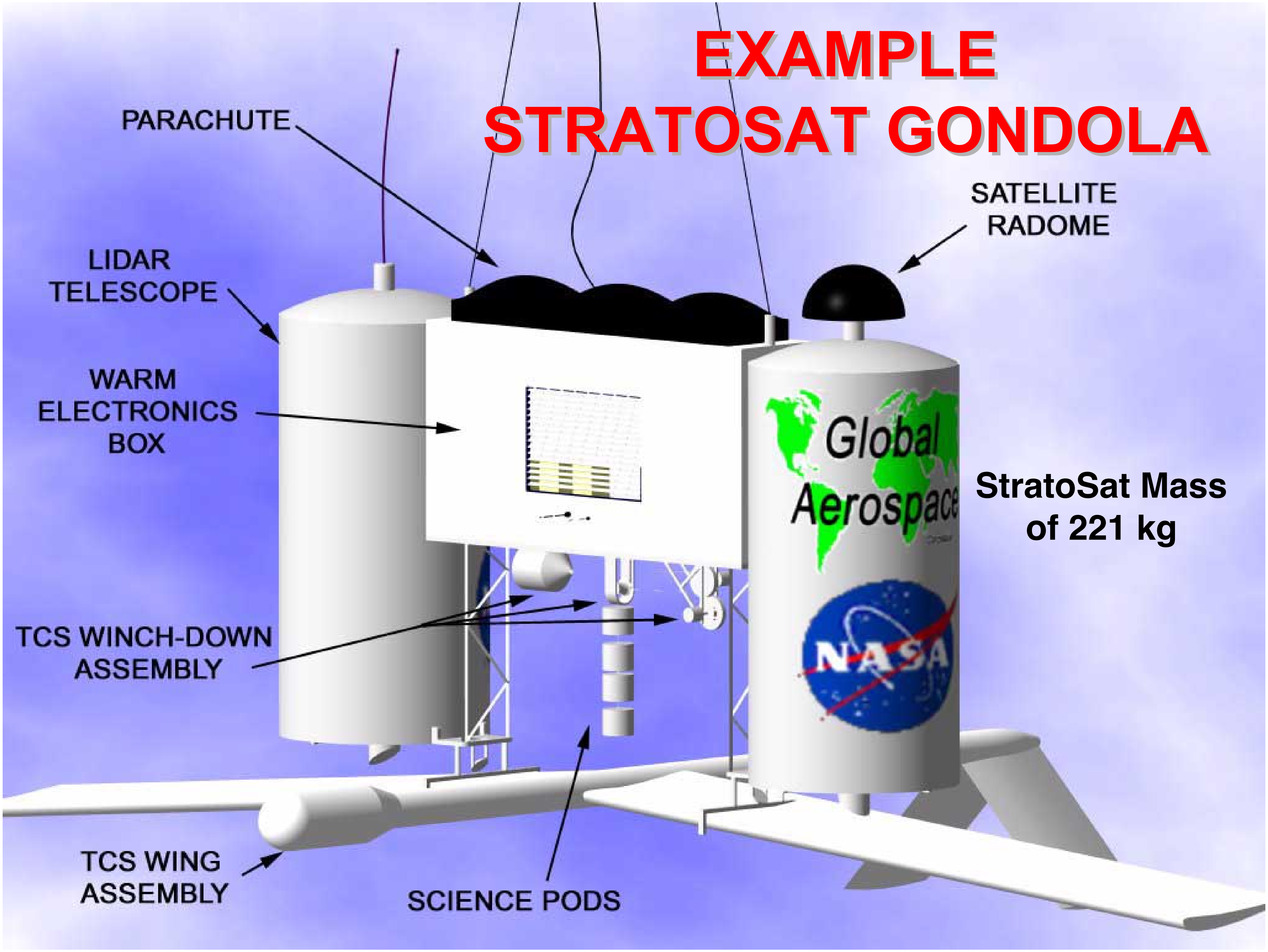
**Constellation Operations Center**

**Stratospheric Forecast Center**

Standard Sat. & In-situ Observations

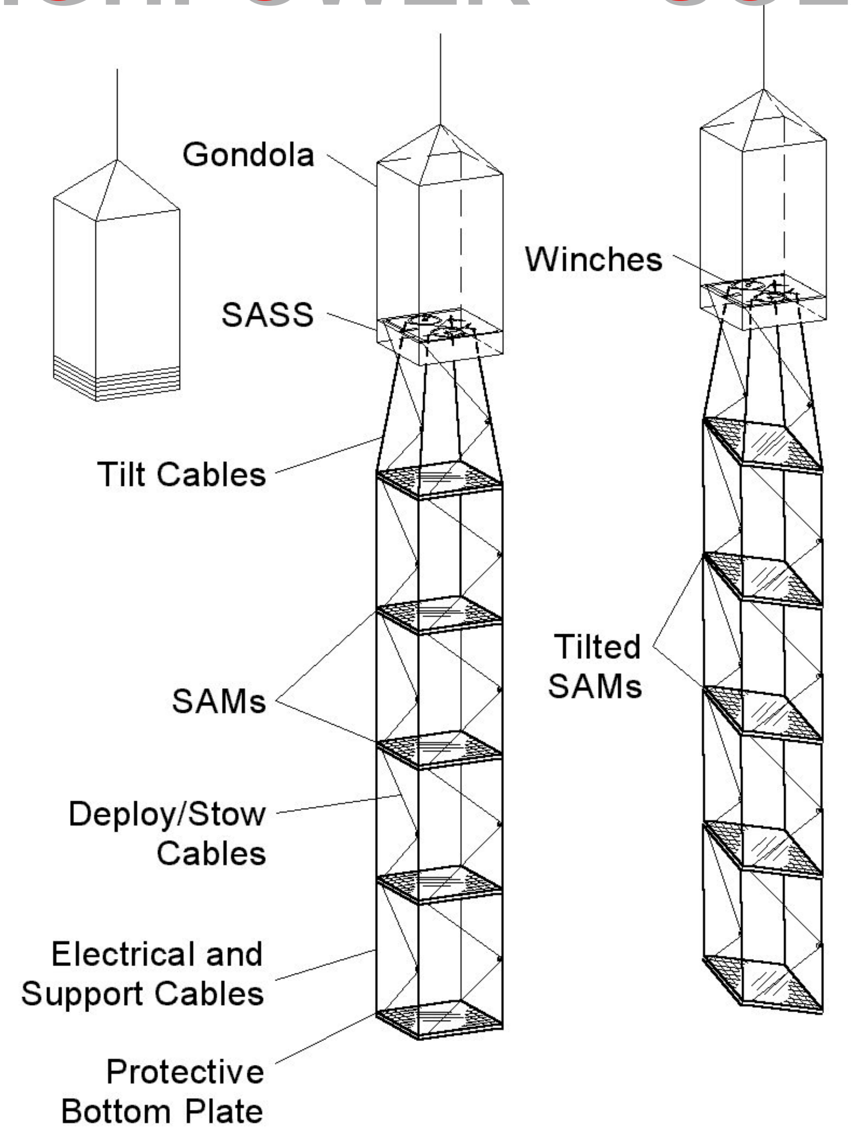
# Example Gondola Systems

# EXAMPLE STRATOSAT GONDOLA



**StratoSat Mass of 221 kg**

# HIGHPOWER™ SOLAR ARRAY



# INTERNATIONAL PATHWAYS TO OVERFLIGHT

# INTERNATIONAL OVERFLIGHT OPTIONS

- Free flight in upper stratosphere
- Expand on the 1992 Treaty on Open Skies
- Leverage World Meteorological Organization (WMO) cooperation
- Seek new treaties
  - Committee on Space Research (COSPAR) study
  - World pollution issues
  - Global missile defense

# Science Mission Cost Estimates

# COST ESTIMATE OF ATMOSPHERIC DYNAMICS CONSTELLATION

| | 100 StratoSat Constellation |
|---|---|
| Hardware | $32M |
| Launch | $7M |
| Total | $39M |

**Operations about $5M/yr.**

# Other Possible Application of Stratospheric Satellites

# POTENTIAL APPLICATIONS

- Communications Networks
  - Independent and secure messaging through cross-links
  - Remote low-power sensor monitoring and relay
  - Comsat augmentation by providing “last mile” capability in remote areas
- Observation, Monitoring and Tracking
  - Long dwell-time observation, tracking and hand-off
  - Missile launch detection and tracking
- Targeted package delivery
  - Micro systems - UAVs, surface sensors, robots
  - Full-scale systems
- Radio Frequency Sensing and Detection
  - Electronic Intelligence
  - ELF signals - Earthquake precursors, communications
  - Underground facility detection and characterization?

# Summary

# Current Status of Technology

- Several ULDB test flights (2000, 2001, 2002). Additional flight tests are planned
- Some constellation management tools (trajectory control, constellation control, solar power, and flight path prediction) are under development (2000-2002)
- NASA funded long duration ULDB flight planned for next December/January

# Next Steps

- Prototype demonstration leveraging current technology: \$1.5-\$2M
- Development of StratoSat™ Platform technology
- Production and launch of “always there” balloon networks

# MAIN POINTS

- Stratospheric satellites can contribute significantly to Earth science, meteorology and disaster management
- Stratospheric satellites are a low-cost and high performance alternative to space satellites
- A demonstration mission is an essential first step
- Stratospheric satellites may have other interesting applications