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Global Constellation of Stratospheric Scientific Platforms

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Abstract

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

- affordable, long-duration balloon systems,
- balloon trajectory control capability, and
- 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 stratospheric superpressure balloons may be competitive with or lower than comparable spacecraft systems due to the inherent high cost of spacecraft and launch vehicles. Indeed, a network of balloons will be less costly than a comparable network of spacecraft if the individual balloons have lifetimes measured on the order of years, thereby reducing the cost of replacement or refurbishment.

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.

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1 Introduction

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, under NASA Institute of Advanced Concepts funding, a revolutionary concept for a global constellation and network of tens to hundreds of stratospheric superpressure balloons. A network of balloons 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 constellation concept.

Each balloon will be designed to operate at an altitude of 35 km for up to 5 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. The structure 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. 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 which is expected to demonstrate 100-day flight missions by the end of 2000.

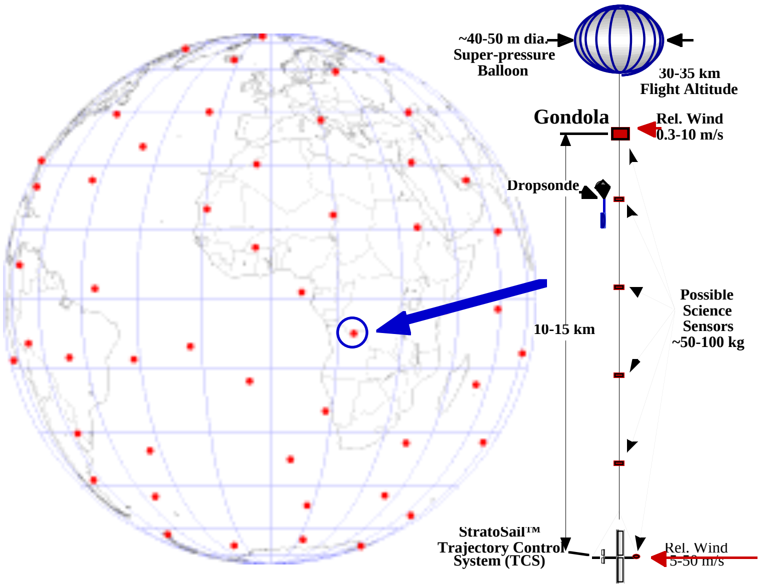


Figure 1.1 Global Constellation of Stratospheric Scientific Platforms

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 including 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 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. 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 general somewhat less than can be placed into lower inclination and altitude orbits.

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 is only possible by means of Hubble-class telescopes, which are heavy, expense 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 money into insuring their spacecraft and instruments will work as required, thereby further driving up the cost of space missions. Second, in general the cost of spacecraft engineering and scientific hardware can be very expensive due to the reliability and space environmental requirements. Finally, 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. 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.

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.

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.

Collecting data with prototype instruments provides scientists the opportunity to develop methodology and algorithms for application to data sets collected with future orbiting systems.

Because the ER-2 is a manned system, the operations cost are relatively high as compared to unmanned systems due to the high level of expertise require of personnel and the high level of safety required to protect pilots.

ER-2 Capabilities and Performance

The ER-2 has a range beyond 4800 km; is capable of an 8-hour flight duration; 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 and 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 Attributes

The strengths of aircraft for high-altitude Earth science research are:

- Low-cost flight systems as compared to satellites
- Swift reconfigurability of instruments
- Can be deployed to specific desired location
- Easily coordinated with other sensor platforms and ground operations

Shortcomings of aircraft for global Earth science observations are:

- High air-relative velocity, which complicates *in situ* chemistry measurements
- Limited range
- High operations costs compared to unmanned systems
- Limited flight duration
- Limited number of aircraft
- Limited altitude

1.2.1.2.4 The Future

NASA Unmanned Aircraft Vehicle (UAV) research continues to pursue long-duration, high–altitude (30.5 km [100,000 ft]) flight goals that enable important Earth science observations. However, at the current time, the realities of UAV performance have yet to meet their promise. Even if this vehicle class meets its goals, there will still be the issue of the limited payload capability and high-speed flight and its effect on sensitive chemistry measurements.

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 element that currently limits 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 Conventional 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 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 typically last 2-3 days at the most. When these same basic balloons (with smaller payloads) 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 two weeks.

1.2.1.4.2 Attributes

At a Workshop for Integrated Satellite Calibration/Validation and Research-Oriented Field Missions in the Next Decade (Fall 1999 Snowmass, CO) Professor William Brune of Pennsylvania State University presented a talk concerning the role of conventional balloon borne atmospheric science payloads. He stated that balloon-borne measurements have unique validation and science capabilities and summarized their strengths as weaknesses as follows:

“Strengths:

- Cover stratosphere and troposphere from 40 to 10 km, [much of this] above aircraft [altitudes].
- Provide simultaneous measurement of multiple species.
- Provide high-resolution vertical profiling across large pressure range.
- Simulate remote sensing footprint of limb sounding satellites.

Weaknesses:

- Provide infrequent measurements, except for small balloons or in intensive mode.
- Give only vertical profiles – no probing of horizontal gradients.
- Are sometimes questionably cost effective for science and validation gained [due to limited mission duration]”.

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.

1.2.1.4.3 The Future

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. We note that while all the strengths listed in the section above are valid for the ULDB-class of very long duration stratospheric platforms, all the weaknesses tabulated above are made moot by this new technology. 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. As with satellites, these platforms will be global in nature and essentially orbit the Earth. As with balloons, StratoSats will fly much lower and slower than satellites, which enables *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. Each of these examples is discussed in more detail in Section 3.

A. Global Change Studies
    1. Water Vapor and Global Circulation in the Tropics
    2. Radiative Studies in the Tropics
    3. Global Radiation Balance
B. Ozone Studies
    1. Mid-latitude Ozone Loss
    2. Polar Ozone Loss
    3. Global Distribution of Ozone
C. Hurricane Forecasting and Tracking
D. Global Circulation and the Age of Air
E. Global Ocean Productivity

1.2.3 Cost and Performance Benefits of Global Balloon Network

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 StratoSats 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 for cost details).

Besides the potential cost benefits of complementary global stratospheric platforms, there are observations that are superior from the StratoSat 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 10^3 higher returned signal as would a satellite observe from a 700 km orbit. 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.

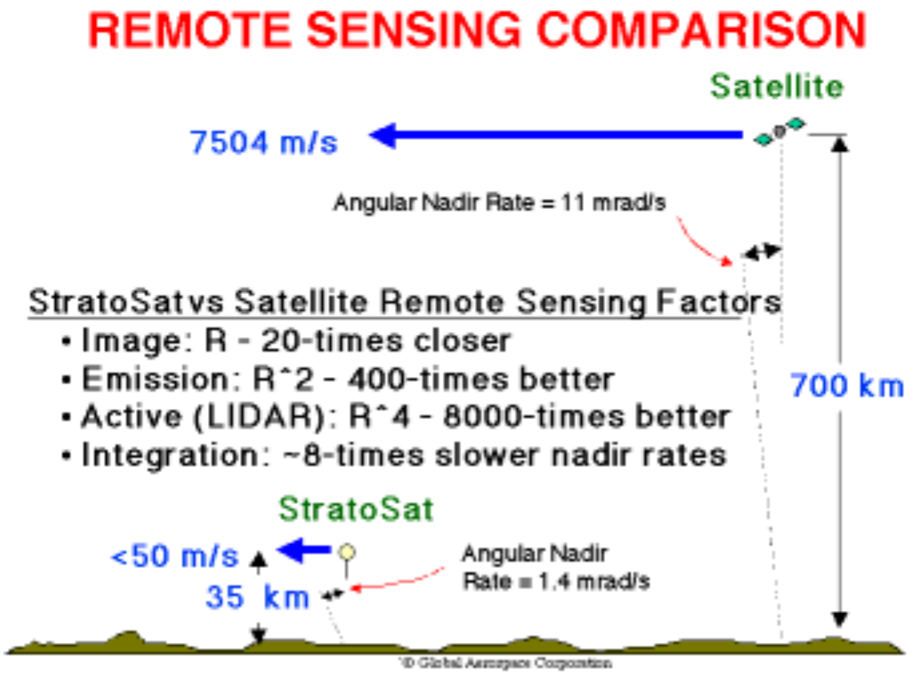


Figure 1.2 StratoSat and Satellite Remote Sensing Comparison

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 the 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

Whether mankind’s role on planet Earth is viewed from a religious or secular vantage point, it is clear that we are entrusted with its guardianship. Whether it is maintaining an international framework providing for peaceful coexistence between nations trying to avoid rapid destruction and global devastation through a nuclear holocaust, or a similar framework to prevent harmful and potentially irreversible damage to our planet through our own neglectful or irresponsible behavior, it is incumbent on government leaders to provide the ways and means to do this. Within the past 50 years, we have become aware of many and diverse examples of human induced global change. With the continued rapid growth in the world’s population, this trend can only be reversed through worldwide cooperative vigilance and action. To quote Dan Albritton, a Director of the NOAA Aeronomy Laboratory: “Understanding our global environment and our role in it is the first step towards living in harmony with it.” While following this advice may seem straightforward, developing and carrying out an efficient cost-effective plan with the proper priorities and vision require significant, flexible, and continuous stewardship.

In the United States, this job has been entrusted to the U. S. Global Change Research Program (USGCRP) that coordinates the efforts of many Federal agencies. According to Ghassem R. Asrar, Associate Administrator for Earth Science, “NASA’s Earth Science Enterprise turns its space-based observing technology and scientific expertise to the study of our home planet. This Earth Science Strategic Enterprise Plan maps out NASA's strategy for observation and research on our home planet for the next 5 years (1998–2002), or through the deployment of the first series of Earth Observing System missions. This 5-year strategy is set in the context of a 25-year roadmap for the future. Concurrently, we have initiated a process to define science questions and mission strategies for the 5 or more years beyond this time horizon. This effort will incorporate the results of the National Academy of Sciences' report on pathways for global change research for the next decade.”

The NASA Earth Science Enterprise (ESE) has identified five research questions as the focus of effort for the next several years.

- What are the nature and extent of land-cover and land-use change and the consequences for sustained productivity?

- How can we enable regionally useful forecasts of precipitation and temperature on seasonal to interannual time frames?
- Can we learn to predict and mitigate natural disasters?
- What are the causes and impacts of long-term climate variability and can we distinguish natural from human-induced drivers?
- How and why are concentrations and distributions of ozone changing?

Based on the global nature of these questions, it is correctly argued that to study these issues, requires understanding how the earth works as a system. It is further argued that "the spatial, temporal, and spectral coverage offered by modern space-based instrumentation best addresses the requirements of researches for long time series of data"[Asrar and Dozier, 1994]. These authors develop the premise that the focus of research for understanding our changing planet should be space-based. They further argue that only satellites can provide systematic and continuous monitoring of the earth's atmosphere for a minimum for 15 years to be able to distinguish between anthropogenic and natural changes. However, alternate points of view on this matter can be presented. For example, there is a significant difference between detecting a change that can be identified as anthropogenic, and making progress in determining the cause for that change. While it is certainly helpful to make the appropriate measurements to for example observe a decrease in air quality in urban regions, without understanding the mechanistic cause of the pollution, any regulations put in place to improve air quality might impose economic hardship on the local community without any noticeable benefit. The question has to be raised as the long term strategy needed to strike a proper balance between space-based monitoring and approaches which in the context of the global perspective provided by satellite data can address key mechanistic questions regarding anthropogenic global change. According to a description of the program,

"ESE seeks to maintain a balanced program across the earth science disciplines and among the various ESE program elements. In most cases this does not imply equivalent resource allocation. We strive to achieve balance in the following key areas:

In situ observations and space-based observations needed for more complete information for calibration/validation purposes.

A broad spectrum of Earth System Science research with a contemporary focus on climate change."

However, it is not clear how the proper balance is 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.

These measurements were carried out as part of the Antarctic Ozone Expedition (AAOE). Key questions have similarly been addressed by missions on aircraft or aircraft and balloons. NASA sponsored campaigns such as the Airborne Arctic Stratospheric Expedition (AASE), the Stratospheric Tracers of Atmospheric Transport (STRAT), the Photochemistry of Ozone Loss in the Arctic Region In Summer (POLARIS), have provided advances in our understanding of ozone depletion processes and stratospheric circulation. Additionally, National Science Foundation (NSF) sponsored campaigns in the tropics have similarly investigated problems relating to climate.

These missions have provided extremely useful data, representing a unique way to make simultaneous measurements of a number of key atmospheric species. However, such missions are both difficult to organize and extremely expensive to fund. Accordingly they occur only at intervals in time such that they often miss the events they have been organized to study. For example, SAGE (Stratospheric Ozone and Aerosol Experiment) Ozone Loss and Validation Experiment (SOLVE) a planned mission to Sweden to study the polar ozone hole and provide *in situ* validation and calibration data has taken about 18 months to organize. It will take place even though delays in launching the satellite will prevent the satellite validation from occurring. It will take place whether or not local meteorology is suitable for significant ozone depletion.

Additionally, current aircraft capabilities limit measurements to 20 km. Most of the ozone depletion occurs above this altitude range. While satellite-borne instruments can observe this region, they can not provide the resolution necessary for doing mechanistic studies. The vast part of the stratosphere has only sporadic *in situ* measurements on balloons. The importance of these measurements can be seen by the role they are taking in the SOLVE mission and in tropical missions.

A critical question facing the USGCRP is what is the proper balance between space-based, surface-based, and *in situ* measurements to most efficiently address the key questions facing our changing environment, and in the face of diminishing resources, what is the proper balance of funding to achieve our goals.

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

The Ultra Long Duration Balloon (ULDB) Project, managed by NASA/GSFC Wallops Flight Facility, is planning the first ULDB demonstration flight to occur in late 2000. The goal of the ULDB program is to fly up to 1000 kg science payloads above >99% of the Earth's atmosphere for at least 100 days. A number of technology efforts relevant to stratospheric balloon constellations are currently ongoing under the ULDB Project including balloon system design, trajectory simulation and prediction and balloon trajectory control.

1.5.1.1 Balloon Design

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 (see **http://www.wff.nasa.gov/~web/ULDB/**). ULDB balloon systems are designed to carry 1600-kg payloads (including 1000 kg of science instruments) to 35-km float altitudes. A pumpkin balloon is constructed of several sector-shaped lobed gores. This new design reduces the radius of curvature of the material and the stress that results from pressurization.

Figure 1.3 ULDB Scale Model Polyethylene Pumpkin Test Balloon

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 [N. Yajima, *A New Design And Fabrication Approach For Pressurized Balloon*, COSPAR 1998]. 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.

The NASA ULDB Project is currently using a high strength composite material for their balloons made of a polyester fabric laminated to layers of thin polyethylene (PE) film. The areal density of this envelope material is 50-60 g/m^2. The ULDB balloon envelope is constructed of several sectors or gores extending from the top of the balloon to the bottom. Each gore is fastened to its neighbor by use of high strength tapes that also accommodate the longitudinal stresses on the balloon.

Under a NASA contract, Raven Industries has developed seaming methods and procedures for the fabrication of high-strength, composite balloon envelopes. These envelopes, made of a high tenacity polyester fabric laminated to layers of thin film, will be used to develop design concepts and prototype balloons for testing. The first flight test of a full-scale balloon is planned for the December 2000. 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 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.

Other relevant research and development activities include the Mars balloon efforts both in France and in the U.S. for the development of very lightweight balloon envelopes (10-20 g/m^2) (Mars 2001 Aerobot/Balloon System Overview, AIAA 97-1447).

The current ULDB balloon envelope material is far 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* - for a more compliant envelope which can lobe naturally relieving the transverse or horizontal stresses on the material
- *Higher modulus stiffeners* - which can take the longitudinal loads and fasten gores together
- *Lightweight* - to reduce total areal density
- *Commercial technology* - to significantly reduce cost of materials / fabrication and
- *Capable of withstanding the environment* - especially the stratospheric UV / Solar radiation for years at a time.

Material design options for a global balloon network include:

- *Lightweight fabric and film composites* - e.g. Nylon/PE
- *Fiber-embedded films* - PE/PE
- *Co-extruded Composite Films*- High/low density PE, PE/PETG
- *Liquid crystal polymers* - which can be stiff in the machine direction and elastic in the transverse direction.

1.5.1.2 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 is supporting NASA’s balloon program by developing a ULDB Trajectory Simulation WorkStation. We are developing the ULDB trajectory simulation tool as a phased activity whose ultimate goal is the production of a Trajectory Simulation and Prediction System (TSPS) for the ULDB Project. 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.

See **http://www.gaerospace.com/publicPages/projectPages/ULDBTrajSimPages/**.

1.5.1.3 Trajectory Control

In 1998, Global Aerospace was awarded a NASA Small Business Innovative Research (SBIR) contract to develop its StratoSail™ balloon trajectory control system (TCS) concept [Aaron, K., M. Heun and K. Nock, Balloon Trajectory Control, Paper AIAA-99-3865, AIAA International Balloon Technology Conference, Norfolk, VA June 1999]. The specific focus of the SBIR award is to develop a preliminary design of the StratoSail™ TCS that could be used to maintain control of trajectories of future missions of NASA's ULDB Project.

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 10-15 kilometers below the balloon at an altitude of 20-25 kilometers. 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.

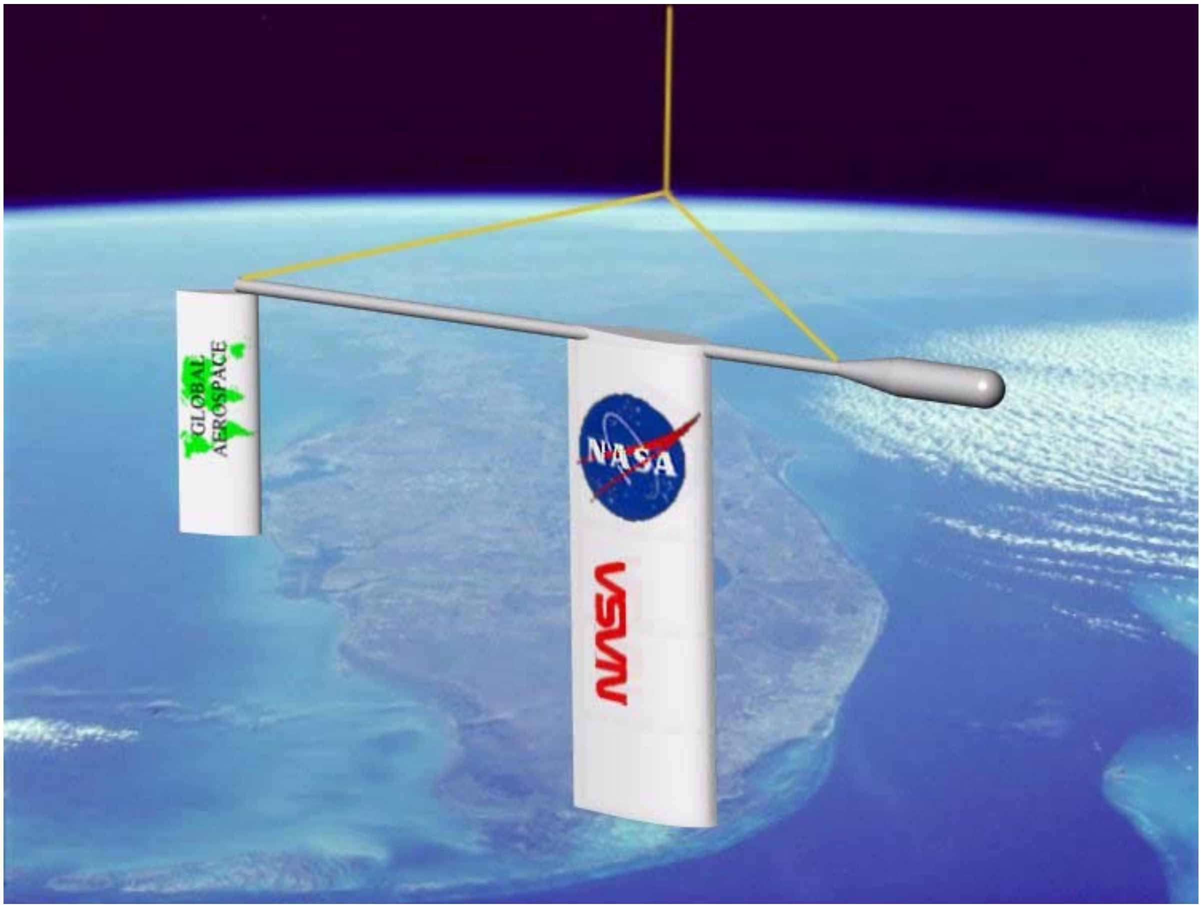


Figure 1.4 StratoSail™ Trajectory Control System

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.

1.5.2 Stratospheric Constellation Management or *Virtual Stationkeeping*

It would be very nice 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.

Balloons and other lighter-than-air systems, which can stationkeep over a geographic point by thrusting against the wind, have been the subject of several studies over the years [Vorachek, J., *A Comparison of Several Very High Altitude Station Keeping Balloon Concepts*, Proceedings 6th AFRCL Scientific Balloon Symposium, 1970. Beemer, J. D., *POBAL-S, The Analysis and Design of a High Altitude Airship*, Raven Industries, AD-A012 292, 15 February 1975. Perry, W., *Sounder: High Altitude Solar Powered Airship*, Mars Areal Platform Workshop, JPL, August 11, 1998. SkyStation, **http://www.skystation.com/**]. 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 replace 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/publicPages/projectPages/index.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.

1.5.3 Power Systems

Solar photovoltaic cell systems (amorphous silicon, cadmium Telluride, Cadmium Indium Diselenide, and Copper Indium Gallium Diselenide) are being developed for application on flexible substrates like thin polymer films. One example, amorphous silicon solar cells, have achieved 10% efficiency for long lifetime and their future is very promising. When compared with conventional crystaline silicon solar cells, amorphous silicon solar cells have several advantages including the physical flexibility afforded by their thin-film construction, their ability to be fabricated into large-area cells and the potential for innovative designs in new applications, such as integrated balloon envelope solar arrays if areal densities decrease sufficiently.

NASA has studied advanced solar array systems for Lunar and Mars surface applications utilizing amorphous silicon solar cells for flexible solar array blankets [Colozza, A. J., *Design and Optimization of a Self-deploying PV Tent Array*, NASA CR 187119, June 1991]. The areal density of these planetary solar array systems is about 20 g/m^2. Since the majority of the mass of the blanket is the substrate underneath the cells, there is a real possibility of integrating the solar array function into a balloon envelope with a very minor mass penalty.

1.5.4 Global Balloon Network Concepts

1.5.4.1 National Oceanic and Atmospheric Administration (NOAA)

A concept currently under development by NOAA utilizes a variable density balloon concept that employs an internal ballonet that enables the system to control its altitude, and thus to a limited degree, its direction. The concept is called Global Air-Ocean In-situ Systems (GAINS). Test flights of the balloon system have been underway since 1998. The primary goal of this global balloon network is to take soundings in the troposphere to increase the availability of *in situ* meteorological data over remote regions, like the great ocean basins, with the goal of improving weather forecast accuracy. Because of safety concerns, the system is designed to fly just above controlled airspace (60,000 feet) in the lower stratosphere and deploy dropsondes to the surface in order to make measurements in the troposphere. [Girz, C., et. al., Global Air-Ocean In-situ Systems (GAINS), AIAA Paper 99-3870, AIAA International Balloon Technology Conference, Norfolk, VA, June 1999]

1.5.4.2 French Space Agency (CNES)

Since 1987 the French Space Agency has been developing a regional constellation concept of constant altitude superpressure balloons for operating in the lower stratosphere at the South Pole between 18-20 km altitude. This concept is called STRATEOLE. The current concept has up to 200, 9-m diameter balloons operating at two altitudes, namely 18 and 20 km. The balloons are fabricated from 2 x 23 micron bi-laminated polyester, and a payload capacity of about 15 kg. Each balloon carries conventional meteorological instruments in addition to GPS for winds. Some balloons perform chemistry and radiation instrument. The primary objectives of the regional networks are the study of the structure and the evolution of polar vortex, the study of the permeability of the vortex edge to chemical fluxes, and the impact of gravity waves and turbulence on dynamics and mixing in the vortex [See Dubourg, V., et. al., The STRATEOLE Project Status: 200 Pressurized Balloons for the Polar Vortex Study, AIAA Conference, 1997].

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 region between airspace and outer space.

On March 24, 1992, 25 nations signed the Open Skies Treaty (OST) 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 OST was originally negotiated between members of NATO and the former Warsaw Pact as a confidence building measure in arms control.

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 OST give one 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.”*

2 Concept Development Summary

2.1 Summary of Phase I Tasks

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

2.1.1 Task 1 Define Preliminary System Requirements

The preliminary requirements will be defined for a global constellation of stratospheric scientific platforms by analyzing the high-level concept objectives (Section 2.2) and determining the derived system requirements.

2.1.2 Task 2 Science Observations Development

A detailed list of potential science observations and measurements will be developed which connects and is responsive to the NASA Earth Science Mission.

2.1.3 Task 3 Conceptual System Design

The conceptual system design will be developed including a preliminary system functional and performance definition, list of subsystem elements, and system mass and power estimates.

2.1.4 Task 4 Estimate System Costs

Develop estimate of overall system costs including development, emplacement and maintenance.

2.1.5 Task 5 Reporting

Monthly status reports and a final report shall be written. We shall participate in and present the final report at the NIAC Fellows Conference in Atlanta, GA in the Fall of 1999.

2.2 Summary of Work Accomplished

This section provides a concise summary of the work accomplished during the Phase I effort. A more detailed description follows in later sections.

2.2.1 Task 1 Define Preliminary System Requirements

In July 1999 we completed the Preliminary System Requirements Document, which has been more appropriately named the Conceptual Design Requirements Document (GAC Report 510-02511-002, see Appendix 3). This document contains a brief description of and preliminary requirements for a global constellation of stratospheric scientific platforms. These conceptual design requirements are levied on the design of the operational system. This document serves to provide conceptual design requirements for use in the preliminary design phase of Phase 1 of the NIAC StratCon study. Understanding developed during the preliminary design effort will be used to revise portions of this Conceptual Design Requirements Document. A revised version of this document without the descriptive section will be developed during the Phase II effort. The revised document will take benefit of the understanding of user requirements and the conceptual design details developed during Phase I.

2.2.2 Task 2 Science Observations Development

Task 2 focused on obtaining information on future Earth science applications of stratospheric networks and the development of a white paper on global balloon constellation observations (GAC Report 510-02511-006, see Appendix 1). Our consultant, Dr. Elliot Weinstock from Harvard University, developed several new observation concepts working with several Earth scientists.

We followed two approaches for investigating promising science observation applications for a constellation of them. Firstly, we made contacts with Earth scientists potentially interested in global networks. Secondly, we have utilized recent books and reports published by the National Research Council, which provide a consensus of the leading atmospheric scientists on the future needs in understanding the most important questions to be explored in atmospheric science. Additionally, we drew upon our own experience participating in balloon and aircraft campaigns, both from the planning and scientific goals points of view, as well as the logistics and cost points of view.

Finally, we developed an example Earth science payload for a particular constellation mission concept including the definition of StratoSat instrument requirements, which include viewing, data and interface needs. After consulting with several scientists, we projected the mass and power requirements of each instrument into the future about 10 years.

2.2.3 Task 3 Conceptual System Design

Task three covered a variety of topics because the conceptual design included many elements. In this section we discuss balloon design, constellation management, telecommunications, trajectory control, and power.

A subcontract was awarded to Raven Industries for their support of the Global Stratospheric Constellation effort. Raven Industries generated parametric balloon design data for pumpkin balloons at 20, 30, and 40 km altitude for materials with areal densities of 20, 30, 40, 50 and 60 g/m^2. Raven also developed several point design balloons in order to compare the performance of various design strategies. This parametric study assumed a 180-kg payload.

Regular conceptual design team meetings were initiated. Several one-year simulations (with and without trajectory control) of a 100 platform constellation were completed, strategies to analyze for constellation maintenance and trajectory control were developed and evaluation made of several trajectory control strategies. Telecommunications options were developed and analyzed. GAC developed an advanced TCS Wing Assembly (TWA).

The StratoSat system was defined to contain the following subsystems: Science, Balloon, Power, Telecommunications, Mechanical and Thermal Control, Guidance and Control, Trajectory Control, Termination and Robotic Controller. Technology innovations were identified for each subsystem implementation of the StratoSat design.

Technology horizon for estimating masses of subsystems and components was 2010. Advanced design technology was incorporated if there is a clear path to achieving technology goals. If there is no clear path to revolutionary advances in StratoSat subsystem technology, future significant cost reduction was assumed. Conceptual design concepts for integrated balloon envelope and power subsystem components were explored. We procured samples of power subsystem components including thin film amorphous silicon solar arrays and Lithium polymer electrolyte battery cells, which were used in exploring innovative balloon/power system integration concepts.

2.2.4 Task 4 Estimate System Costs

Task 4 focused on the development of first-order cost estimates for a global constellation for its emplacement and maintenance. An assumed network size, lifetime and balloon system mean-time-to-failure (MTF) were chosen in order to estimate StratoSat replenishment necessary for constellation maintenance. In addition, space launch vehicle costs were complied in order to estimate the cost of satellite deployment as a comparison to a StratoSat constellation.

2.2.5 Task 5 Reporting

Monthly status reports and a final report have been written and submitted. We participated in and presented the final report at the NIAC Fellows Conference in Atlanta, GA on November 9, 1999.

3 Earth Science Observation Scenarios

Within the context of the areas of global change that are being addressed by the Earth Science Enterprise (ESE), the recommendation of the Pathways report and the monograph, *Atmospheric Sciences entering the 21st century*, and the specific areas of research/ scientific questions to be answered within the context of environmental global change, we enumerate here a set of scientific observations from a network of tethered balloon platforms. This can in no means be thought of as a comprehensive set, but rather as one representative of the types of observations that can be made, the flexibility of this approach in terms of the ability to reposition platforms to observe specific seasonal or geographical environmental issues. Because, as evidenced by our experience with ozone depletion, the planned network would be in position to observe the unpredicted events as they happen.

It is also important to understand that because of the nature of the instrumentation proposed on the balloon platforms, that calibration and long term accuracy are a critical part of this plan, and the nature of the platform is amenable to this. We will emphasize this in each of the areas of research that we discuss. We will also choose sample payloads for which we project detailed information on the scientific instrument package.

3.1 Summary of Earth Science Mission Scenarios

The following is an example list of Earth science missions for global and regional constellations of stratospheric platforms that address major Earth science issues. Each of these examples is discussed in more detail below.

A. Global Change Studies
    1. Water Vapor and Global Circulation in the Tropics
    2. Radiative Studies in the Tropics
    3. Global Radiation Balance
B. Ozone Studies
    1. Mid-latitude Ozone Loss
    2. Polar Ozone Loss
    3. Global Distribution of Ozone
C. Hurricane Forecasting and Tracking
D. Global Circulation and the Age of Air
E. Global Ocean Productivity

3.2 Climate Change Studies

The following concepts focus on climate change research.

3.2.1 Water Vapor and Global Circulation in the Tropics

It is currently understood that air enters the stratosphere in the tropics from where it slowly rises and heads poleward. Key issues regarding global change involve the water vapor mixing ratio in the upper troposphere, the mechanism that controls the water vapor mixing ratio entering the stratosphere, and the rate in which the air and that water vapor mixing ratio is transported poleward. Questions of ascent velocities in the tropical stratosphere are critical in understanding the general circulation. Stratospheric models need data on these velocities on an ongoing basis. Current approaches rely on aircraft-borne, a few balloon-borne CO_2 profiles and some radiative transfer calculations to determine ascent velocities. Both carbon dioxide and water vapor exhibit seasonal cycles with water vapor ranging from a 3 ppmv minimum Northern Hemisphere (NH) winter to 6 ppmv in the summer. CO_2 exhibits varies by about 3 ppmv with its maximum in NH fall and minimum in spring. Measurements of carbon dioxide at the surface and at the tropical tropopause have served to characterize its variability very well. The phasing of the water vapor signal is well understood from satellite measurements and *in situ* measurements have started to provide accurate quantitative information on its seasonal cycle. Measurements of CO_2 and water vapor have already been used to give ascent velocity information but the data is sparse. The availability of continuously measured water vapor and CO_2 profiles from the tropopause up into the middle stratosphere would provide invaluable information for stratospheric circulation and would help provide better understanding of the overall lifetime of atmospheric species. These data would also provide the first picture of the interannual variability of atmospheric circulation. 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.

Accurate high-resolution measurements of upper tropospheric water are critical for our understanding of global warming. Water vapor is the principal greenhouse gas and measurement of its concentration in the upper tropical troposphere, along with concurrent ozone and temperature measurements from about 12 to 18 kilometers is critical. Satellite-based measurements can provide neither the resolution nor the accuracy needed in the tropopause region where ozone and water vapor mixing ratios vary significantly with altitude.

We would envision 35-50 of these payloads from 15 S to 15 N latitude. This coverage will map out the seasonal, latitudinal and longitudinal dependence of the flux into the lower tropical stratosphere. The payload configuration is schematically represented in Figure 3.1. The payload consists of a microwave temperature profiler at the Trajectory Control System (TCS), water vapor and ozone LIDAR instruments at the gondola, and *in situ* water vapor ozone, instruments on the tether and CO_2 on the sail. A new *in situ* absorption technique called cavity ringdown-laser absorption spectroscopy using a multipass cell will provide high accuracy. For CO_2, where 0.1-ppmv accuracy is the goal, a small gas addition system will be used to periodically calibrate the instrument.

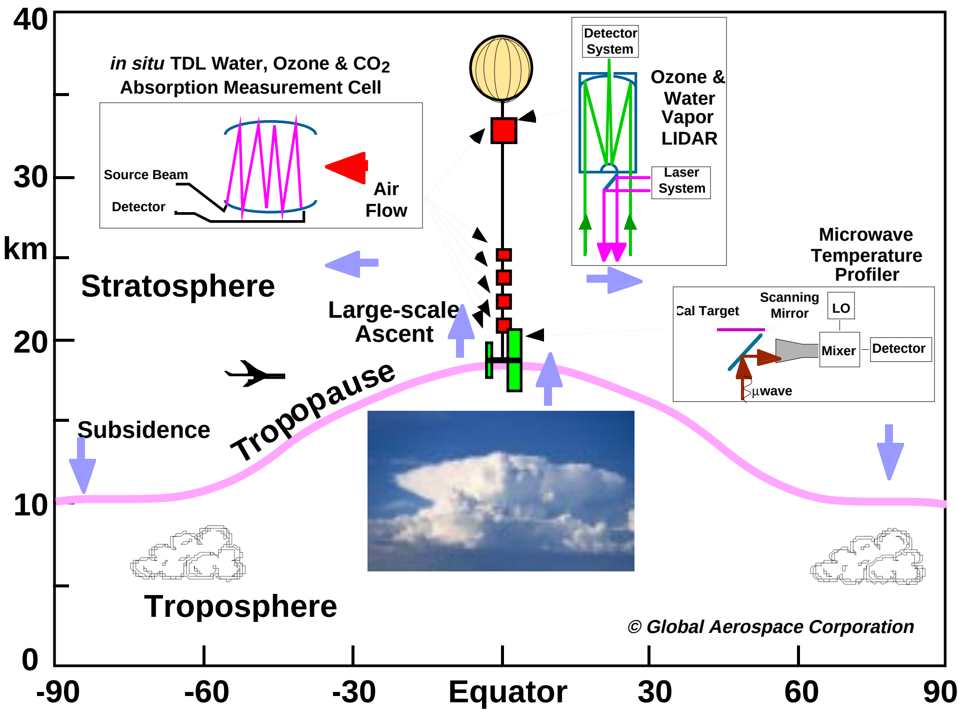


Figure 3.1 Climate Change: Dynamical Processes in the Tropics

3.2.2 Radiative Studies in the Tropics:

It is well understood that much of the infrared radiation that escapes the earth does so in the dry or down-welling regions of the tropics, where the relative humidity is low enough. Monitoring the emitted radiation of the atmosphere from the near to far infrared in this region with an accurately calibrated Fourier Transform Infrared Radiometer will provide invaluable information on climate change. While projected satellite based instrumentation will provide a global picture, resolution from a satellite often is insufficient to clearly isolate homogeneous regions. However, balloon-borne instruments have a small enough “footprint” to do just that. Additionally, by providing a cloud LIDAR instrument with the same footprint, both through verification of clear sky as well as through the measurement of change in emission in the presence of clouds at specific altitudes, these measurements will provide a thorough determination of the radiative feedback properties of optically thick and thin cirrus clouds.

Scientifically, simultaneous measurements on the particle size distribution in clouds would allow a relationship between the particle size and its infrared properties to compare with models. Additionally, information will be provided on the radiative properties of aerosols. Aerosols have been found to play both a direct and indirect role in climate change. Calculations show that the direct contribution of aerosols is a cooling effect of on average about -2.5 W/m^2 which is significant relative to greenhouse gases. Unfortunately, understanding the details of aerosols and their radiative properties requires simultaneous measurements of their size distribution and particle density as well as their radiative effects. The study of the radiative properties of aerosols has been severely limited because or the difficulty of doing such an experiment. While there are *in situ* measurements from aircraft instrumentation and sondes of aerosol properties as well as from satellites (SAGE) and radiative measurements from satellites there is little if any data linking the two, especially in the tropics. Accordingly, having dropsondes on these gondolas with particle counters would provide the link between the optical depth of the cloud, its radiative properties, and its microphysical properties. This combination of experiments focused on a localized air mass can not be accomplished by satellite-based instrumentation.

Additionally, because the emission measurement will provide a reasonably accurate measurement of ozone and water vapor, the primary absorbers of infrared radiation, a full radiative heating rate calculation can be made on the air below the gondola, providing an independent determination of ascent rates in the stratosphere.

This payload would consist of Cloud LIDAR, and FTIR instruments at the gondola, both providing remote measurements of the air column below. The FTIR would take highly resolved infrared emission spectra and the LIDAR would identify the altitude and character of clouds present. Measurement of clouds at certain altitudes can be used to trigger the dropping of sondes from the gondola to measure water vapor, ozone,particle size distribution in the clouds, as well as pressure and temperature. The ozone and water vapor measurements can be used to compare with the FTIR measurements.

3.2.3 Global Radiation Balance

As part of NASA’s directive to detect long-term climate change, a simultaneous measurement of the total energy entering and leaving the atmosphere has been undertaken in an effort to determine whether the atmosphere is warming. Because this requires global coverage, the approach has been to use satellite-based radiometry to make this measurement. The program uses filter radiometers on satellites in morning, afternoon, and inclined orbits to measure the Earth’s radiation balance. Because the satellite is in orbit at approximately 800 km, far above that part of the Earth’s atmosphere that has a significant role in radiative balance, models must be used to convert the measured radiance to a flux at the top of the atmosphere to compare with the measurement of solar flux. This conversion significantly limits the accuracy of the radiation balance determination. In addition, radiation is emitted in all directions. A satellite instrument observes the radiation from only one direction. To understand total energy flux one needs to integrate over all angles. To verify this conversion to flux would benefit greatly from detection radiation emitted by the same volume from different angles. A constellation of balloon platforms would provide this opportunity. Finally, the footprint of a satellite-based instrument is often too large to provide a homogeneous radiative field. Radiation measurements will often be from a mixed clear air and cloud-filled region, thus making interpretation of the data significantly more complicated.

A constellation of balloons can be used to position radiometers globally in the stratosphere for a direct radiation balance determination. This can be accomplished by positioning a pyronometer on the balloon tether. This pyronometer can be automatically flipped to alternately measure outgoing and incoming radiation to an accuracy of better than 1%, equal to the absolute radiative accuracy of the satellite instruments. The radiation must be measured from the ultraviolet (0.2 microns) through the infrared (100 microns), using filters to divide this full region into about 5 regions so that changes can be isolated to specific physical causes.

Because of the versatility provided by the tether for positioning instruments, we propose to position pyronometers at the bottom of the tether at about 20 km, and above the ozone layer at the gondola at 35 km, allowing duplicate measurements for each balloon platform. Because the ability to interpret the data is related to the effects of cloud cover, we include a cloud LIDAR instrument at the balloon gondola as well. Additionally, it is currently believed that using an FTIR would be the most accurate way to do this experiment. While it may be prohibitively expensive to plan for an FTIR on every balloon platform, this global monitoring approach lends itself to cross calibration in the infrared with one or more platforms with FTIRs specifically flying for reference measurements. Together these options show the advantages of making these measurements using a constellation of balloon-borne payloads. Figure 3.2 illustrates this constellation mission concept.

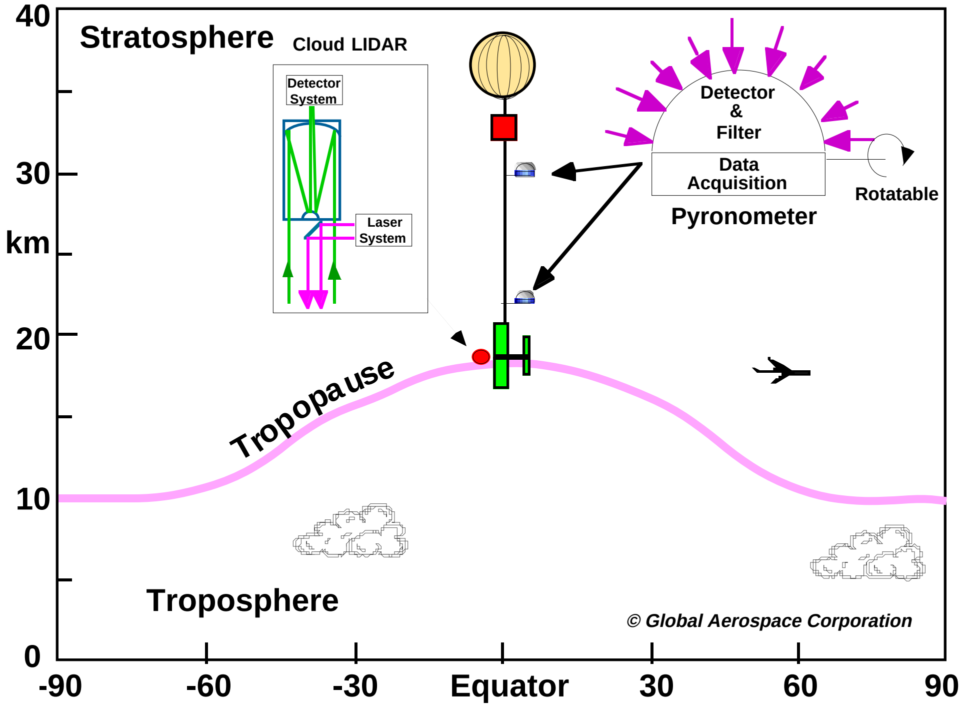


Figure 3.2 Climate Change: Global Radiation Balance

3.3 Ozone Studies

3.3.1 Mid-latitude Ozone Loss

The recent Stratospheric Processes and their Role in Climate (SPARC) report on ozone showed that during the past ten years mid-latitude ozone in the lower mid-latitude stratosphere from about 12 to 15 km has decreased by about 1%/year. It has been postulated that *in situ* heterogeneous chemistry on thin cirrus could be responsible for this decline. Alternatively, transport of low ozone air from the tropics or from the polar region has also been suggested as a possibility. It has also been suggested that variability of tropopause height could be the cause. The ambiguity results from the fact that any other tracer of atmospheric transport did not accompany the ozone measurements. Because of the high resolution required by these measurements, where only measurements above the tropopause are to be considered, satellite instrumentation can not address this problem, which requires continuous monitoring. This constellation mission concept addresses a key question which is listed above as the fifth research question to be addressed by the ESE during the next several tears, namely, how and why are ozone concentrations and distributions changing?

The payload, pictured in Figure 3.1, would provide simultaneous measurements of ozone, water vapor, and nitrous oxide at intervals above the tropopause, as well as the temperature profile above and below the sail. For this payload, three highly accurate *in situ* multipass absorption instruments can be positioned at 1-km intervals above the sail, with an additional one close to the sail. A microwave temperature profiler, alternately upward and downward looking, will locate the tropopause. To provide adequate coverage for this experiment will require a approximately 10 balloon payloads stationed in northern mid–latitudes.

3.3.2 Polar Ozone Loss

Data have shown that the potential for Polar ozone depletion is prevalent and depending on the length of time the vortex holds together, how long the temperatures in the vortex are 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. Quantitatively understanding ozone loss requires the ability to calculate the fraction of air mixed into the vortex and what is the character of that air.

3.3.2.1 Current Plans

A NASA sponsored mission: SOLVE, utilizing balloon and aircraft instrumentation is designed to study the formation and breakup of the vortex. This type of mission requires 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 balloon payloads with proven instrumentation are planned and are listed 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.

Harvard Smithsonian FIRS-2 far-infrared spectrometer provides 2 km altitude resolution and measures O_3, N_2O, nitric acid (HNO_3), nitrogen dioxide (NO_2), nitrogen pentoxide (N_2O_5), H_2O, the hydroxyl radical (OH), and hydrochloric acid (HCl).

3.3.2.2 Proposed Constellation Concept

Balloon payloads similar to these that are deployed in the Arctic and maintain their position throughout the fall winter and spring would provide critical information during years with and 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, a Microwave Limb Sounder would be flown. This instrument would be similar in capability to the one flown on the Upper Atmosphere Research Satellite and would specifically be used to measure reactive species responsible for ozone loss. These include chlorine monoxide (ClO), bromine monoxide (BrO), key radicals responsible for ozone destruction. The *in situ* payload would be used to quantitatively measure ozone loss in the vortex, 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 3.3 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 constellation of 10-20 StratoSats each operating in a region from 60° to the pole.

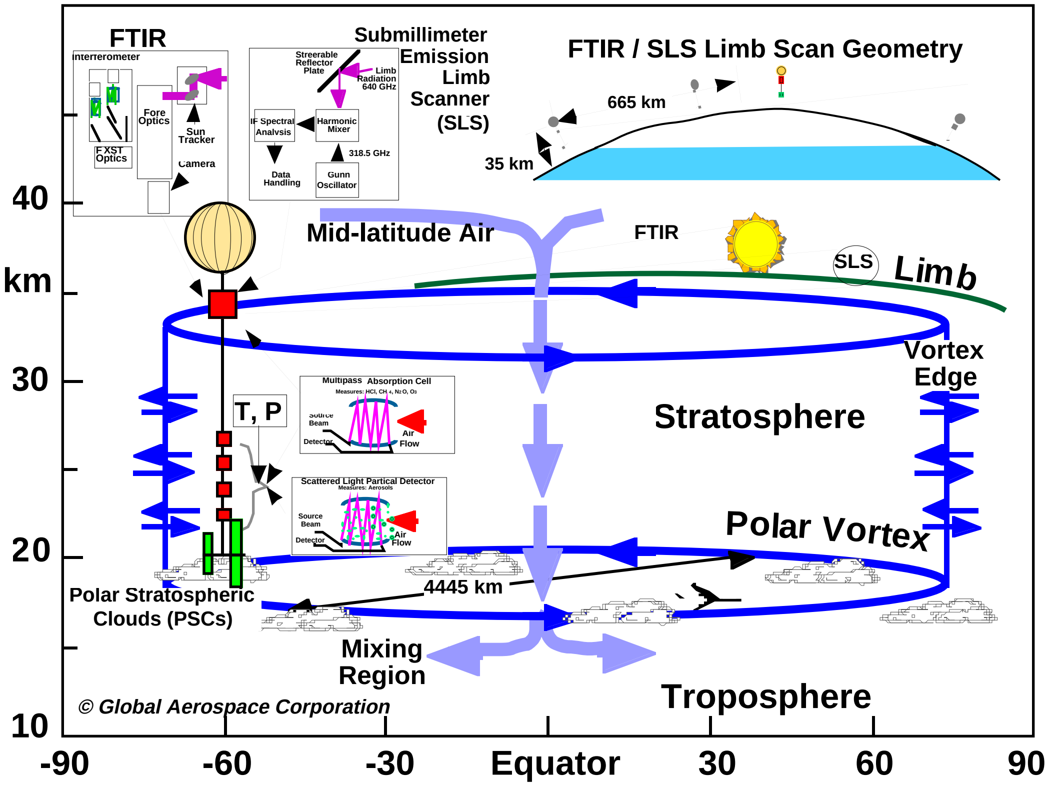


Figure 3.3 Ozone Studies: Polar Ozone Loss

3.3.3 Global Distribution of Ozone

This constellation concept addresses global ozone distribution; tropospheric monitoring for trends in rural areas as well as in outflow region from large emission areas; global determination of stratospheric-tropospheric exchange.

Monitoring ozone concentrations both by satellite and using ozone sondes has provided a means of determination variations or trends in ozone both in the stratospheric and in the troposphere. While satellite based instrumentation provides worldwide coverage of the stratosphere, they are of limited value in the troposphere. The sondes can only be launched from land or in special instances from ships. This means that there are large remote areas, especially in and near the tropics, where there is no coverage. There are a number of areas of research that could benefit from the measurements of ozone profiles in remote areas. In the region of the tropopause, understanding the mass flux from the stratosphere into the troposphere is required understand the sources of ozone in the troposphere. Making these measurements on a regular basis in the context of various meteorological conditions would allow for a statistical determination of this mass flux. To do this properly, it would be very valuable to simultaneously measure water vapor and temperature on the sonde. However, because these sondes would be dropped from about 35 km, the utility of adding nitrous oxide or methane to the measurement, would provide invaluable information on transport of air in the stratosphere as well. New infrared measurement techniques are currently under development which can be extended from water vapor to N_2O and/or methane and potentially result in a powerful experiment, monitoring tropospheric ozone, investigating stratospheric tropospheric exchange, and supplementing the radiosonde network, especially in the tropics where it is severely lacking. It is especially important to monitor tropospheric ozone in remote rural regions far from pollution sources because this represents a worldwide background level of pollution and is important to measure when considering the magnitude of pollution sources in urban areas. Figure 3.4 illustrates this constellation and payload concept.

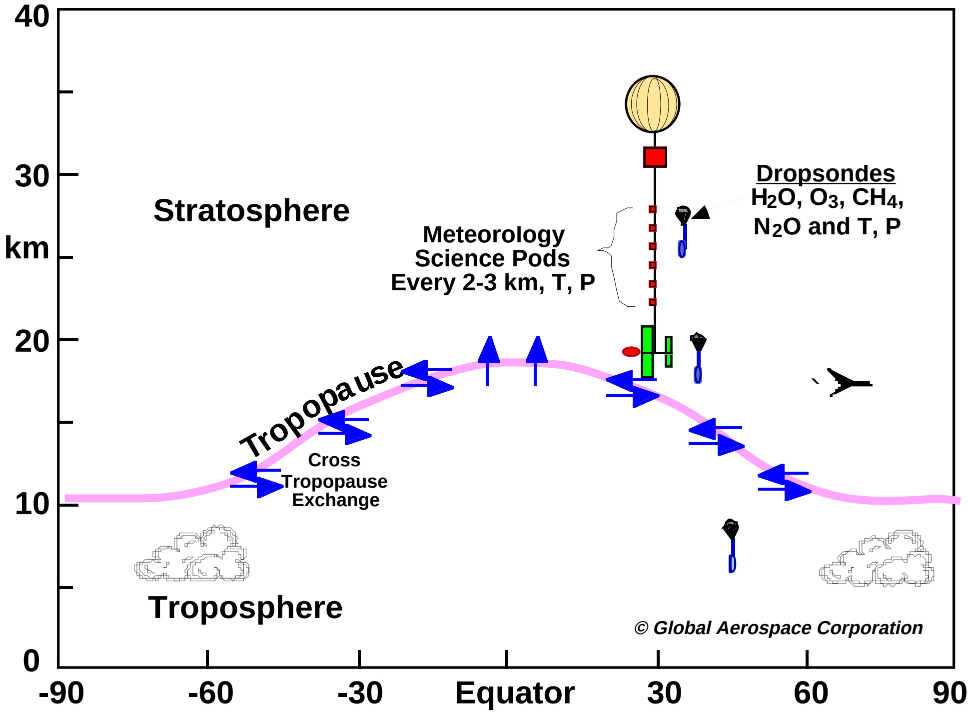


Figure 3.4 Ozone Studies: Global Ozone Distribution.

This payload would contain dropsondes to measure the suite of molecules described above. With the advances in technology currently being proposed for a water vapor sonde extended to ozone and methane or N_2O a sonde package of about 0.25 kg is projected. Accordingly, 400 sondes could be carried and launched at a rate of 1/day

Additionally, certain areas, whether it is the Asian continent coast of the United States, or biomass burning regions in South America, monitoring significant pollution sources it critical in understanding their contribution to global pollution levels. For monitoring these pollution sources, a nadir looking FTIR on the gondola monitoring thermal emission can provide the continuous operation necessary for this experiment, again where satellite instrumentation can not make these continuous regional tropospheric measurements. These instruments, looking at thermal emission, can make simultaneous measurements of ozone, water vapor, carbon monoxide, and nitric oxide.

The experiments near the tropopause require simultaneous high-resolution measurements that are beyond the capability of satellite-based instrumentation. While satellite-based instruments designed to detect tropospheric species are planned, because of their lack of resolution and orbital characteristics they are not appropriate for continuous monitoring of localized pollution sources in the troposphere.

3.4 Hurricane Forecasting and Tracking

Disruption of life and devastation of property typically occur along the path of a hurricane. 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.

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 balloons 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 10 to 25 grams, each balloon payload could have more than 1000 sondes for this experiment. Which provide profiles from balloon altitude to the surface.

Because this balloon constellation 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 were 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 a climatology 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.

3.5 Global Circulation and Age of Air

All models that integrate transport and chemistry depend on their ability to model the transport of air. Currently models have difficulty with transport times in the stratosphere. Also, there are predictions that that there might be a relationship between global warming, ozone depletion, and changes in the global circulation. Monitoring the age of stratospheric air would provide significant help in understanding global change. This stratospheric monitoring on a continuous basis global circulation can be best accomplished by continuous *in situ* measurement of tracers of stratospheric transport, CO_2, N_2O, H_2O, CH_4, temperature, and pressure, at 2-3 km intervals along the tether. The most significant challenge to this experiment involves measuring CO_2 with sufficient accuracy under severe weight restrictions. This payload will require significant technical innovation to provide a calibration system adequate for the enumerated science goals. A 1-ppmv accuracy for CO_2 will provide one level of information, yielding the mean age of an air mass. A 0.1-ppmv accuracy will reveal the age spectrum of the air, meaning how old are all the individual air parcels that make up the sampled air mass. A lightweight calibration system is required for this experiment.

3.6 Global Ocean Productivity

Oceans play a critical role in the global carbon cycle, other biogeochemical cycles, and have significant potential for affecting global change. Phytoplankton help regulate the partial pressure of carbon dioxide in the water thereby affecting its air-sea exchange rate. As such, monitoring aspects of ocean properties relevant to their productivity is a valuable means of monitoring ocean changes. Satellite instruments have been developed to do this as part of the SeaWiFS (Sea-viewing Wide Field of view Sensor) project. This instrument measures ocean reflectivity in a series of visible and near infrared bands from 400 to 855 ηm to monitor ocean color and chlorophyll levels with a goal toward tracking changes in different ocean regions.

Satellite-based instruments such as this must rely on difficult calibration techniques using the sun and moon as light sources. Additionally, measurements have a large footprint meaning the data is averaged over a large potentially inhomogeneous ocean region. Furthermore, the data analysis must include an understanding of the absorption and scattering properties of the atmosphere in the field of view of the instrument. These limitations make it very difficult to validate this satellite-based data set for trend measurements.

Utilizing a constellation of balloons, visible filter radiometers, or possibly a grating spectrometer for improved resolution, similar to the aircraft-borne AVARICE instrument, positioned on the gondola could provide a data set much more straightforward to analyze. Additionally, each instrument’s footprint is significantly smaller and therefore can be positioned to characterize a part of the ocean where specific questions might be of interest. For example, the impact of increasing ultraviolet radiation on ocean organisms in polar regions can be most efficiently monitored with one or more strategically positioned payloads. In another example, coastal regions, especially where there is strong interaction between rivers and the ocean waters, provide another ideal application for a balloon-borne monitoring instrument. Finally, continuous monitoring of the extent of ice cover in regions where satellite coverage is difficult or limited can be an ancillary result of this monitoring constellation, again with strategically placed balloon platforms.

The flexibility of this monitoring system allows identifying specific regions of ocean activity or potential change, and adjusting to this characteristic.

4 Key System Requirements and Assumptions

4.1 Introduction

The following requirements are a summary of those presented in our *Global Constellation of Stratospheric Scientific Platforms (StratCon) Conceptual Design Requirements Document, Version 0.4* (GAC Report 510-02511-002, July 31, 1999).

4.2 Definitions

In order to understand the system requirements and the subsequent descriptions, we define some key terms that are used throughout.

- Global Constellation – A global constellation is defined as a collection of balloon platforms that are globally distributed.
- Regional Constellation - A regional constellation describes a collection of balloon platforms that are distributed over a major fraction of the Earth, such as the North or South Pole.
- Network – A network is a collection of balloon platforms that operate together to perform a task or to achieve a particular observational or communications objective. A network can be comprised of a global or regional constellation of balloons.
- System – A system is collection of interacting hardware and/or software elements that form a unified whole (e. g. platform system). Also, a group of platforms forming a network for distributing something (e. g. data) or for serving a common purpose (e. g. constellation).
- Platform – A platform is the combined balloon, gondola, trajectory control and payload system.
- StratoSat – StratoSat is another name for an individual stratospheric platform.
- Subsystem – A subsystem is a collection of hardware and/or software elements within a system which perform a specific, high-level function (e. g. power subsystem)
- Component – A component is hardware and/or software elements which are assembled into subsystems

4.3 Constellation Assumptions

4.3.1 Classes of Constellations

At this time there are several different types or classes of constellations largely based upon their science application objectives. For some science applications, such as *in situ* atmospheric and global circulation measurements a sparsely populated network may meet the science requirements. For global and simultaneous remote sensing scientific observations and reconnaissance, a densely populated network that has few, if any, gaps will be required, depending upon science objective. In addition, there appears to be strong scientific interest in sub-constellations that might only provide regional coverage, e. g. South Pole scientific ice observations or studies in the tropics. There may well be an evolution of constellations driven by scientific, political, and economic factors.

4.3.2 Science Capabilities

4.3.2.1 Communications

Data rate requirements will vary considerably depending on the objectives of the constellation. For making basic meteorological and *in situ* measurements, data rates on the order of <10-100 kbits/s may be sufficient. For surface remote sensing the required rates could be quite high. For example, if a StratoSat is required to image the Earth at 10 meters/pixel (measured at the nadir) every 5 km of its motion, a equivalent uncompressed data rate of about 6 Mbits/s per platform would be required, assuming a 50 m/s wind speed and 8 bits/pixel quantization level. Of course, if the imaging occurs less frequently or at a lower resolution, data rate requirements are lowered. It is expected that the communications requirements will be more demanding for the larger continuous networks with surface remote sensing science requirements than for sparse networks with *in situ* objectives.

4.3.2.2 Science Payload Mass

Science payload mass is defined as science instrument and sensor hardware and does not include engineering support hardware such as power, robotic controller, basic attitude sensing and control, telecommunications, mechanical structure, trajectory control nor basic thermal control subsystems. However, science payload mass includes specialized thermal (cryogenic) and pointing (arc sec) control subsystems when required to perform the basic science activity and when these requirements are not generally needed by the other science instruments carried. Science payload mass capability shall be 25-140 kg depending upon altitude and allowable balloon size selected. Lower altitudes and large balloons will yield larger gondola masses and subsequent larger science-mass capability. It is a goal to have a science-to-gondola mass ratio of 70% or greater.

4.3.3 Political Overflight

It is assumed that future agreements and treaties will allow and enable overflight of Earth's political boundaries by a global Earth science StratoSat network. The 1992 Open Skies Treaty is a step in this direction. At this time many countries have signed this treaty including all NATO countries, Russia, Ukraine, Belarus, Hungary, Poland, Romania, Czech Republic, Slovakia, Bulgaria, and Kirgizstan. To date, Japan, South Korea, Australia, and several Middle Eastern nations have expressed interest.

4.3.4 Telecommunications

It is assumed that sufficient telecommunications infrastructure will exist in the future, in space and on the ground, to support the communications needs of a global StratoSat constellation. (Our studies have also looked at augmenting or developing independence from this infrastructure using the StratoSat systems.)

4.3.5 Environment

It is assumed that worldwide stratospheric wind information is available with sufficient accuracy to support constellation guidance and control and maintenance operations. (Indeed, a balloon constellation will likely contribute to the database from which this wind information will be available.)

4.3.6 Balloon Technology

Continued advance in balloon technology for stratospheric systems is assumed, including lightweight balloon envelopes, trajectory control systems, lightweight gondola components and termination subsystems.

4.4 Network-level Requirements

These requirements are intended to drive the conceptual design of the overall network including the stratospheric platforms or StratoSats and the operations elements such as operations control and network replenishment centers.

4.4.1 Float Altitude

The StratoSat system design shall have a basic capability of carrying payloads to 30-45 km altitudes. The exact altitude is dependent upon the balloon size and payload mass. It is expected that a fixed balloon size and altitude will eventually be selected within this range. For purposes of design studies a nominal altitude of 35 km will be assumed. (The impact of float altitude differences on balloon design has been analyzed parametrically, see Section 7.1.1.)

4.4.2 Number of StratoSat platforms

The number of StratoSats in a global constellation can vary from a few to several hundred. For the purposes of this study several constellations sizes will be examined depending upon science requirements. For a polar science, sub-network a constellation of 25-50 may be needed. For global circulation and *in situ* observations a network of 100 StratoSats may be required. Where science requirements demand complete, simultaneous coverage of the Earth, 500 StratoSats will be required, assuming a float altitude of 35 km.

4.4.3 Replenishment Rate

For the purposes of the systems design and costing, a per year 3% replenishment rate will be assumed, although this number is very uncertain at this time before the conceptual design has matured. The exact determination of this number requires information on subsystem reliability, especially balloon envelope lifetime and degradation processes.

4.4.4 Constellation Geometry Control

The basic requirement is to maintain as uniform a constellation as possible. Science requirements, which demand complete and simultaneous coverage of the Earth's entire surface, could involve a high level of control authority and complexity. The current requirement for constellation control is to achieve an average separation of 1800 km ± TBD for a 100 StratoSat constellation.

4.5 Platform-level Requirements

4.5.1 Safety

The StratoSat shall meet all the applicable requirements of world aviation authorities (See for example Federal Aviation Administration, Federal Aviation Regulation (FAR) Part 101--Moored Balloons, Kites, Unmanned Rockets and Unmanned Free Balloons). The StratoSat shall have a means of determining and to monitoring the health of key subsystems, including the balloon. In addition, the StratoSat shall have an ability to safely terminate a mission in the event a catastrophic failure occurs.

4.5.1.1 Health Monitoring

Each StratoSat shall have an independent means of determining and monitoring the health of its subsystems. In the case of the balloon subsystem, a means shall exist of monitoring buoyant gas leakage and balloon envelope degradation and predicting future performance. Sufficiently instrumented, a StratoSat mission termination can be planned over a desired landing and recovery zone before its health deteriorates to a level where a catastrophic failure can occur without warning.

4.5.1.2 Termination

Each StratoSat shall have redundant means to safely terminate its mission either from self monitoring or from ground command (See Section 7.2.8 for definitions of termination modes).

4.5.2 Recovery

In order to minimize the environmental impact, all major StratoSat subsystems and assemblies shall be recoverable after nominal platform mission termination. There are no requirements for reuse of any subsystem after recovery.

4.5.3 Connectivity

Several types of connectivity are required to enable data return and command capability, safety, and termination and recovery capability. Some connectivity requirements will require redundant systems to provide the required level of reliability.

4.5.3.1 StratoSat / Operations

Each StratoSat shall be able to transmit equivalent uncompressed data to one or more ground stations at 6 Mbits/s and receive low rate commands from an operations center.

4.5.3.2 StratoSat / Satellite

StratoSats shall be able to transmit data to and receive commands from TBD satellites. StratoSats shall be able to receive signals from Global Positioning System satellites for navigation purposes.

4.5.3.3 StratoSat / World Aviation Authorities

Each StratoSat shall be able to be identifiable by world aviation authorities. This will include radar reflectivity and transponders where operation is expected within controlled airspace (generally considered below 18.3 km or 60,000 ft.)

4.5.4 Reliability and Lifetime

StratoSats shall have a nominal lifetime of 5 years with a goal of 10 years life. We know that the buoyancy gas loss and balloon envelope degradation will limit lifetime. In addition, periodic (but rare) failures are expected of other subsystems. StratoSat failure rates are expected to be initially high as infant mortality drives the reliability. As mission duration continues the rate again grows as buoyancy gas leakage and balloon envelope material degradation (UV in particular) begin to take their toll. In fact, the structure of the failure rate curves will be similar to those of the global LEO communications networks currently being put into orbit. As indicated above, a 3% replenishment rate is being assumed at this stage of the design in the absence of definitive information on overall subsystem reliability.

5 Advanced Technology

5.1 Introduction

A number of new technologies were investigated for StratoSats. These new technologies included balloon envelope materials and new structural designs, stratospheric wind and trajectory simulation modeling capability, balloon trajectory control, power generation and energy storage and telecommunications. This section describes the advanced technology requirements identification, comparison and analysis.

5.2 Balloon Envelope Materials and Structural Design

5.2.1 Materials

The properties of the balloon shell material determine the ultimate mass and size of the balloon more than any other factor except nominal payload and altitude. The selection of materials is based on the maximum stresses the balloon will encounter based on ambient conditions at float and on thermal conditions during the day/night cycle. The absorptivity and emissiviy of the material are of concern as are the material's ability to prevent helium molecules from diffusing through the material and escaping to the atmosphere. The properties of some current and future balloon materials are presented in Table 5.1. "Advanced ULDB" materials refer to the most likely candidate that is a co-extrusion of low-density polyethylene with a layer of gas barrier material with something added to increase the yield strength of the material.

Table 5.1 Films for Balloon Use

Name	Design Strength Limit (MPa)	Density g/cc	Low Gas Permeability
Polyester (Mylar)	69	1.34	Very Good
Polyethylene	10.3	0.92	Good
Nylon	82.7	1.2	Very Good
PBO	1034	~1.5	Excellent
ULDB Advanced	20.7	0.92 - 1.0	Excellent

Note: To convert material density to grams/m^2, multiply the density by 25.4 and by the film thickness in mils.

Many of these films would be excellent candidates for deposition of thin film photovoltaic layers so that part or all of the gores would contain a power generating solar array for the balloon payload. The primary concern in taking advantage of the large surface area of the balloon as a solar array would be to dissipate or reflect the solar heating that would occur on the balloon film/solar array. Building the balloon with a double layer to prevent the hot outer layer from touching the inner layer could solve this problem.

In addition to films, fibers are currently used to weave high performance fabrics for laminating to the films above to produce a composite material that would gain its strength from the fabric and gain gas barrier properties from the film. Current fibers are presented in Table 5.2

Table 5.2 Fibers for Balloon Use

Name	Tenacity (g/denier)
Polyester	7
Vectran	20
PBO	41

5.2.2 Manufacturing Methods

Following is Table 5.3 describing seaming methods and which Raven has identified in previous work as being compatible with the potential materials for StratCon. Many of these methods have been used in the production of test articles in the development of the NASA ULDB.

Table 5.3 Seaming Method Matrix

Seaming Method	Compatible Materials	Remarks
Heat sealing	Polyethylene	- Severely weakens highly oriented films such as Mylar and Nylon
Ultrasonic sealing	Dense weave fabrics	- Excellent results on synthetic fabrics. - Results on fabric film composites were disappointing because the amount of energy required to form a gas tight seal also damaged the fibers in the fabric.
Sewing	Dense weave fabrics	- This method is applicable mostly to dense weave fabrics and some fabric/film composites that have dense enough weave patterns. - Sewing needle holes must be covered by tape.
Adhesives	All films	- Current method of choice for ULDB project - Temperature range is a challenge for current adhesive technology. - Adhesive formulations are proprietary

5.2.3 Structural Design

Two basic options exist for the StratoSat balloon design, namely a (1) zero pressure, open balloon or a (2) superpressure, fixed-volume, closed balloon. Because the open balloon requires the use of consumables to stay aloft at a particular float altitude, it is not considered a viable candidate for a very long duration balloon system. Fixed volume, superpressure balloons offer the ability to float at a density altitude equivalent to the average density of the entire balloon system. These balloons are called superpressure because as they reach ceiling altitude, the balloon envelope becomes pressurized as the skin is stressed because it can no longer expand. The level of superpressure depends on the initial buoyant gas loaded and the design altitude. The key elements limiting the performance of superpressure balloons are balloon structural design and envelope material strength.

At least two types of super pressure balloons have flown, namely Euler Elastica or pumpkin balloons (Figure 5.1 for a comparison of spherical and pumpkin balloon shapes) and spherical balloons. For a spherical balloon, the stress on the envelope is defined by classic “hoop stress” equation. The stress is equal to the level of overpressure, relative to the ambient, times the balloon radius divided by twice the thickness of the material (for homogeneous, single-component materials). Since the radius of a balloon can be large, the stress on the spherical balloon envelope can also be large. The pumpkin balloon design attempts to minimize this radius through a lobed, multi gore structural design where in the transverse direction the radius is no more than one or two meters. In the longitudinal direction, load bearing “tendons”, usually bundles of strong fiber or stiff tapes, carry the longitudinal stress on the envelope. A pumpkin balloon design can reduce the material stress by almost an order of magnitude. The penalty of a pumpkin balloon is the 10-15% more surface area for the same volume as a spherical balloon.

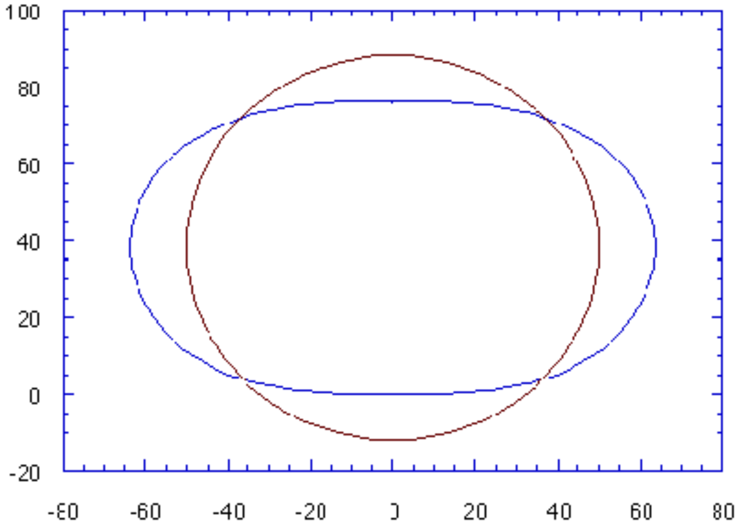


Figure 5.1 Comparison of spherical and pumpkin balloon shapes for constant volume

Because the load carrying function is assigned to meridional load tendons instead of the envelope film, it forces the load tendons to follow the outline of the zero-pressure “natural shape” balloon as shown above.

Because of the surface area penalty and the inherent stress on the lobed film gores of pumpkin balloons, a spherical balloon concept using film with embedded high strength scrim is attractive. We investigated the spherical designs that represent an advance over current ULDB technology. The trade off between spherical and pumpkin balloons is discussed further in Section 7.

5.3 Stratospheric Winds and Trajectory Simulation

Analysis of the behavior of a constellation of global stratospheric scientific platforms (StratoSats) can only be conducted by knowing the environment in which the constellation operates. In particular, stratospheric winds determine the evolution of the geometry of the constellation. This section reviews data sources for stratospheric winds, discusses the processes used to compile and make sense of the data, reviews the state of the art in trajectory simulation, and suggests a future direction for a technology advancement that combines stratospheric forecasting with trajectory simulation and constellation management.

5.3.1 Background

5.3.1.1 Stratospheric Data Sources

Although most atmospheric environment resources are confined to the troposphere, some stratospheric data sources exist. We discuss three types of stratospheric data sources below: climatologies, the rocketsonde network, and daily operational analyses and assimilations.

5.3.1.1.1 Climatologies

Climatologies provide monthly, or better, averages of atmospheric parameters, including temperature, pressure, and winds. One example climatology is a computer-based model that was developed in response to the need for design reference atmosphere. It provides complete global geographical coverage and complete altitude coverage (surface to orbital altitudes) as well as complete seasonal and monthly variability of the thermodynamic variables and wind components. It can calculate representative atmospheric conditions at any point in the atmosphere. Simulated, not actual, daily variability of winds and temperature are included.

Another stratospheric climatology resource is an “atlas” of climate conditions from 1979 to 1990 consisting of charts of geopotential heights, altitude-latitude slices of zonal averaged quantities (temperature, zonal-averaged winds, momentum fluxes, vorticities, etc.), latitude-time slices, and daily and interannual variations. The data for the graphs and charts originates from daily operational analyses, which are based on radiosonde soundings and TOVS satellites.

By their nature, climatologies do not provide sufficient temporal or spatial resolution to perform realistic trajectory simulation.

5.3.1.1.2 Rocketsondes

A second type of stratospheric environment data, rocketsonde data, provides measurements of instantaneous, not averaged, stratospheric conditions. For decades, a worldwide network has probed the stratosphere, providing the first glimpses of stratospheric circulation patterns. However, rocketsonde data is limited in the Southern Hemisphere, and the data are not readily available in electronic format. Furthermore, the amount of rocketsonde data per year is diminishing as the number of rocketsonde launches declines each year.

5.3.1.1.3 Daily Stratospheric Analyses or Assimilations

A third type of stratospheric environment data, daily operational analyses or assimilations, provides daily, global, gridded, digital “snapshots” of the state of the atmosphere. They are built from observational data sources that include the radiosonde and rocketsonde networks, NOAA polar-orbiting satellites, GOES satellites, ship and aircraft reports, and ocean buoys. Observational data flow into the Global Telecom System (GTS) and subsequently to atmospheric centers where analysis or assimilation systems ingest the data and produce “snapshots” of the condition of the atmosphere.

There are several organizations with the capability to perform daily stratospheric analyses or assimilations. Each center uses a different numerical algorithm to produce the gridded, digital data products. Broadly speaking, the methods can be categorized by those that utilize a General Circulation Model (GCM) to assist the analysis and those that do not. *Assimilation* is the process by which atmospheric observations are inserted into a running GCM to influence the GCM toward minimization of the differences between the observations and model. *Successive correction* is the process by which first-guess fields of temperature and height are adjusted by weighted averages of nearby observations. Successive correction does not utilize a GCM to interpret the observational data. Assimilation is a newer and more computationally intensive technology than successive correction.

5.3.1.2 Stratospheric Forecasts

Typically, those organizations that provide daily stratospheric assimilations also have the capability to perform short-range stratospheric forecasts (~5 days) using the daily stratospheric assimilations as the initial conditions for each forecast. The forecasts are often run using the GCM that performed the assimilation. In the present study, forecasts were not utilized for any of the constellation simulations.

5.3.1.3 Need for In-situ Stratospheric Data

Today, the dearth of *in-situ* observational data in the stratosphere is a significant issue for stratospheric data assimilation and forecast systems. The worldwide radiosonde network does not collect data above 10-hPa pressure altitude and is therefore not useful for stratospheric forecasting. Historically, rocketsondes have provided some *in-situ* observational stratospheric data, but rocketsonde launches are becoming less frequent. In addition to decreasing data frequency, rocketsondes have the additional drawback of providing data at only one location at only one point in time. Without high-quality stratospheric input data, forecast accuracy suffers. Stratospheric weather forecasters are in need of improved *in-situ* stratospheric observations.

5.3.1.4 Current Trajectory Simulation Technology

Trajectory simulation technology is being developed by Global Aerospace Corporation to support NASA Ultra Long Duration Balloon Project. Specifically, we are developing a Trajectory Simulation and Prediction System that provides the capability to simulate trajectories in the mission operations environment. The TSPS can simulate either (a) actual real-time or historical balloon flights or (b) simulated balloon flights based on assimilated or forecast environment conditions at a particular time.

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. Figure 5.2 shows the TSPS display.

During Phase 1, we extended our existing trajectory simulation technology and developed new capabilities to simulate the evolution of networks of stratospheric platforms. This new simulation technology includes the capability to predict the trajectories of hundreds of balloons simultaneously, to utilize arbitrary methods of controlling the trajectory of individual balloons, to analyze the state of the network at any instant during the simulation, to display and save the state of the network during simulation.

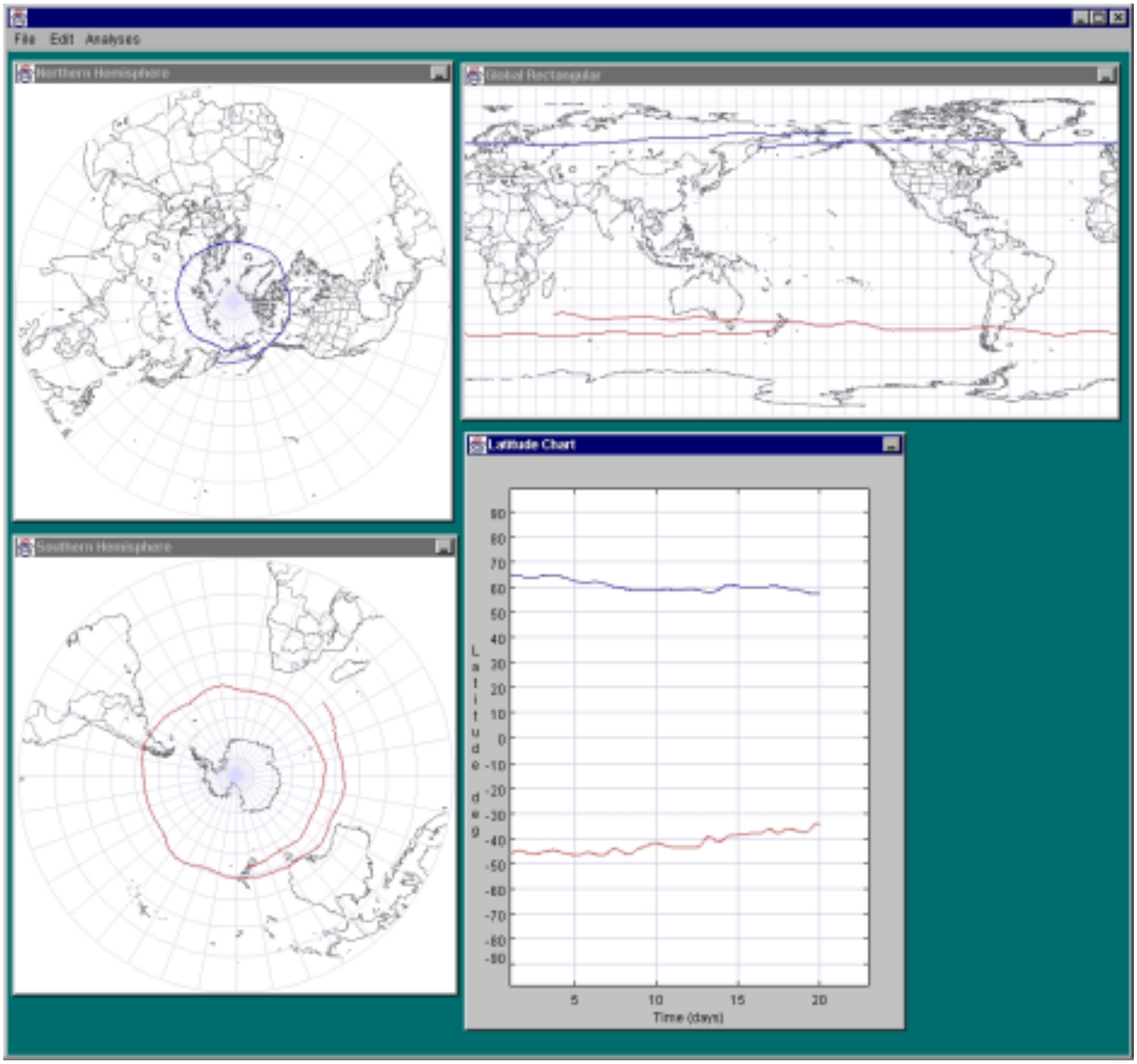


Figure 5.2 TSPS Screen Display

5.3.2 Improving Forecasts and Trajectory Simulations

A global constellation of stratospheric scientific platforms may fill the need for *in-situ* stratospheric observations by providing a continuous stratospheric presence on a platform that can directly sense the winds. Advantages of using a stratospheric constellation for *in-situ* observations include continuous temporal and spatial coverage and direct measurement of the winds.

Figure 5.3 shows how a constellation of stratospheric scientific platforms could be used to improve stratospheric forecasts which, in turn, assist in managing the geometry of the constellation. Wind observations from the StratoSats are used as input data for the stratospheric forecast process. By using the StratoSat data, the accuracy of the forecasts will be improved. The operations center uses the improved forecasts (from the stratospheric forecast center) and the constellation geometry (as reported by the StratoSats) to determine the optimal control for each individual StratoSat. The operations center effects this control over the constellation by sending commands to each individual trajectory control system.

This potential use of in-situ data obtained by the constellation represents a revolutionary opportunity to increase the accuracy of stratospheric assimilations and forecasts.

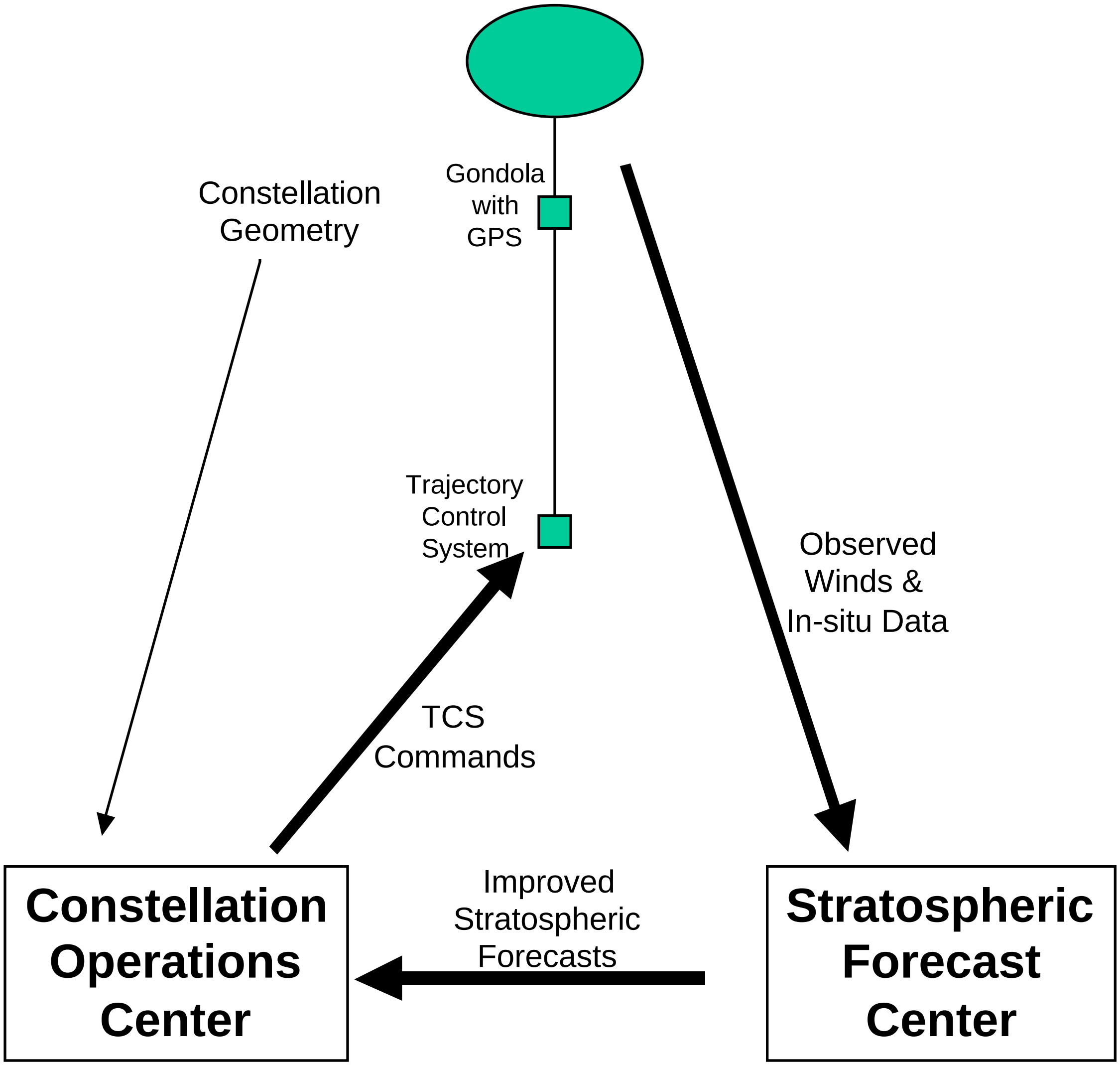


Figure 5.3 Integration of StratoSat observed winds with stratospheric forecasts.

5.3.3 Future Constellation Control Strategies and Algorithms

In the future, additional technology developments will make it possible to incorporate the use of stratospheric forecasts and detailed trajectory control system models when controlling the geometry of the constellation. To date, we have analyzed several constellation management strategies and algorithms. Details of those analyses can be found in Section 6.

5.4 Trajectory Control Concepts

In this section we discuss a variety of approaches to balloon trajectory control, describe the design planned for the ULDB Project under NASA SBIR funding and explore possible future TCS concepts; their advantages and disadvantages.

5.4.1 Background

Until Global Aerospace Corporation began developing the StratoSail™ TCS, no known devices have used or even suggested the use of a lift-generating device, such as a wing, suspended on a long tether, to effect trajectory control of a balloon. However, a very few devices have been used to control the trajectory of free balloons, such as balloons carrying scientific atmospheric sensing instruments. Propeller-driven airships obviously control their trajectories. However, the attainable altitude and payload mass for airships are quite restricted in comparison to free balloons. Free balloons carrying science instruments typically drift freely in the prevailing wind at the operating altitude. In many cases, launch of such balloons must be delayed until forecast winds are projected to carry the balloon system into a region of interest, or away from a forbidden zone. Frequently, such balloon flights must be terminated prematurely to avoid flying over countries that have not given permission, or to ensure that the payload descends into an appropriate landing site, or to avoid endangering densely populated regions. The ability to provide even a small amount of trajectory control could eliminate these reasons to terminate the flight early.

Previous approaches considered to control the trajectory of free balloons have included propellers, altitude control to select different wind directions, and drag chutes on long tethers. Propellers require substantial power to drag a balloon through the atmosphere. At the high altitudes typical of scientific balloons, the air has very low density. At these high altitudes, propellers need to be quite large in order to generate substantial lift. Also, significant amounts of power are typically unavailable from balloon systems, again due to the inherent need to keep weight to a minimum. If the power is generated using solar cells, then nighttime operation is not possible without very heavy batteries. If combustion provides the propulsive power, then the duration is limited by the weight of fuel that can be carried. These requirements for propulsive power are at odds with the need to keep the weight low.

5.4.1.1 ULDB StratoSail™ Design

Under a recent Small business Innovative Research (SBIR) grant, Global Aerospace Corp. developed a conceptual design of a trajectory control system for use with NASA's Ultra Long Duration Balloon (ULDB) systems. In this section, we describe that design since it represents the current state of the art, and was the starting point for advanced TCS concepts developed in the current NIAC contract.

The ULDB Trajectory Control System (TCS) comprises three major elements, which will be discussed in turn: the tether, the TCS Interface Package (TIP), and the TCS Wing Assembly.

5.4.1.2 Tether

The tether is made of Polybenzoxizol (PBO), a high strength, low weight polymer known by the trade name Zylon. Braiding 12 yarns of 500 denier PBO to form a 6000 denier tether core forms the tether. This core is the load-bearing part of the tether. Figure 5.4 shows a close-up of the tether braid.

Figure 5.4 Tether Braid

PBO degrades when exposed to sunlight for extended periods, so some additional material must be added around the core to protect it. Various options are available: overbraids of other materials, extruded sleeves of black polyethylene, or wrapping with adhesive Mylar tape. The specifics of material choices and application methods will be developed during StratoSail™ Phase II.

5.4.1.3 TIP

The TCS interface Package (TIP) constitutes the TCS elements that remain attached to the gondola and “interface” with it. The main element in the TIP is a winch, which reels out the tether and controls the rate of descent of the TWA. Interface electronics, winch controllers, and computing and communications equipment are mounted in a small thermally-controlled enclosure. These avionics receive power from the gondola power subsystem. A mounting structure supports the winch and avionics.

5.4.1.4 TWA

Figure 5.5 shows an overall view of the TWA. The following sections describe the design of the TCS Wing Assembly (TWA). The main element of the TWA is the wing. Its function is to generate a side force that can be used to maneuver the balloon. The rest of the TWA orients the wing and controls its attitude in support of its primary function. The wing has a rectangular planform to aid the deployment and to permit each wing rib to be identical. A specific airfoil section has not been selected, but desirable attributes are a high maximum lift coefficient, low section drag coefficient, and gentle stall characteristics.

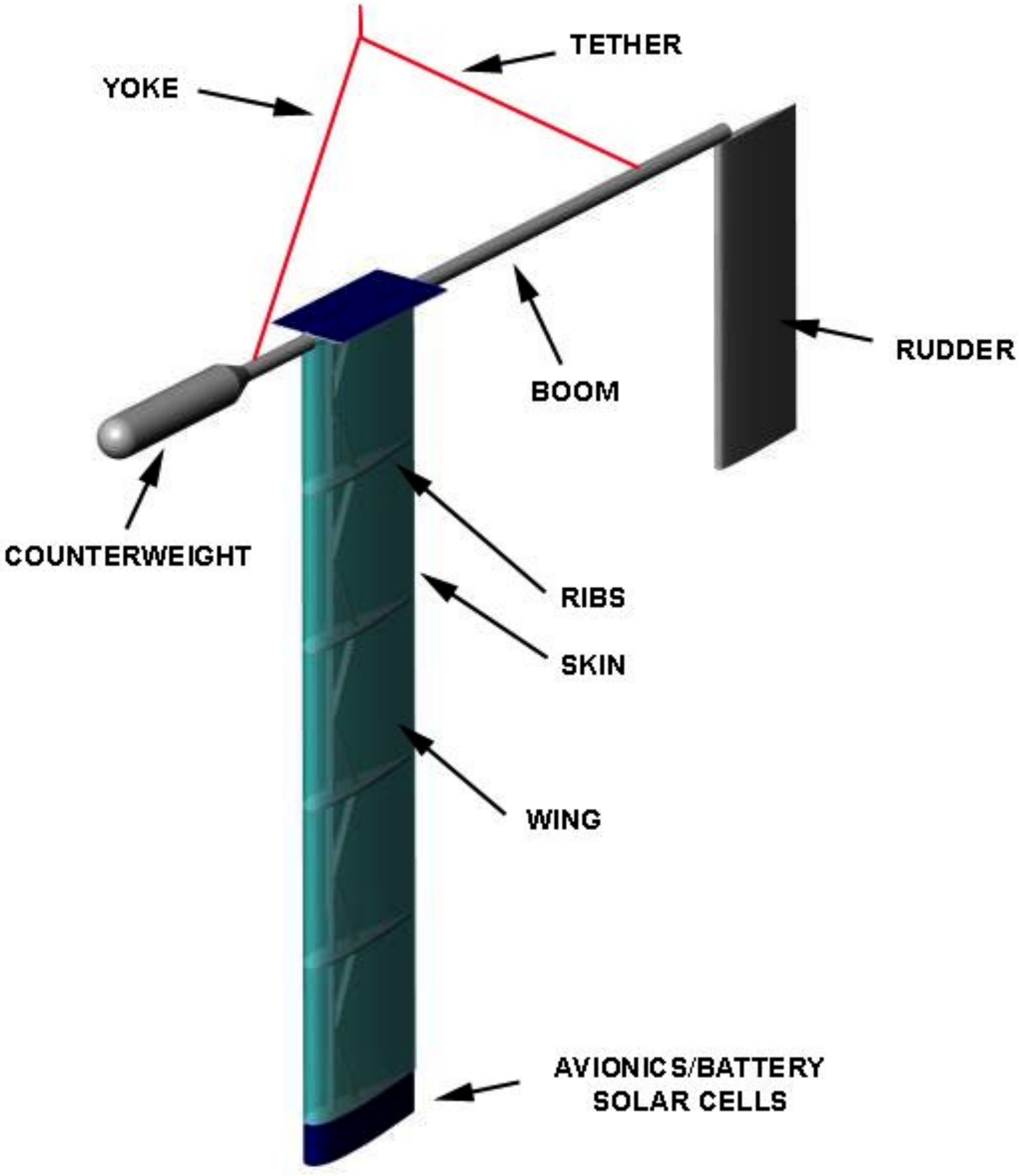


Figure 5.5 TWA Assembly

Because the wing must generate lift to both sides equally, we select a symmetric airfoil section. A cambered (asymmetric) section would produce a greater maximum lift force to one side, but would have lower maximum lift in the other direction. In principle, one could bias the design if it was known *a priori* which direction of control would be required for a particular flight. However, it is unlikely that a control direction would be known before a flight.

The purpose of the rudder is to stabilize the wing in pitch and to vary the wing's operating angle of attack. In the normal configuration of an aircraft, the stabilizer (horizontal tail surface) serves this function. On an aircraft, the rudder is the vertical tail surface and controls yaw. Given the vertical orientation of this surface, we chose to call it as the rudder. The entire rudder is rotated about a pivot at its quarter chord rather than using a separate hinged surface at the rear of the rudder.

5.4.2 Advanced StratoSail™ Design Options

Several options were considered for future StratoSail™ Trajectory Control Systems Wing Assemblies. These will be described in this section.

5.4.2.1 Biplane Arrangement

A biplane arrangement, rather than a single wing, is an option to increase wing area and increase structural stiffness. The two wings can be braced with wires. A disadvantage is that the bracing wires add a certain amount of drag. However, the tether already contributes a significant drag force, so the incremental drag from bracing wires may not be very important. The biplane arrangement may also be more difficult to stow compactly.

5.4.2.2 High Lift Coefficient Airfoil Sections

The original TWA included a symmetric wing suspended from one end. Since the lift force was changed from right to left by changing the angle of attack from positive to negative, a symmetric airfoil section was used to give the same performance to either side. This precluded the use of a cambered airfoil section. A moveable flap could have been used to increase the maximum lift coefficient, but the adding a flap would be difficulties due to the accordion folding nature of the stowed wing. Moveable flaps and cambered airfoils are more readily incorporated into the advanced symmetric wing described below.

5.4.2.3 Roll Control

Since the original TWA was suspended from one end, the lift force produced a moment about the support point, and there was a resultant roll of the system that depended on the lift force. This version of TWA was designed for light winds, and so the assumption was made that the weight of the wing assembly would significantly exceed the magnitude of the lift force. When heavier winds are expected, this assumption is not valid. In fact, in some conditions, the lift force magnitude can be greater than the TWA weight. In this case, the wing will swing well up to one side, eventually working its way up into lower density air and reducing the lift force until an equilibrium configuration is reached. The addition of some form of roll control would increase the operational flexibility of the TWA. Of course, this would also imply the need for some means of controlling the roll angle of the wing assembly.

5.4.2.4 Symmetric Dual Wing

The ULDB TCS wing deployed accordion-like in the vertical direction. This led to a configuration with just one wing supported at the top end. Unless the center of pressure and center of mass are balanced, there is a dynamic rolling tendency. A symmetric arrangement of two wings (left and right) would look much like a glider. The construction of such a TCS would naturally tend to be balanced (both mass and aerodynamic forces) by its natural symmetry. However, this arrangement does not lend itself to the accordion-style deployment. This arrangement is appropriate for a configuration that can be launched fully deployed. Also, the tether needs to be attached close to the center of mass. A possibility is to attach the tether using a yoke fastened to the front and back ends of the boom (fuselage).

5.4.3 Baseline Design Selection and its Characteristics

GAC has selected an advanced TCS Wing Assembly (TWA) option that uses a symmetric, dual wing design. Experiments performed in April 1999 indicated that roll control was attractive for a more capable TWA. Roll control will make the TCS more robust in very high winds and gusts that can be expected for long-duration global constellation control. Roll control also enables the TWA to easily generate more lift than its own weight, a limitation of the current ULDB TWA design. In the current ULDB design, when the winds are strong the TWA swings up and to the side, and climbs into lower density air. Also, the magnitude of the relative airspeed decreases as the wing swings higher. These factors reduce the lift force achievable from the ULDB TCS. In addition, as the conventional TWA swings to the side, its lift is directed more upwards and less horizontally. The ability to control the roll of the TWA enables rotation of the lift vector that can mitigate the tendency of the TWA to swing up to the side. With roll control, the same weight and size TWA can thus provide greater horizontal control forces, which are useful for translating the balloon.

A symmetric TWA is better suited to roll control. The arrangement looks much more like a conventional glider hanging on the bottom of the tether. Since the wings now have to support bending moments due to their own weight as well as due to the lift force, the ULDB TCS deployment scheme is no longer appropriate. For the current application, we have chosen to stow the TWA fully deployed. The TWA is stowed beneath the gondola. However, the benefits of a symmetric TWA probably outweigh the less straightforward deployment associated with this configuration. The following figure illustrates one symmetric wing design concept.

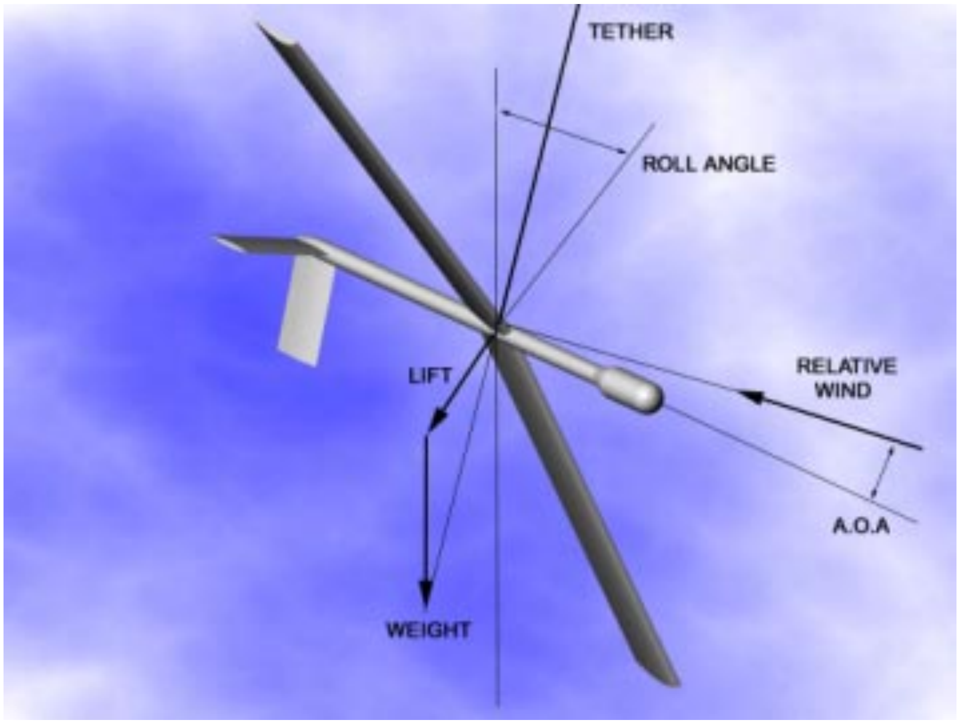


Figure 5.6 Symmetric, Dual Wing TCS TWA Design

5.4.4 TCS Dynamic Model, Performance Analysis and Results

We developed a model of this advanced Trajectory Control System TWA. The model establishes the optimum roll angle that produces the maximum horizontal trajectory control capability for a given wind profile. The model accounts for the swinging up to the side, the air density variation with altitude, and the reduced wind speed as the TWA climbs in altitude.

The model indicates that in light winds, the roll angle should be quite large (70° or more) meaning the wing is almost vertical, with the lift force mostly horizontal, but aimed down a little. As the wind increases speed, the optimum roll angle decreases. That is, the lift vector is aimed more downwards. This opposes the tendency of the wing to swing up to the side and keeps it down in denser air. The model clearly indicates that useful side forces in excess of the weight of the TWA can now be applied. And, TCS performance is clearly improved by this new design.

Examples of the performance of the system are illustrated in the following figures, which show the TCS performance in winds varying from very light to very strong. For very light winds, the best performance is obtained with a roll angle close to 90°. This means the wingspan is essentially vertical. This situation corresponds to the ULDB TCS for which it was assumed that the weight of the TWA would be much greater than the lift force. For very strong winds, the maximum trajectory control occurs at a roll angle close to 60°. For this particular case, the tether hangs about 30° from the vertical. In the figure captions, L/W refers to Lift-to-Weight ratio at the optimum roll angle. Since the weight is relatively unimportant, the lift force is directed essentially right along the tether for this particular case. For the intermediate case with moderate winds, the optimum roll angle is about 83° and the tether hang-off angle is about 18° from the vertical.

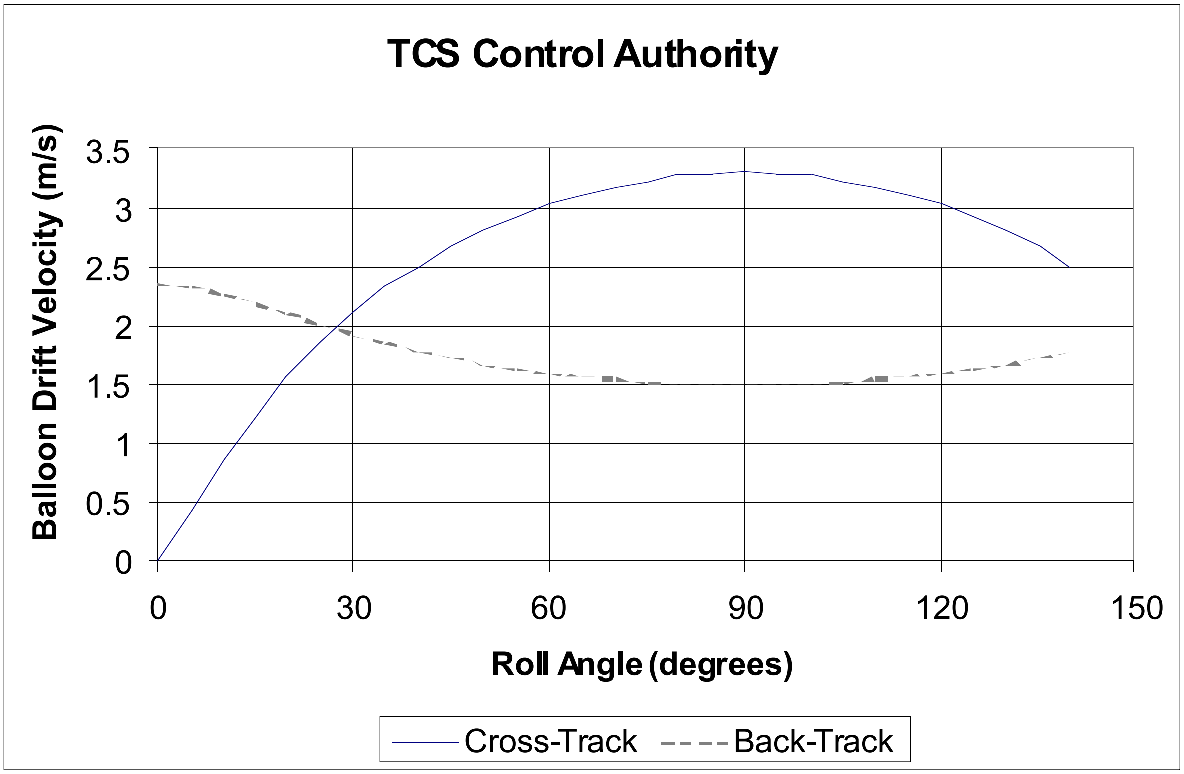


Figure 5.7 Performance in Very Light Winds (L/W ~ 0.08)

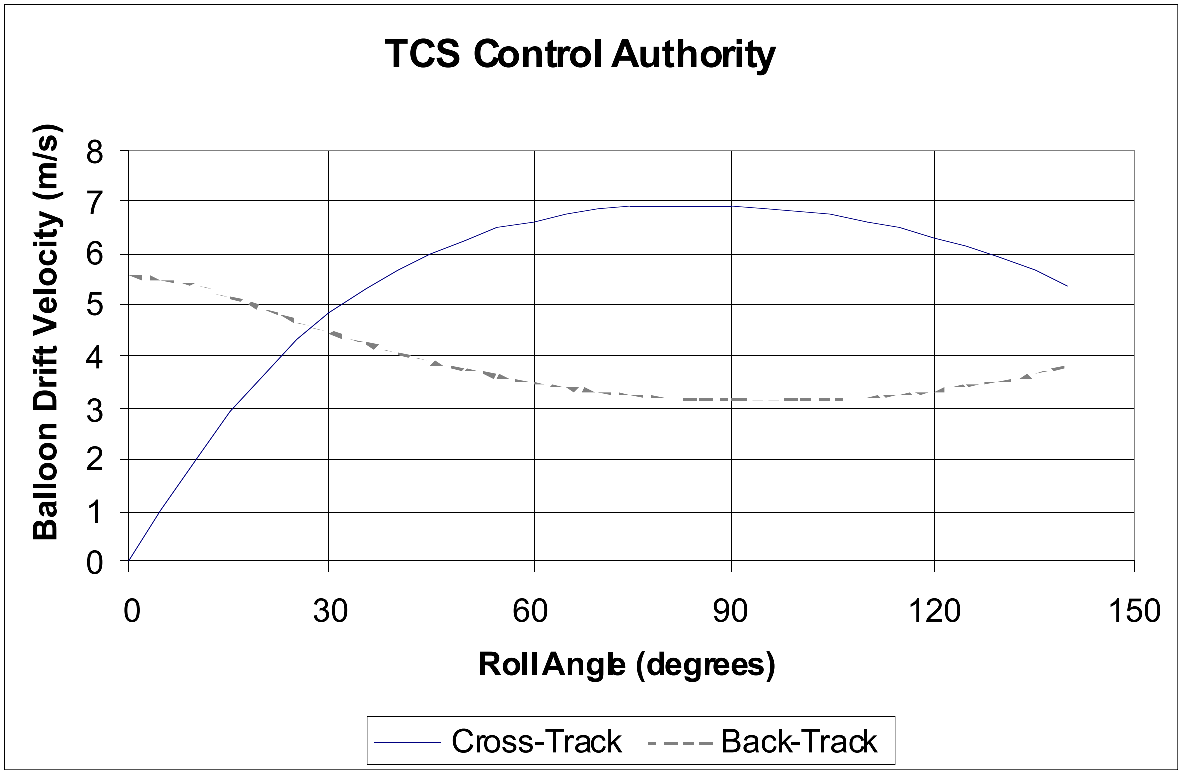


Figure 5.8 Performance in Moderate Winds (L/W ~ 0.35)

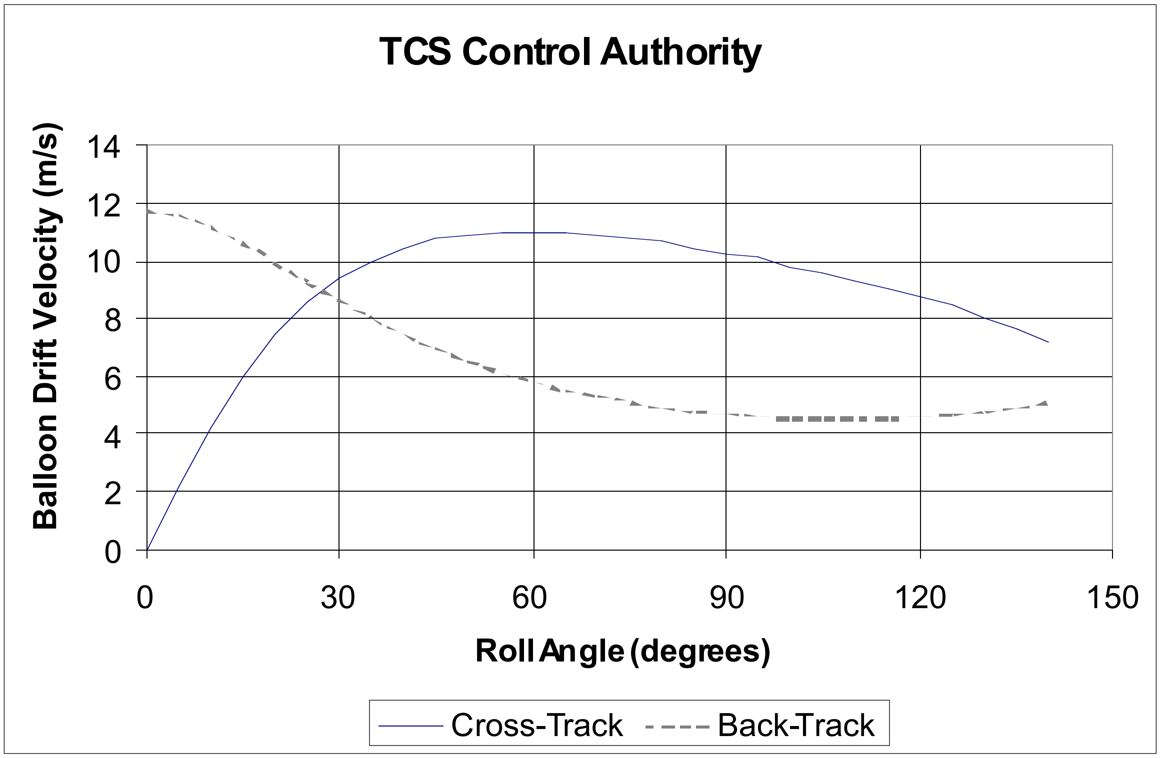


Figure 5.9 Performance in Very Strong Winds (L/W ~ 2.0)

5.5 Power Systems

This section describes future directions and technology drivers for battery and solar cell technology advancements.

5.5.1 Current State-of-the-Art for Balloon

Currently, conventional balloon payloads can require high power levels, however this is usually for short-duration due the short length of the balloon flight (~2-3 days). Primary lithium batteries often supply power on conventional balloon flights. Long-duration balloon (LDB) flights which occur in polar summer, and which can last 10-15 days, have used terrestrial single crystal (c-Si) solar cells on lightweight, rigid honeycomb core panels with custom power controllers and silver-zinc (AgZn) batteries.

A recent LDB balloon power subsystem employed an experimental thin-film solar array, a commercial controller and nickel metal hydride (NiMH) batteries. The solar array consisted of 1–micron thick, low-cost, thin-film triple junction amorphous silicon (a-Si) cells on a stainless steel substrate. This solar array tracked the sun by use of the balloon’s platform gimbal.

The state-of-the-art for low-cost balloon power will be defined by the ULDB flight systems expected to be flying regularly by 2001. The ULDB power subsystem has a high power requirement, namely 2 kW for 24 hours of operation for 100 days. Thus the power needs must be met by use of presently available technologies for lightweight and economical power generation and storage subsystems.

A number of power technologies were reviewed for the StratoSat power subsystem in both power generation and power storage areas. Many of these technologies have also been examined for satisfying the ULDB requirements and are discussed in this context.

5.5.2 Power Generation

5.5.2.1 Consideration of Alternative Power Generation Systems

A number of power conversion system choices for StratoSat missions were examined: fuel cells, batteries, radioisotope thermoelectric generators, solar thermal (Stirling engine) and photovoltaic arrays. Factors considered in power generation technology selection for StratoSat missions are life cycle cost, specific power (power generated divided by generation and storage mass), modularity, and safety.

5.5.2.1.1 Fuel Cells

Fuel cells using hydrogen and oxygen are used in the space shuttle and are a proven technology. Fuel cell energy conversion systems for StratoSat missions would require pressurized tanks for both fuel and oxidizer. These tanks with their liquefied gases create fire and explosion hazards during launch and mission termination, Since fuel cells can operate continuously there is no problem with nighttime energy storage. Oxygen and hydrogen for fuel cell operation is a concern for long missions due to the large amount of consumables required**.** Estimated specific power for a fuel cell is 700-1000 Wh/kg [Nesmith, W., DOE HQ, Personal communications, October 1997]. A more generous rule-of-thumb is about 1200 Wh/kg with the mass of the tanks and fuel included. A 100 W continuous power generation requirement results in a mass of 2 kg/day or 730 kg/year. The fuel mass that would be required for a StratoSat mission is therefore not practical. However, as discussed below, regenerative energy storage using fuel cells is a viable option that needs to be investigated.

5.5.2.1.2 Primary Batteries

Primary batteries have been used on many balloon missions. Batteries are modular, handle switching transients and provide continuous power over a wide range of loads. Primary battery mass becomes prohibitively large for long missions even when available new battery technology is considered. Advanced primary batteries have energy densities of about 4 kg/kWh. This results in a power generation mass of 9.6 kg/day or 3504 kg/year for a 100 W continuous power requirement.

5.5.2.1.3 RTGs

NASA has explored the use of RTGs for ULDB scientific missions. Radioisotope thermoelectric generators (RTG) have been used extensively for space applications including the Apollo, Viking, Voyager, Galileo and Cassini Projects to name a few. RTGs offer the option of relatively lightweight, long-duration power generation without need for sun visibility. While a number of environmental hazard issues have complicated recent space uses of RTGs, many of these issues are non existent for balloon missions, namely, ^{238}Pu dispersal by (a) launcher explosions and (b) re-entry burn up. The main concern with RTGs is the potential high cost. The cost for five RTGs for the Cassini mission was about $30 M. There are the additional concerns of ground personnel safety and the potential loss of nuclear materials to uncooperative nations in the event of unplanned mission termination.

5.5.2.1.4 Solar Thermal

Solar-thermal power conversion systems such as Stirling engines have demonstrated very high conversion efficiencies of about 35% of solar insolation. Since these are sun-powered systems, like solar photovoltaic, there must be a energy storage capability to handle nighttime power needs. Stirling engine systems require a well focused optical system and a radiator. A Stirling engine system, without the mirror heat source and radiator, has a power generation capability in the range of 6.5-8.0 W/kg [Underwood, M. L., "Advanced Radioisotope Power Source Options for Pluto Express", 30th IECEC Conf. Orlando, FL, August 1995, pp. 625-630 and Schock, A., et. al., "Radioisotope Power Systems Based On Derivative of Existing Stirling Engines", 30th IECEC Conf Orlando, FL, August 1995, pp. 649-656]. If no economies of scale are considered this gives a 400 W Stirling engine system a mass of about 60-kg not including energy storage.

5.5.2.1.5 Photovoltaic

Photovoltaic energy conversion systems, or solar arrays, have been used on most space missions and on many balloon missions. Since photovoltaic energy conversion requires sunlight there must be a power storage system to handle nighttime power needs. Lightweight, deployable, photovoltaic arrays have been demonstrated for space missions ["Advanced Photovoltaic Solar Array Design," TRW Report No. 46810-6004-UT-00, 3 November 1986] and are being incorporated into a number of programs. The specific power of lightweight space solar arrays is about 100-150 W/kg and can be increased to about 200-300 W/kg or above if mass is a major driver.

Solar photovoltaic cell systems (amorphous silicon, cadmium Telluride, Cadmium Indium Diselenide, and Copper Indium Gallium Diselenide) are being developed for application on flexible substrates like thin polymer films. One example technology, amorphous silicon solar cells, has achieved 10% efficiency for long lifetime and their future is very promising. When compared with conventional crystal silicon solar cells, amorphous silicon solar cells have several advantages for StratoSat application. Advantages include the physical flexibility afforded by their thin-film construction, their ability to be fabricated into large-area cells and the potential for innovative designs in new applications, such as integrated balloon envelope solar arrays if areal densities decrease sufficiently.

NASA has studied advanced thin-film, flexible solar array systems for Lunar and Mars surface applications utilizing amorphous silicon solar cells for flexible solar array blankets [Colozza, A. J., *Design and Optimization of a Self-deploying PV Tent Array*, NASA CR 187119, June 1991]. The areal density of these planetary solar array systems is about 20 g/m^2. Since the majority of the mass of the blanket is the substrate underneath the cells, there is a real possibility of integrating the solar array function into a balloon envelope with a very minor mass penalty. Much needs to be understood about the economical incorporation of solar cells into balloon envelopes including lightweight concepts for electrical interconnects and other discrete hardware components. In addition to the planetary missions, there are currently other similar applications, e.g. power for solar powered airplanes.

5.5.2.2 Photovoltaic Power Generation System Selection

Non-regenerative fuel cell systems have problems with the mass of fuel and oxidizer required for long-duration operation. Battery systems are also far too massive for long missions. RTGs are not considered further due to cost and nuclear material security concerns. Solar thermal systems have minor problems with modularity and end-of-mission recovery and a major problem with mass per kilowatt of power generation. Photovoltaic systems are inherently modular, have no serious safety problems and have at least a factor of ten better mass per kilowatt-hour of power generation than any other system. Because of these advantages, photovoltaic systems were selected for additional design.

5.5.2.2.1 Solar Cell Choice

Five different cell types were considered: gallium arsenide, multi-junction, concentrator, silicon and thin film. Gallium arsenide (GaAs) solar cells cost about $1000 per watt when assembled and are the present standard for severely mass limited space missions. GaAs cell technology combines high efficiency (18-19.5%) with a low thermal coefficient for voltage (about 0.23% per degree Centigrade). The high cell efficiency allows low array area and therefore low deployment mass and low array stowage volume. The low thermal coefficient for voltage makes power system control easy over the wide range of solar array temperatures. GaAs cells are fabricated on a germanium substrate wafer that has a specific gravity of 5.7. Because of process handling fragility reasons, the minimum cost effective thickness of the germanium substrate is about 150 microns.

Multi-junction cells (MJC) are now being used in some space programs. MJCs provide higher conversion efficiency than GaAs (20-24%) but mass the same as GaAs cells since they are usually made on a germanium substrate. Each MJC may have to have a built-in bypass diode or an external diode since these cells are very sensitive to back biasing such as occurs from shadowing of one cell in a series string.

Concentrator cells are also being used in some space programs and are often MJCs. Concentrator cells have additional conversion efficiency advantages (25-35%) with no increase in cell mass. In fact concentrator cells have lower cell mass and cell costs than any other crystalline space solar cell system since fewer cells are used. Concentrator cells however do require an optical concentration system, which can be difficult to restow, and some additional mass for thermal conduction.

Single crystal silicon (c-Si) space cells cost about $500 per watt when assembled and have an energy conversion efficiency of 16-22%. Single-crystal silicon, terrestrial cells cost about $50 per Watt, when assembled into a lightweight module, and have an energy conversion efficiency of 14-17%. Single crystal silicon cells have a specific gravity of about 2.7 and have about twice the thermal coefficient for voltage (0.48%) as GaAs cells. In addition, single crystal silicon cells are comparatively rugged and mass per cell is low since silicon is half the density of germanium and substrates as thin as 50 microns can be used.

Thin film arrays are now a very promising technology with low mass and low-cost potential. A number or organizations are now racing for the goal of 10% efficient thin film modules. Even at present 5-7% conversion efficiencies the presently available thin-film solar arrays have a specific power of up to 275 W/Kg.

After examining the cell choices the following factors seemed most important: GaAs cells are expensive and about one-fourth to one-tenth as robust for handling as Si cells and this would probably carry over into higher refurbishment costs after balloon recovery. MJCs are fragile and very expensive. Concentrator cells require an optical system that makes sun tracking and end-of-mission recovery difficult. C-Si cells are inexpensive and have low-mass but still require a rigid support panel. Thin film modules are still a new technology but were promising enough to be selected for further review.

5.5.2.2.2 Thin-Film Cells

Thin-film cells have the potential advantages of lightweight and low cost [A. Shah et al, “Photovoltaic Technology: The Case for Thin-Film Solar Cells”, Science, v 285, n 5427, 30 July 1999, p. 692-698]. Thin-film photovoltaic cells have been under intensive development for about 20 years. One of the earliest thin-film cells was made from copper sulfide/cadmium sulfide (Cu_2S/CdS) and was actively pursued in the early 1980's. These cells were found to be unstable. In 1981 additional cell developments were in copper indium diselenide ($CuInSe_2$) and in 1982 amorphous silicon (a-Si) and cadmium telluride (CdTe). Presently, $CuInSe_2$ or more recently copper indium gallium diselenide ($CuIn_xGa_{1-x}Se_2$ or “CIGS”) and CdTe have power conversion efficiencies of over 15% for small cells [R.W. Birkmire, “Recent Progress and Critical Issues in Thin-Film Polycrystalline Solar Cells and Modules”, Proc. of 26th IEEE PVSC Conf., Sept. 30-Oct. 3, 1997, p. 295-300]. Unfortunately there is no commercial production of most of these cells into modules due to scale up problems. The a-Si cells have achieved commercial production.

The appeal of a-Si is twofold: first, silicon is the second most common element in the Earth’s crust so its supply is essentially unlimited; second, silicon is not toxic unlike cadmium, selenium and tellurium. The early promotion of amorphous silicon was unfortunate since the original cells were unstable and lost power when exposed to sunlight and power conversion efficiencies of cells and small modules made by these systems were somewhere between 1% and 5%. A dual junction laboratory cell has been demonstrated by Fuji Electric Corp. of Japan [S. Fujikawa, et al, “Film-Substrate a-Si Solar Cells and Their Novel Process Technologies”, Proc. of 25th IEEE PVSC Conf., May 13-17, 1996, p. 1045-1052]. Recently a triple junction amorphous silicon cell was shown to be stable after an initial burn-in in sunlight. The triple junction amorphous silicon cell has a very high voltage and can have efficiency above 10%.

The United Solar Systems Corp. (Uni-Solar) in Troy, Michigan makes their commercial a-Si cells in a continuous machine about 140 feet long with nine separate plasma-enhanced chemical vapor deposition chambers. The substrate is 125 micron thick (.005") stainless steel coated with silver/zinc oxide. The a-Si technology used by Uni-Solar utilizes a triple junction to achieve stabilized module efficiencies of about 5-7%. Triple junction a-Si cells have achieved 13% stabilized efficiency [J. Yang, et al, “Recent Progress in Amorphous Silicon Alloy Leading to 13% Stable Cell Efficiency”, Proc. of 26th IEEE PVSC Conf., Sept. 30-Oct. 3, 1997, p. 563-568][S. Guha, “Amorphous Silicon Alloy Solar Cells and Modules - Opportunities and Challenges”, Proc. of 25th IEEE PVSC Conf., May 13-17, 1996, p. 1017-1022]. Figure 5.10 illustrate the design of triple junction a-Si cells using a flexible stainless steel substrate as opposed to polymer.

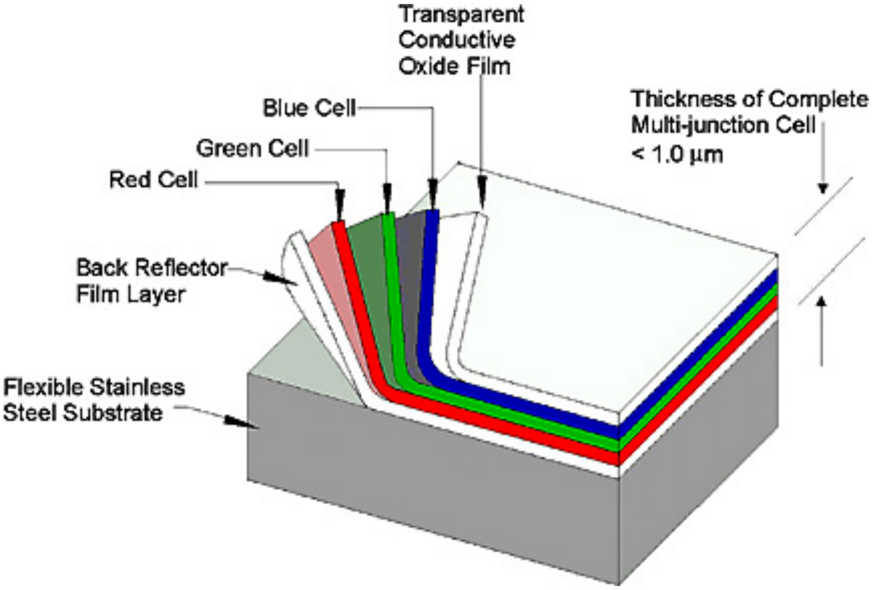


Figure 5.10 Triple junction a-Si cells design concept

This technology is only available on stainless steel substrates at present and achieves a specific power of about 96 W/kg (assuming a 7% efficiency and ignoring the mass of supporting structure) and a power density of 96 W/m^2.

A more appropriate available thin-film solar cell technology is by Iowa Thin Film (ITF) Technologies, and consists of a single-junction a-Si cell on a 2-mil (50 um) thick polyamide (Kapton) substrate [F.R. Jeffrey et al, "Polyamide Based Amorphous Silicon Solar Modules", Proc. of 12th SPRAT Conf., 1993, p. 88-97]. With its present 5% energy conversion efficiency this technology achieves a specific power of 275 W/kg (ignoring the mass of any supporting structure) and a power density of 68.6 W/m^2. The specific power is calculated using cells which have about 4.5-mils (113 micron) of polyester encapsulant for terrestrial environments. If this encapsulant could be reduced to just 1-mil (25 micron) for the less humid stratosphere then the specific power would be about 516 W/kg (again ignoring supporting structure). ITF has recently completed a program for DOE where they successfully reduced the Kapton substrate thickness to 25 microns and with difficulty to 13 microns. The thinner substrates are not commercially available at present nor is reduced encapsulant thickness. ITF does not use the triple-junction a-Si technology as yet.

Presently being readied for production by ITN Energy Systems is a thin-film solar cell consisting of a copper-indium-gallium-diselenide (CIGS) cell on a 1.6-mil (40-micron) thick polyamide (Upilex) substrate. The module energy conversion efficiency of this technology is initial targeted for at least 5% with expected growth to a range of 8-10% while small laboratory CIGS cells have achieved 18.8%. This technology will initially achieve a specific power of about 295 W/kg (assuming 5% efficiency and an encapsulant film thickness of 4.5-mil is used). The initial power density will be 68.6 W/ m^2 which is the same as the ITF a-Si cells.

5.5.2.2.3 Thin-film Solar Array Modules

Only a-Si modules are discussed in this section since there are no other presently available commercial thin-film modules. Amorphous silicon modules with power conversion performance in excess of 10% have been achieved. Commercially available modules, however, have a range of about 5-7% after they have been stabilized. The price range for terrestrial a-Si modules is $5.00-$6.50 per watt which is about the same as that of terrestrial c-Si modules. During module fabrication the cells are automatically connected into series strings and the strings are usually factory connected in parallel to make modules. For use in high altitude balloons the design of a multiple junction a-Si cell may have to be altered to allow for the change from the terrestrial, Air Mass 1 or 1.5 (AM1 or AM1.5), to the near-space AM0 solar spectrum.

5.5.2.2.4 Comparison of Single Crystal and Thin-Film Silicon Solar Arrays

The cost of space quality c-Si cells is about $80/W and the cost of GaAs based cells is about $150/W. These level of costs probably put these cells out of the competition when the power needs are 1000 W. The two remaining solar array types are made from terrestrial c-Si and a-Si cells. A number of solar array properties are listed below in terrestrial c-Si and a-Si solar arrays along with values or comments.

Table 5.4 Solar Array Properties

Property	c-Si Solar Array	a-Si Solar Array
Cost per W	$5.00	$5.00-6.50
Power Density (W/m^2)	178.4	68.6
Specific Power (W/kg)	38.4	275
Structure	Rigid panels	Flexible panels
Handling	Cells are fragile	Cells are robust

The only property where there is an advantage for c-Si solar arrays is that of power density. Here the disadvantage in thin-film solar arrays is the additional structural mass penalty incurred from the lower module efficiency. This mass penalty is discussed below where all elements of the power system are considered to be the same for c-Si and a-Si arrays except for the thickness of the solar cell and the quantity of array structure. A terrestrial c-Si solar cell can be 200-300 microns thick while an a-Si cell is only 1-2 microns thick. This difference in cell thickness then results in a mass benefit for using a-Si cells. A terrestrial c-Si cell has an efficiency of about 13%. This means that there is a little over two times more array structural mass required to support a nominal 6% efficient thin-film solar array assuming the type of structure remains the same. Unfortunately, the mass decrease for thin-film cells is usually smaller than the mass increase due to the required additional support structure. This results in a mass penalty for missions where mass is critical. The obvious solution to this problem is to design a support structure for the a-Si arrays which is lighter per unit area than that for a c-Si array or to integrate the flexible a-Si array into the balloon structure.

5.5.3 Energy Storage

5.5.3.1 Energy Storage Options

There are several options that could be considered for energy storage. If the primary power source were a Stirling engine, for example, it probably would be advantages to use heat storage. The other types of energy storage that could produce electricity directly are fuel cells, ultra capacitors, and batteries. For larger systems flywheels sometime can also become competitive in energy density with some types of batteries. Regenerative fuel cells for energy storage have been investigated for application to solar-powered aircraft at energy densities about 450 Wh/kg including tanks [see http://www-atp.llnl.gov/str/Mitlit.html]. For the energy levels needed and high estimated cost for StratoSat, batteries become the preferred storage devices. In the next phase of study it may be important to revisit this initial choice

Considering only batteries, the types that should be considered are nickel-hydrogen, perhaps nickel-metal hydride, lithium-ion, and lithium-ion polymer. These presently have the approximate energy densities (Wh/kg) shown (cell size and packaging dependant):

Table 5.5 Battery energy densities

Nickel-hydrogen	60
Nickel-metal hydride	80
Lithium-ion	100
Lithium-ion polymer	130

Nickel-hydrogen has been shown because of its continuing outstanding performance in space. Information is available that shows performances of 60,000 cycles at 60% depth-of discharge (DOD). However, the energy density really has not changed. Some improvements have been obtained in smaller batteries with common (2 cells per pressure vessels) and single pressure vessels (all cells in one).

Nickel-metal hydride promised the volume of nickel-cadmium with the energy density exceeding nickel-hydrogen. Larger cell sizes are becoming available.

Lithium-ion is being made in larger sizes and they may even exceed the 100 Wh/kg given. Charging has been somewhat critical with successful methods using bypass circuits across each cell to prevent overcharge on a cell level. A concern is that high cycle life has not really been demonstrated. Additionally data shows a loss capacity with cycling that seems to level out after about 500 cycles.

Lithium-ion polymer is really a lithium-ion battery with a different kind of separator and packaged differently. The comments on lithium-ion charging and capacity loss apply. At this time, the lithium-ion polymer appears to be the best candidate for StratoSat because of projected improvements in energy density and the low cycle life requirement.

5.5.3.2 Baseline StratoSat Energy Storage Selection

For StratoSat the number of cycles is only 365 per year, which is not large. For a 5 years lifetime there are only 1825 cycles and for the 10-year goal the number of cycles is 3,650. The energy needed for a 100 Watt power level is 1600 Wh, and at an assumed 75% DOD the battery would be sized at 2133 Wh. This could be met with a 75 Ah battery (or three 25 Ah, etc.)

The emerging lithium-ion polymer technology is generally referred to as lithium polymer. This battery was developed and patented by Bellcore. The polymer separator material is made by Valence Technology under a Bellcore patent. Valence and at least two other companies are making cells using this separator material. The other companies are Alliant (part of Power Sources Company) and Ultralife. The cells are thin and somewhat flexible and have an energy density around 130 Wh/kg.

At present, Valence is making four cell sizes for commercial evaluation; the maximum capacity being 3 Ah sizes. Custom cell sizes can be made by varying the cell dimensions and thickness. The maximum thickness seems to be about 10mm.

Alliant recently was making two standard cell configurations and varying the thickness to get desired capacities. The standard sizes are 4 by 4 inches and 5 by 7 inches. In the 5 by 7 size, a 10 mm thickness would result in a capacity of about 12 Ah. They will make custom dimensions and shapes.

Ultralife, several months ago, was developing two small sizes, a 600 mAh and a 750 mAh for cell phone applications. They call their unit a solid polymer rechargeable battery, but it is the same type as the others.

Table 5.6 Typical lithium-ion polymer cell characteristics

Energy density:	125-140 Wh/kg
Operating/storage temperature range	-20°C to + 60°C
Charge conditions	C/2 max. to 4.2V max. (0 to 40°C)
Discharge voltage	4.0 to 3.25 V (3.7typ @ 25°C)
Typical discharge rate	(C/2)

For StratoSat it has been assumed that in 10 years, available cells of at least 25 Ah and energy density of at least 200 Wh/kg will be available.

Figure 5.11 and Figure 5.12 shows how lithium-ion polymer cell characteristics vary with temperature at a discharge rate of C/2 and, discharge characteristics at C/5, C/2, and 1C. As can be seen, the lithium-ion polymer is a fairly low rate battery. On StratoSat, the battery is sized for 16-hour maximum night duration, so the discharge rate will not exceed C/16.

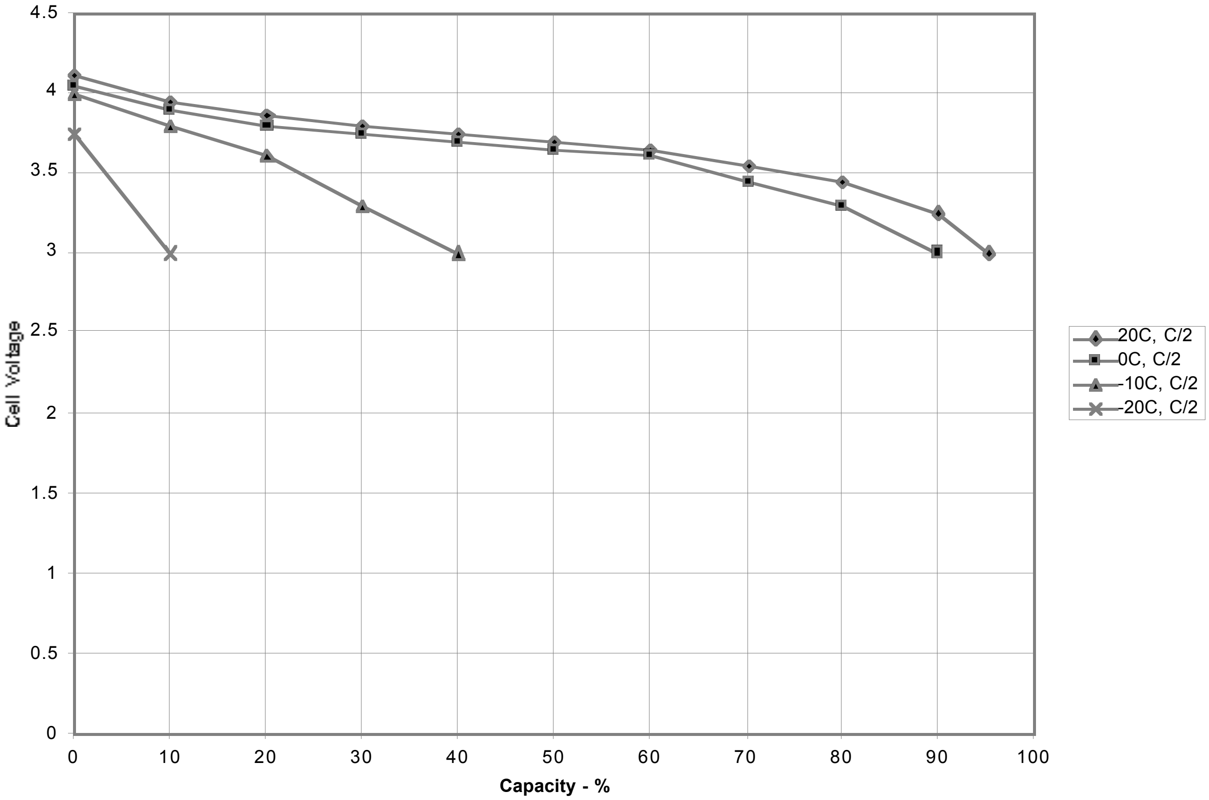


Figure 5.11 Lithium-ion polymer temperature characteristics

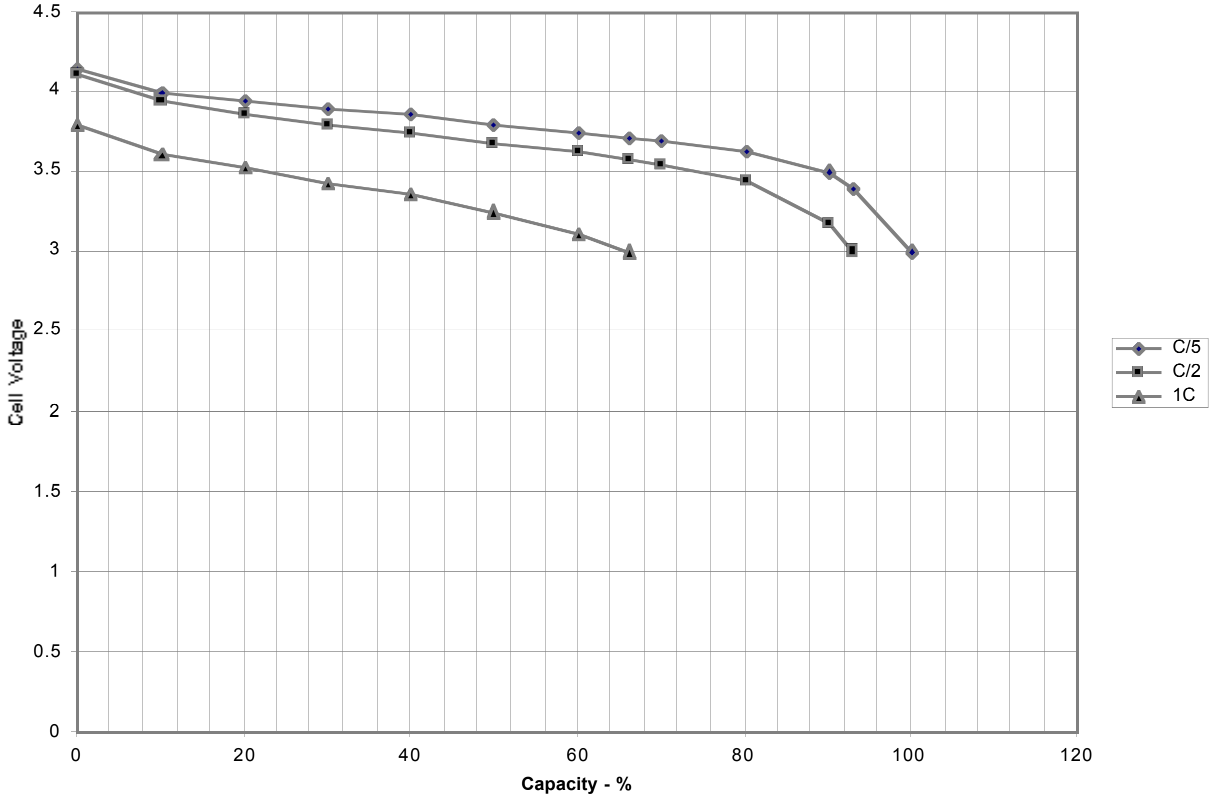


Figure 5.12 Lithium-ion polymer discharge characteristic

5.5.4 Power Management and Distribution (PMAD)

Spacecraft technology for PMAD (as well as other spacecraft electronics) is heading rapidly towards high-density packaging as is being demonstrated by NASA's X2000 Deep Space Technology Program at JPL. This program is developing hardware that will reduce volume by half and mass by 75%, can be scaled up or down and can be upgraded without requiring major system revisions. In the ten-year time frame for this project, this kind of PMAD hardware will be available. The specific PMAD hardware will include the following functions; bus voltage control, battery charge control and load power switching (along with overload protection). The mass estimates for PMAD have incorporated the mass numbers for this new generation of hardware

5.6 Telecommunications

A global stratospheric balloon constellation will rely heavily on the commercial global communications infrastructure currently being constructed. Advanced technology in this arena is expected to continue the move to miniaturization of transmitters and receivers and the reduction of the cost per byte of information transferred. Current global communications networks in place or on the verge of being operational include Orbcomm, Iridium, Teledesic and others. In 10-15 years these or other similar companies are expected to be in place. For the purposes of this study we will assume the use of an Orbcomm-like system for low bandwidth data communications and a Teledesic-like system for the high bandwidth data communications. We will make assumptions in the hardware size and mass consistent with about 10-years of technology advanced and we will assume that wider use and economies of scale will have at least a 10^4 reduction in cost per byte of information transferred by these systems.

Iridium currently has a communication unit costing $2k and they charge of up to $3 per minute. Assuming a data rate of 4,800 b/s, this corresponds to roughly 1 cent per byte. Iridium does not have the temporal coverage gaps and message limitations that Orbcomm currently has because they utilize cross-links. Iridium is a connection oriented system and long messages can be sent as a single stream. Orbcomm is a packet message system that requires any message longer than 108 bytes to be broken up into multiple packets.

What is possible 10-15 years in the future? In the future one can expect the commercial broadband wireless community to have base stations that cost about $0.5k. It is further expected that these systems will enable low-cost high-speed communications to 10 cents per minute or less for a 64 kb/s link, i.e. 48,000 bytes for 1 cent or 4.8 MB for $1. This is 48,000 times cheaper than the current cost of Orbcomm or Iridium. [R. J. Rusch, “Using Mobile Satellites for Fixed or Multimedia Services”, *International Mobile Satellite Conference Proceedings*, p. 103-107, 1997]

6 Constellation Geometry Management

6.1 Introduction

A significant element of the Phase 1 work involved investigation, analysis, and evaluation of constellation geometry management strategy and algorithm options. This section describes the work done on this task. We begin with some definitions.

6.2 Definitions

6.2.1 Constellation Management

Constellation management is the process of maintaining an overall constellation geometry or configuration by commanding and controlling the trajectory of individual StratoSats.

6.2.2 Constellation Management Strategy

A constellation management strategy is the manner or mode of controlling the constellation. A strategy is used to effect constellation management. One example strategy is the “molecular control strategy” in which each StratoSat is controlled based only on it’s proximity to it’s immediate neighbors. There may be one or several algorithms that implement the constellation management strategy.

6.2.3 Constellation Management Algorithms

A constellation management algorithm is a set of instructions or formulas that, based on the current geometry of the constellation, determine the trajectory control commands that should be sent to each StratoSat. Within one constellation management strategy there may be several choices for algorithms that implement that strategy.

6.3 Evaluating Success of Constellation Management

Each constellation management algorithm will have a different effect on the arrangement of the StratoSats in an evolving constellation. When evaluating different algorithms, it is important to devise a measure of the success of controlling the constellation.

For the purposes of this study, we assume that a uniform, global arrangement of StratoSats is desired. This assumption is consistent with the desire for global scientific or communication coverage. By “uniform” we mean equal distance between each StratoSat.

Given the objective of global and uniform StratoSat coverage, we can define a measure of the quality of any given arrangement of StratoSats with the concept of "Nearest Neighbor Separation Distance," or NNSD, which is the distance between a given StratoSat and it's 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 (σ_{NNSD}) can be determined.

The objective for constellation maintenance of a global balloon network becomes ensuring that NNSD is uniform and large. In mathematical terms, the objective of network control is minimization of the standard deviation of NNSD in the network (σ_{NNSD}). When σ_{NNSD} reaches zero, the constellation is perfectly distributed. With high σ_{NNSD}, the network will exhibit clusters and voids. We can graph as a function of time to track the quality of the constellation as it evolves.

6.4 Constellation Management Strategies

During Phase 1, we investigated several options for constellation management strategies. Constellation management strategies can be divided into several categories. The subsections below discuss these categories and strategies.

6.4.1 Environment Information Used

Constellation management strategies can be categorized by the environment information used by the strategy. There are several options (1) successive correction data which are created by interpolating satellite measurements, (2) assimilations which are created by tuning an atmospheric model with measurements, and (3) forecasts which are generated using recent assimilations as initial conditions. Of these three options, forecasts are the most interesting, because they can be used for look-ahead decision making.

During the present study, we used assimilation data for all the constellation evolution experiments that we performed.

6.4.2 Level of TCS Model Fidelity

Constellation management strategies can be further categorized by the level of Trajectory Control System (TCS) model fidelity used for the simulation. The following subsections describe three options.

6.4.2.1 Omni-directional V of Fixed Amount Applied at StratoSat

Under this option, the differential velocity (V) applied to the StratoSat is omni-directional and of fixed magnitude. It is assumed that the V 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 describe elsewhere in this report.

This option requires the least computational effort of any discussed here.

6.4.2.2 V Proportional to True Relative Wind at TCS

With this option, the V applied to the balloon is a function of the relative wind speed between the balloon and the TCS. It is assumed that the V 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.

6.4.2.3 Actual TCS Aerodynamic Model and Sophisticated TCS Control Algorithms

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 angle of attack for the StratoSail™ TCS to maximize control authority in a desired direction.

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

6.4.2.4 Selection of TCS Model For This Study

For the purposes of this study, we utilized the omni-directional V model as a reasonable approximation to the behavior of the StratoSail TCS. This model is a reasonable compromise for this Phase 1 study because it approximates the behavior of the TCS under typical conditions (zonal atmospheric flow and crosstrack TCS control) with minimum computational requirements.

6.4.3 Network Control Strategies

6.4.3.1 Randomization Constellation Management Strategy

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.

6.4.3.2 Molecular Constellation Management Strategy

Under molecular control strategies, each StratoSat responds only to it’s nearest neighbors like gaseous molecules. The purpose of molecular control is to maintain equal spacing between any given StratoSat and it’s neighbors. 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.

6.4.3.3 Macro Constellation Management Strategy

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

Macro strategies can be used in conjunction with molecular strategies. When a StratoSat is selected for a zone jump, it is typically removed from any other molecular or randomization strategy.

6.4.3.4 Network Control Strategy Selection for this Activity

During this Phase 1 activity, we evaluated all three strategies discussed above: randomization, molecular, and macro. This was an important aspect of the constellation management work during Phase 1. There are several sections below which discuss our findings in these areas.

6.4.4 Coordinate System for Control Strategy

Another way to categorize various control strategies is by the coordinate system employed for the control algorithm.

6.4.4.1 Planetary Coordinate System

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. Below, we discuss an example of using a planetary coordinate system: the zonal control algorithm where we used the Earth's coordinates.

6.4.4.2 Cyclone-Scale Coordinates for Control Strategies

Another option for control algorithm coordinates is cyclone-scale coordinates. For example, StratoSats that are captured by the polar vortex can be analyzed in a coordinate system that is fixed to the current position of the vortex rather than to the Earth's coordinates. This becomes 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.

6.4.4.3 Coordinate System Selected for this Activity

For the purposes of the present Phase 1 activity, we utilized planetary coordinate systems throughout the work. Planetary coordinates were selected for expedience because implementation of cyclone-scale coordinates can be difficult due to difficulty in determining (via computer) boundaries of meteorological features.

6.5 Evaluation of Some Constellation Management Algorithms

The following sections evaluate some constellation management algorithms. We begin by discussing our approach.

6.5.1 Approach to Evaluation of Constellation Management Algorithms

If infinite control authority were available for each StratoSat in the network, the trajectory control system would be able to overcome the natural circulation of the atmosphere and maintain an evenly distributed network of stratospheric platforms. But, infinite control authority implies unlimited resources. Realistically, constellation management algorithms must be devised to maximize the positive effects of limited control authority.

Our approach to investigating network control algorithms utilized a step-by-step plan wherein we started by demonstrating that a free-floating (uncontrolled) network has unacceptably high levels of σ_{NNSD}. Thereafter, we applied simple constellation management algorithms, each with increasing intelligence and sophistication. The application of these algorithms was measured in terms of their success in using limited available control authority to maintain the desired constellation geometry. In future follow-on phases, we will use the lessons learned from applying these algorithms to devise increasingly intelligent algorithms for constellation management.

6.5.2 Constellation Management Algorithms Studied During Phase 1

The following, Table 6.1, shows the constellation management algorithms that we studied during this Phase 1 activity.

Table 6.1 Constellation Management Algorithms Studied During Phase 1.

Algorithm Name	Type (Strategy)
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/Macro

These algorithms and their results are discussed in the following sections.

6.5.3 Uncontrolled Network

We have made several simulations of the evolution of free-floating networks of balloons at 35 km. Figure 6.1 shows an initial configuration of the network. The network consists of 100 balloons, and the initial configuration has no balloon closer than 1500 km to any other balloon.

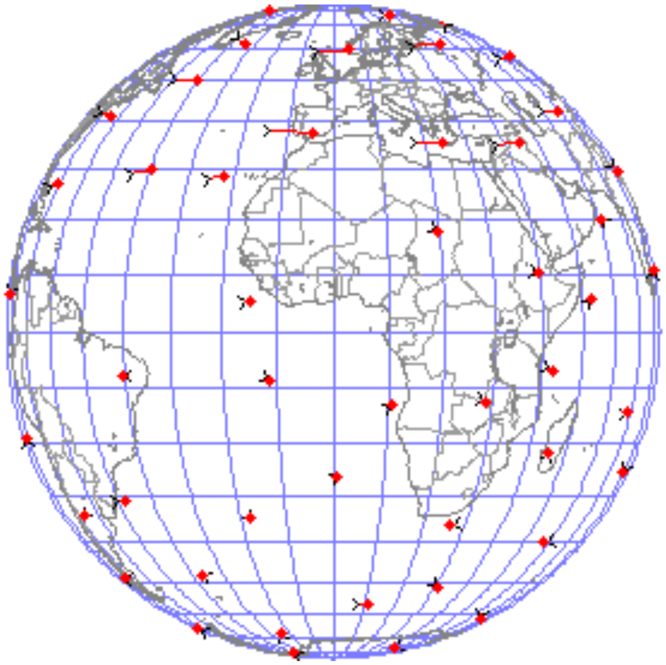


Figure 6.1 Initial Configuration of Free-Floating Network.

Figure 6.2 shows the configuration of balloons after 82 days of 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.

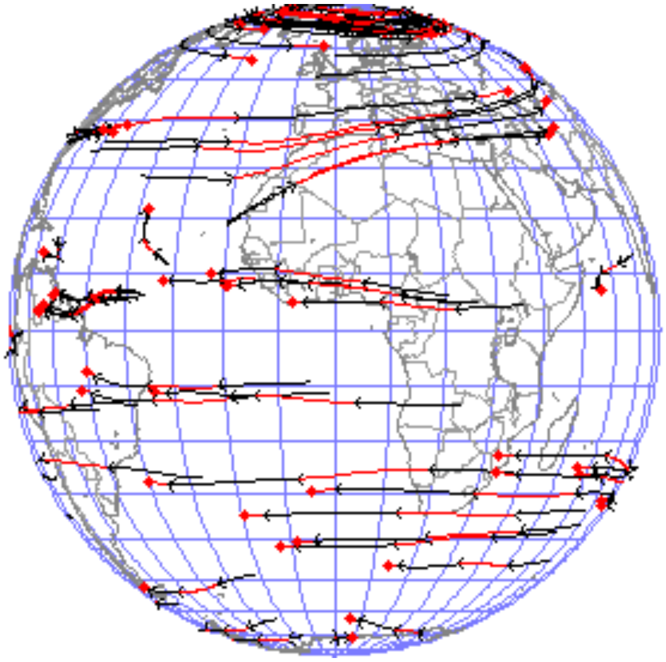


Figure 6.2 Free Floating Network After 82 Days.

Below are two graphs (Figure 6.3 and Figure 6.4 of results from a simulation of free-floating constellation evolution. The first shows the average, minimum, and maximum NNSD. The second shows σ_{NNSD}. The initial condition for the simulation was a random arrangement of 100 StratoSats with NNSD for all StratoSats > 1500 km, thereby assuring a relatively uniform initial distribution.

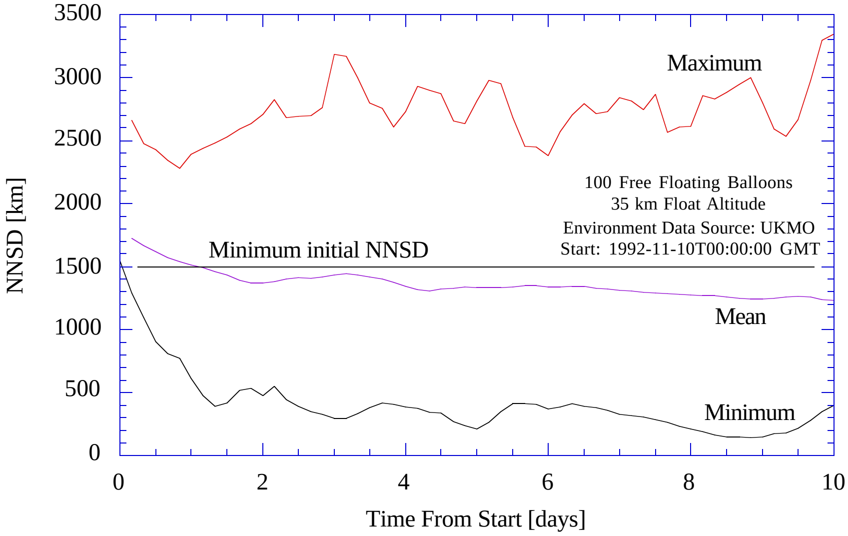


Figure 6.3 NNSD versus time.

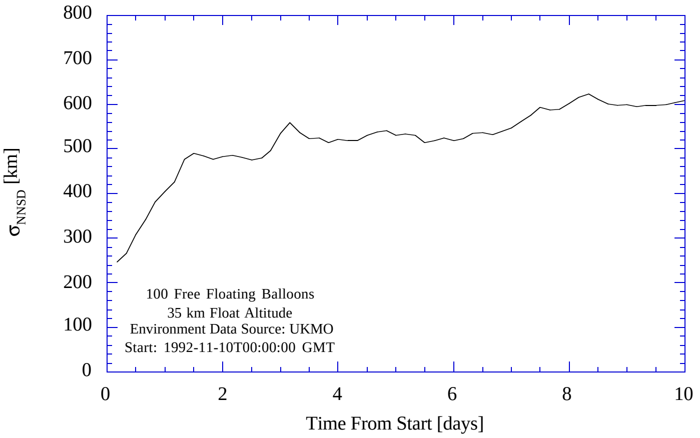


Figure 6.4 Standard deviation of NNSD versus time

Note that σ_{NNSD} increases rapidly within the first 2 days of the simulation, indicating that free-floating networks do not maintain uniform global spatial distribution.

By simulating free-floating networks, we learned that the chaotic processes of atmospheric circulation lead to deterioration of an initially distributed network. This result confirmed expectations that some level of trajectory control is needed to maintain a uniformly distributed network.

6.5.4 Move to Equator/Poles Algorithms

To investigate the effect of meridional-only control on StratoSat trajectories, we simulated "Move to Equator" and "Move to Poles" control algorithms. The goal was to establish that small amounts of control authority would be sufficient to significantly redistribute the balloons in the constellation. Furthermore, we wanted to verify the qualitative knowledge that about 1 m/s total overall meridional drift to the poles occurs at altitudes of interest (35 km). By evaluating 5 m/s and 2 m/s meridional control authority in the move to equator/pole control algorithms, we established that, in fact, it is possible to overcome the overall airflow toward the poles in the stratosphere at these altitudes.

The move to equator algorithm can be summarized as follows:

- Every four hours, identify StratoSats in the northern hemisphere and StratoSats in the southern hemisphere.
- All StratoSats in the southern hemisphere are commanded north with full control authority.
- All StratoSats in the northern hemisphere are commanded south with full control authority.

In the first test case, the StratoSats were pushed to the equator at 5 m/s. Within a few weeks, all balloons were at the equator. The simulation ran for 72 days. We noted that balloons form clusters along the equator. This clustering is due to the natural distribution of high and low pressure regions around the equator. According to Guang Ping Lou of the GSFC Data Assimilation Office (one of our advisors on this activity), the appearance of several lows around the equator is quite normal at 35 km altitude, and that the balloons, if constrained to the equator, would tend to cluster in the lows.

The move to poles simulation showed similar results. With an identical starting network, only 5 m/s control authority moved the balloons to the poles.

Later, we ran the move to equator and move to pole cases with 2 m/s control authority and achieved similar results, albeit with slower motion to the pole or equator.

Figure 6.1 shows the initial starting network, Figure 6.5 and Figure 6.6 show the move to equator poles cases for 5 m/s control authority.

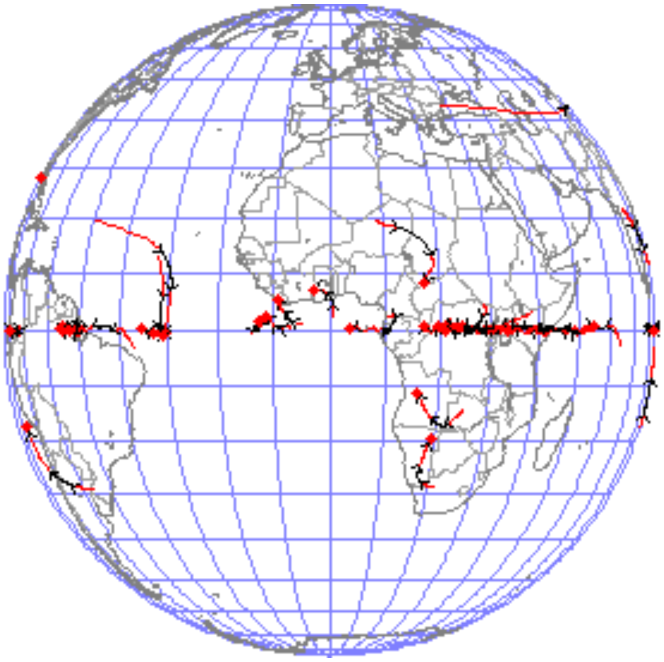


Figure 6.5 Move to Equator Result.

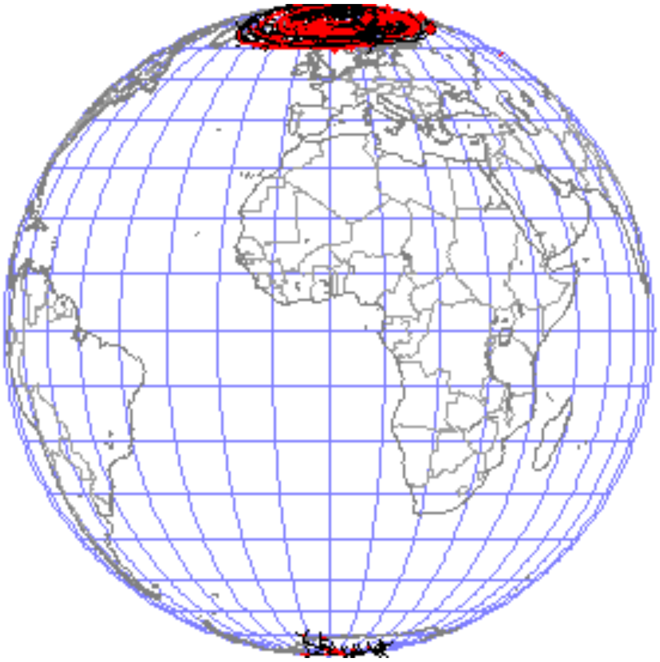


Figure 6.6 Move to Poles Result.

6.5.5 Randomizer 1 Algorithm

Another control algorithm that we evaluated has been termed the “Randomizer 1” control algorithm. Randomizer 1 can be summarized as follows:

- Every X days, pick a random number between 0 and 1 for each StratoSat in the network.
- If the random number is equal to or greater than 0.5, move that StratoSat north.
- If the random number is less than 0.5, move that StratoSat south.

The Randomizer strategy randomly decides which StratoSats to push toward the equator and which to push toward the pole. The goal of this randomization technique is to re-distribute the network, breaking up clusters and filling voids. We observed that this control algorithm significantly re-distributes the StratoSats, but that the re-distribution does not result in uniformity of the constellation. Based on this result, we developed a second Randomizer algorithm which is discussed in the next section in more detail.

6.5.6 Randomizer 2 Algorithm

A second version of the Randomizer algorithm was developed and evaluated. The second Randomizer algorithm can be summarized as follows:

- Every Y days, identify the StratoSats that are in the winter hemisphere.
- Select X % of those StratoSats and push them toward the equator.
- Push the remaining StratoSats (100-X % of the StratoSats) toward the pole.
- Do not move the StratoSats in the summer hemisphere.

We tried this version of a randomizer strategy because we observed that free-floating networks exhibit significant voiding and clustering. We suspected that the constellation was building up spatial coherence as the network evolved in time. By randomizing the network, we hoped to break up that coherence, eliminating the voids and clusters, thereby obtaining an even distribution of StratoSats in the constellation.

We tried two cases: (1) Y = 4 days and X = 75% and (2) Y = 4 days and X = 50%. The simulations were initialized with a randomized network where each balloon has an initial spacing of at least 1.5×10^6 m from its nearest neighbor. The starting time for both simulations was 1992-11-10T00:00:00, the integration time step was 1 hour, control authority was 10 m/s, and the UKMO environment was used.

We learned several things from evaluating the Randomizer control algorithm. First, visually, the evolution of the network showed that the effect of randomization was significant. Equatorward and poleward StratoSat motion was clearly visible as the network evolved.

Second, this algorithm tends to create voids in the mid-latitudes. This is, perhaps, not surprising because the only balloons that will be at mid latitudes are the ones that are moving northward or southward.

Third, this algorithm tends to make the balloons exchange hemispheres, whether at 75% or 50%.

Fourth, we learned that significant visual motion did not necessarily improve the actual distribution of the StratoSats. Figure 6.7 shows results from the Randomizer 2 control algorithm. Note that the value of σ_{NNSD} shows little difference between the free floating case and the randomized case.

Fifth, we observed that using a 50% fraction to move toward the equator was superior to the 75% fraction. This result was not unexpected due to the unbalanced character of the 75% case leading to more StratoSats at the equator.

Sixth, we learned that more intelligence would be required to effect constellation control. We demonstrated that modest levels of trajectory control could effect significant changes in the constellation geometry. But, in order to be useful, the control authority would have to be managed intelligently.

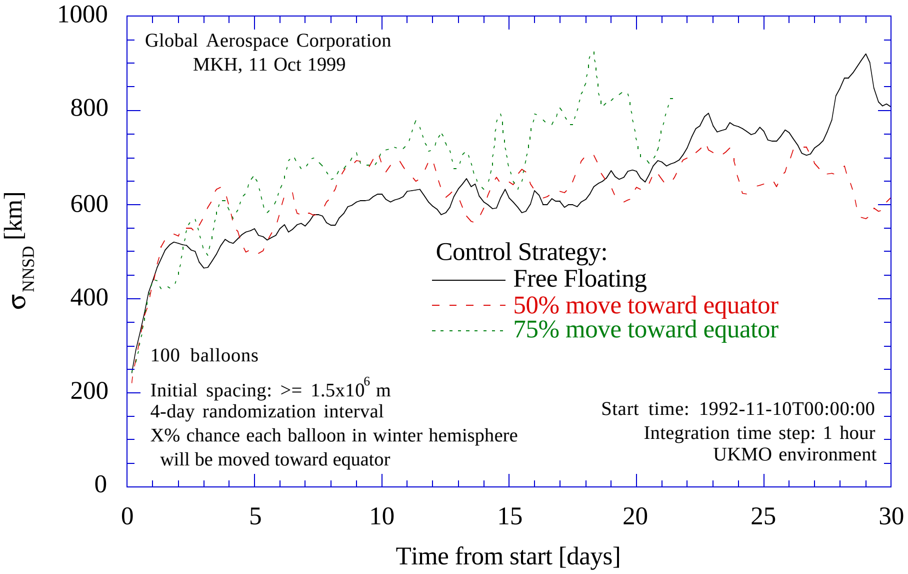


Figure 6.7 Results from Randomizer 2 Control Algorithm.

6.5.7 Simple Push-Apart Constellation Management Algorithm

We evaluated the effect of a simple Push-Apart algorithm. The push-apart algorithm is a type of Molecular constellation management strategy in which each StratoSat responds only to it's neighbors.

The Simple Push-Apart algorithm can be summarized as follows:

- Each StratoSat is pushed away from it's nearest neighbor at all times,
- Each StratoSat pushes away from it's nearest neighbor using the maximum control authority available at all times, and
- The direction in which to push is re-calculated every 4 hours.

Figure 6.8 shows results from the Simple Push Apart algorithm with varying levels of control authority.

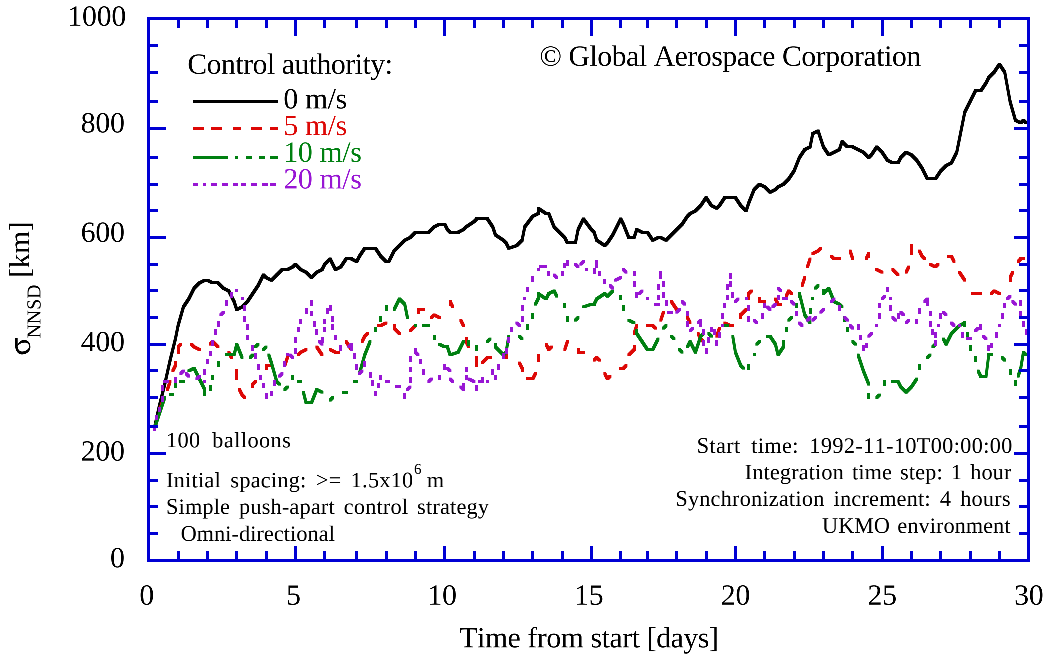


Figure 6.8 Results for Simple Push-Apart Constellation Management Algorithm.

We learned several things from the Simple Push-Apart constellation management algorithm. First, any control is better than no control. The cases with 5, 10, and 20 m/s control authority all show significant improvement over the uncontrolled case (0 m/s).

Second, more intelligence is required in the control algorithm. There are significant periods of time when the 5 or 10 m/s cases show better results than the 20 m/s case. (See days 4–7, 12–17, and 25–28, for example.) More control authority does not necessarily provide better control with the simple push-apart algorithm. This “more-is-not-necessarily-better” characteristic has been observed in previous Global Aerospace Corporation studies of latitude maintenance with a trajectory control system. High levels of control authority could be better utilized with additional intelligence or an improved algorithm.

Third, the frequency for evaluating the trajectory control direction should be adjusted based on the available control authority. In the 20 m/s case, 4 hours of continuous trajectory control leads to 288 km of motion which is 19% of the initial spacing between balloons (1500 km). We suspect that for the 20 m/s case individual balloons often overshoot by moving closer to other balloons that were not their nearest neighbor at the start of the 4 hour time period. Days 3 and 13 in Figure 6.8 are cases where overshoot may be occurring due to the fact that 20 m/s of control authority is always fully applied. (The algorithm always uses 20 m/s control authority, even when there is a cluster of balloons or one balloon in a large void.) A more-intelligent version of the Simple Push Apart algorithm could use full control authority when the StratoSats are closer than X meters from each other and use proportionally less when they are further apart (i.e. they're OK already).

Fourth, we learned that significantly less than 20 m/s control authority will be sufficient to provide good control of the constellation. The 5 m/s case shows significant improvement over the uncontrolled case.

6.5.8 Paired North-South Control Algorithm

The Paired North-South (or Paired N-S) algorithm was developed in attempt to introduce more intelligence than the simple push-apart control algorithm. The algorithm can be summarized as follows:

- Only apply control when a StratoSat is closer than 2000 km from its nearest neighbor.
- The control direction (when applied) is either north or south, nothing else.
- If a StratoSat is north of it's nearest neighbor, it is commanded north.
- If a StratoSat is south of it's nearest neighbor, it is commanded south.
- Re-evaluate control direction for each StratoSat every 4 hours.

This algorithm takes advantage of the fact that the predominant circulation patterns at 35 km are zonal, i.e. west-to-east or east-to-west, and that the zonal distance around the earth varies with latitude. So, two StratoSats in equal-velocity zonal flow will move apart from each other if they are at different latitudes.

Figure 6.9 shows the result of Paired N-S control after 82 days with 5 m/s of control authority. (The initial starting configuration is shown in Figure 6.1) Comparison between the free-floating case (Figure 6.1) and the Paired N-S control case shows significant improvement in the distribution of StratoSats.

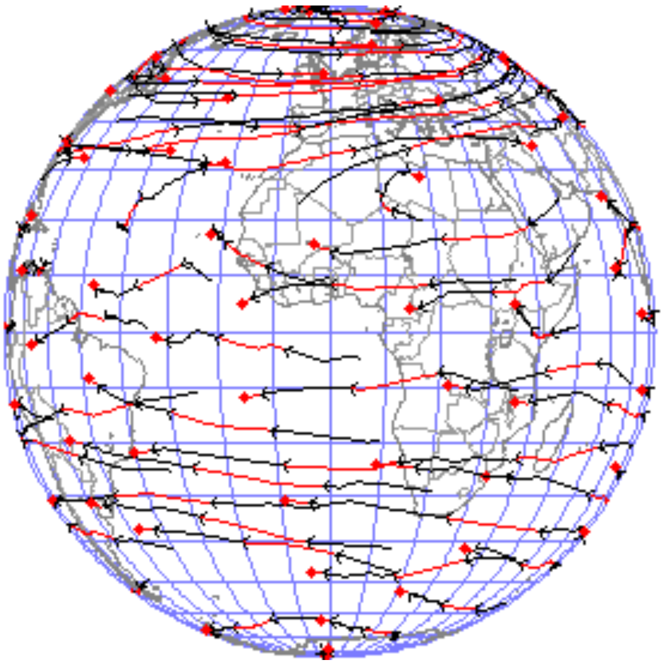


Figure 6.9 Paired N-S Control After 82 days

We learned several lessons from the simulations using the Paired N-S control algorithm. First, by including additional intelligent control, we reduced voiding and clustering significantly. Taking advantage of natural wind patterns and spherical geometry of the Earth, we developed a control algorithm that makes good use of a modest amount of control authority.

Second, there remain times of the year when the Paired N-S control algorithm is not sufficient to overcome natural circulation patterns. For example, the winter polar vortex is strong enough to capture many StratoSats, leading to decreased uniformity of distribution.

Third, it may be necessary to introduce zonal management of the network to overcome those times when local features capture groups of StratoSats and cause clusters to appear. These local features include polar vortices, stratospheric warming events, or other cyclonic or anti-cyclonic features that capture StratoSats.

6.5.9 Paired N-S with Zonal Control Algorithm

The Paired N-S/Zonal control algorithm was devised to introduce a layer of regional control on top of the Paired N-S control that was discussed in the previous section. The goal is to ensure even distribution of balloons between latitude zones. And, when the distribution is distorted, the algorithm remedies the situation by moving balloons between zones. The Paired N-S/Zonal control is described as follows:

- Zones are defined as -90 to -45, -45 to 0, 0 to 45, 45 to 90 latitude. The target number of balloons in each zone is 15, 35, 35, and 15, respectively.
- Every four hours, count the number of balloons in each zone.
- If the actual number differs from the target, specify StratoSats to be moved from or to nearby zones, give them appropriate control instructions, and remove them from paired North-South control.
- Continue moving these StratoSats that are under zonal control until the destination zone is reached.
- For those StratoSats not under zonal control and whose nearest neighbors are not under zonal control, apply paired north-south control as discussed above.

The results of the Paired N-S/Zonal control are shown in Figure 6.10. (Note that the initial starting network is shown in Figure 6.1.)

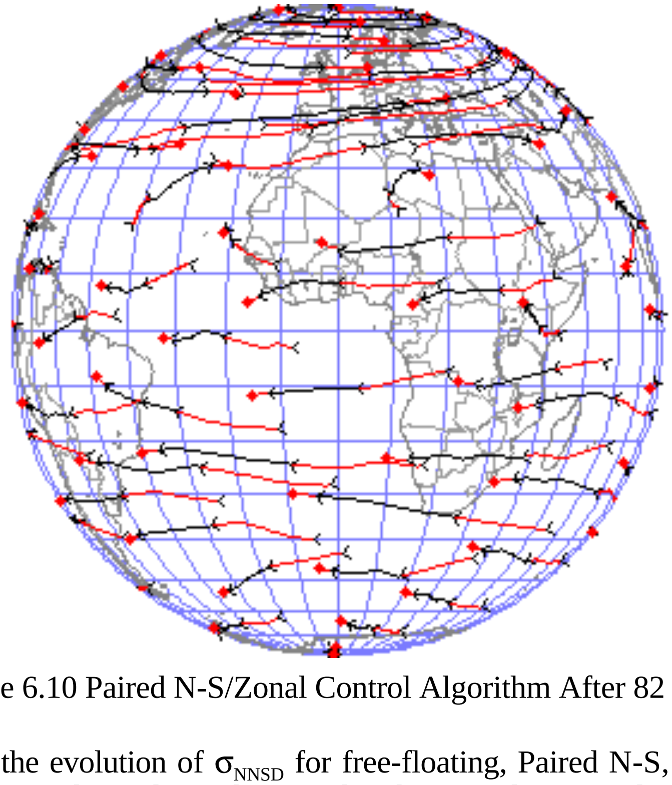


Figure 6.10 Paired N-S/Zonal Control Algorithm After 82 Days.

Figure 6.11 compares the evolution of σ_{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.

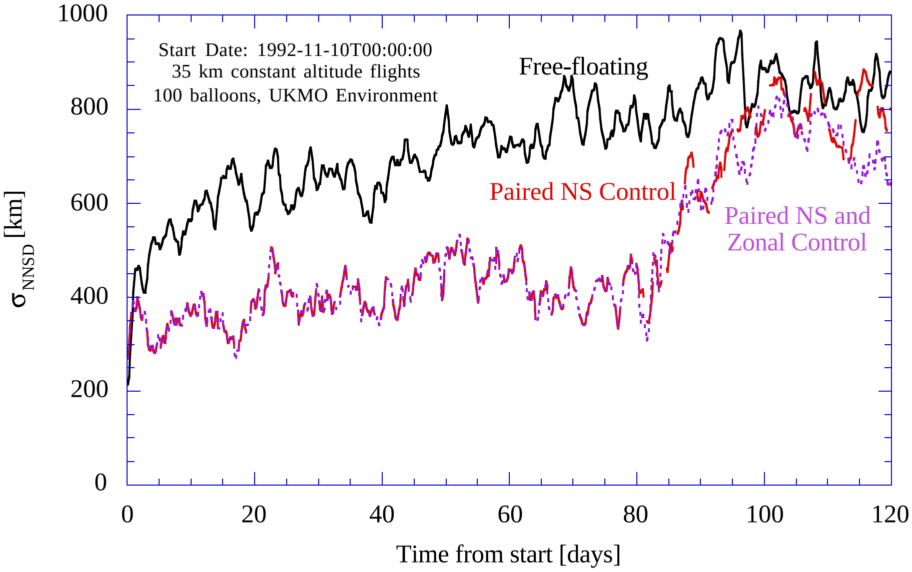


Figure 6.11 Comparison: Free-floating, Paired N-S, Paired N-S/Zonal Control Algorithms.

We learned several lessons from evaluating the Paired N-S/Zonal case. First, for most of the simulation, the zonal control aspect of the simulation was not needed because the predominantly zonal character of the winds maintains the correct distribution of StratoSats in the latitude zones.

Second, at the time when the polar vortex is most dominant (80–120 days), the zonal control capability is most needed. At these times, the Paired N-S/Zonal control algorithm has the most effect and shows the most improvement over the Paired N-S case.

Third, we realized that the zonal control algorithm ideas should be introduced for meso-scale meteorological features, i.e. individual cyclones or anti-cyclones as they develop. Use of latitude bands for zonal control is probably not sufficient.

Fourth, we realized that additional study is required to address difficulties posed by some of these challenging meteorological features.

7 Conceptual Design Description

7.1 System-level Trades

In the development of the baseline system conceptual design we investigated a number of system trades including balloon design options, multi-function power systems, and telecommunications.

7.1.1 Balloon Trades

We investigated the sensitivity of the balloon performance to float altitude, material, structural design, and payload mass.

7.1.1.1 Balloon Volume and Mass Sensitivity to Envelope Areal Density and Flight Altitude

The nominal balloon subsystem design currently assumes the *Euler Elastica* (pumpkin) shaped balloon design that is now being developed by NASA for the Ultra Long-Duration Balloon (ULDB) Project. Raven Industries has generated parametric balloon design data for pumpkin balloons at 20, 30, and 40 km altitude for envelope materials with areal densities of 20, 30, 40, 50 and 60 g/m^2. The sensitivity of balloon volume and mass to envelope material mass and balloon altitude are shown in the following tables and figures. This parametric study assumed a 180-kg payload.

Table 7.1 Balloon Volume Sensitivity Matrix

All designs are for a 180 kg payload

Material wt (g/m^2)

Altitude (km)	20	30	40	50	60
20 km	3,287	3,461	3,647	3,845	4,058
30 km	22,119	25,850	30,343	35,746	42,226
40 km	304,800	458,000	684,000	1,005,400	1,444,555

Balloon Volume in cubic meters

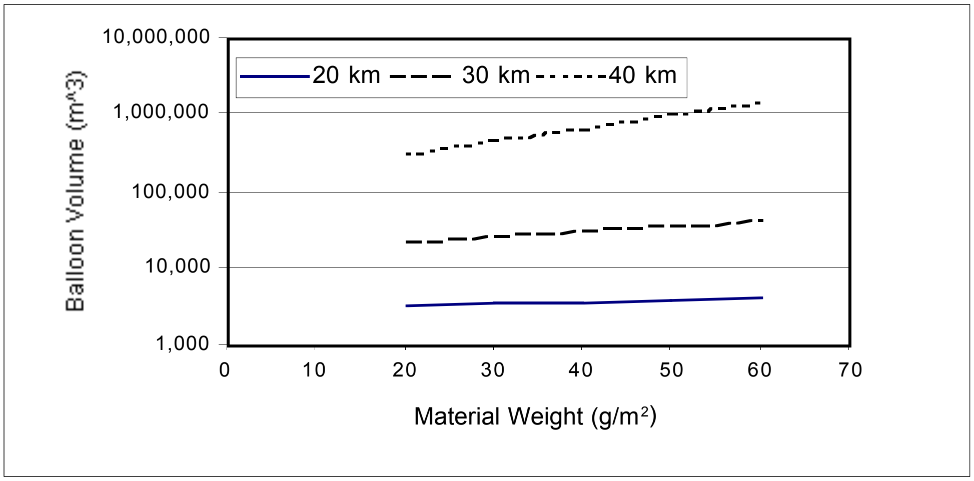


Figure 7.1 Balloon Volume Sensitivity

Table 7.2 Balloon Mass Sensitivity Matrix

Material Areal Density (g/m^2)

		20	40	60
Altitude	20	60.9	89.4	118.8
	30	155.9	291.2	494.8
	40	607.4	1885.4	4517.4

Balloon Mass (kg)

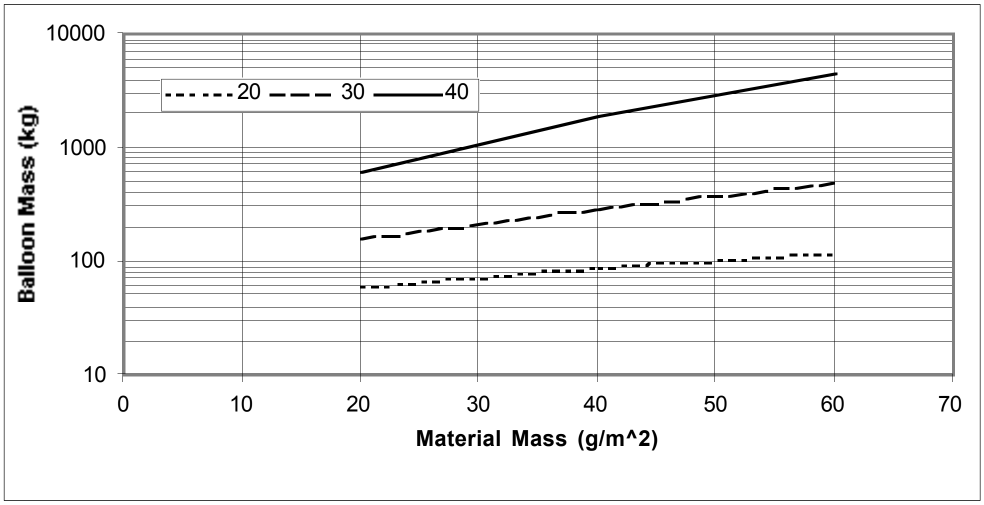


Figure 7.2 Balloon Mass Sensitivity

These figures show that there is significant growth in balloon mass and volume as the areal density of the balloon material increases and as the flight altitude is pushed above 30 km. Feasible designs are expected in the range of 35 km altitude and 15 g/m^2 envelope areal densities. Balloon cost is proportional to surface area, so larger balloons cost more. Larger balloons will also be more difficult to launch successfully.

7.1.1.2 Spherical Balloon Diameter vs. Payload Mass

Figure 7.3 shows the trade off of pumpkin balloon payload versus equivalent spherical balloon diameter assuming a 20-g/m^2 average balloon areal density and an altitude of 35 km. Average balloon envelope areal density includes the mass all balloon components and is typically larger than the actual film areal density.

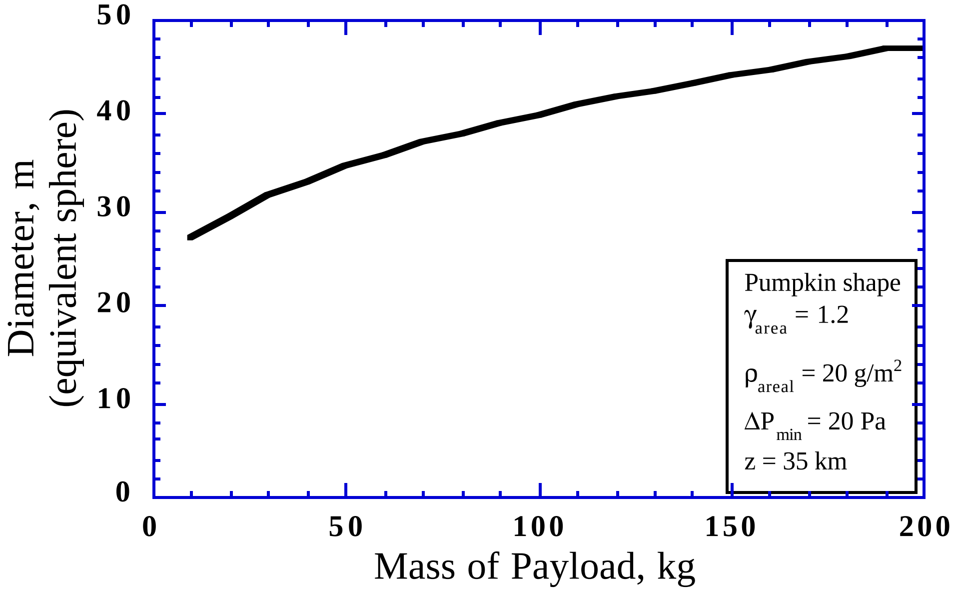


Figure 7.3 Balloon Size vs. Payload Mass

7.1.1.3 Spherical Balloon Payload vs. Altitude

Figure 7.4 shows the trade off of balloon payload as a function of average balloon envelope areal density for spherical balloons.

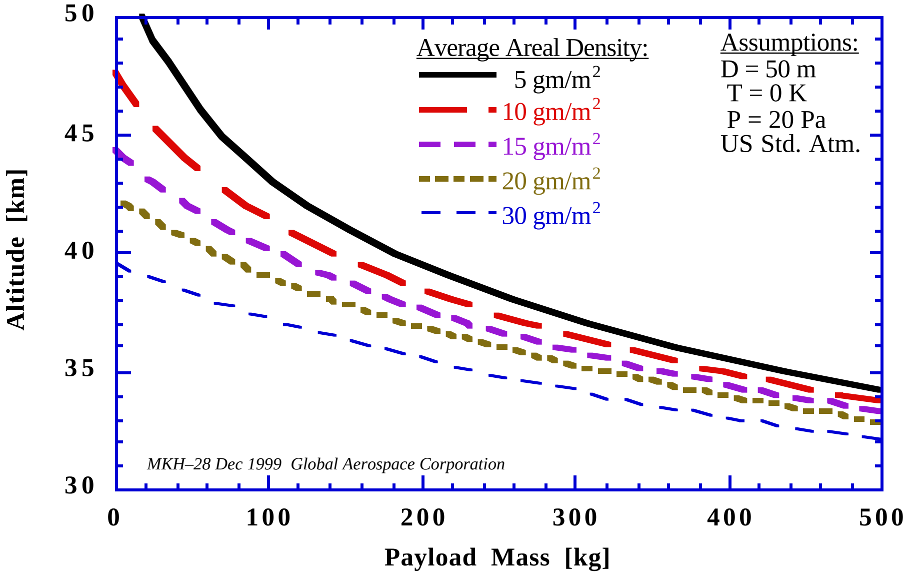


Figure 7.4 Balloon Payload vs. Altitude

7.1.1.4 Pumpkin vs. Spherical Balloon Envelope Design

The sphere is obviously the shape with the highest volume to surface area ratio, but the very high stresses associated with the large radius of curvature cause the design of the sphere to be weight inefficient when present material technology is taken into consideration. If materials with extremely high strengths and low weights were available, the sphere design would become the most attractive again strictly from the weight standpoint.

Fabrication cost, difficulties of attaching very massive payloads to the balloon and the current state-of-the-art of material design and envelope fabrication technology have dictated the choice of pumpkin balloon design for the ULDB Project. Material designs and concepts are expected to continue to advanced i.e. multi-component, co-extruded and liquid crystal polymers and integrated film/scrim concepts. Such advanced material concepts could effect the choice of balloon design. Even with the current ULDB pumpkin design the material must be at least 15 g/m^2 to withstand the film stress in the transverse direction.

A spherical balloon made from a laminate of very thin films (5 g/m^2), acting as a gas barrier, and a very high-strength scrim (Zylon) has the potential of being lighter than a pumpkin balloon of the same volume. A pumpkin balloon uses about 15% more envelope for the volume contained as compared to a spherical balloon. The primary strength of the pumpkin balloon comes from the load tendons that come in discrete sizes. A spherical balloon essentially distributes this load bearing capability throughout the envelope. The only requirement of this spherical balloon film is to contain the gas, the scrim withstands all the stresses within the balloon film. Because the scrim is distributed throughout the envelope it is not as easy to protect the load-bearing fiber from UV and light damage. Such a balloon would likely need to be covered with an opaque layer or the film must be made with opaque materials and UV inhibitors.

Two examples of advanced materials are a PBO film and a PBO scrim laminated to polymer films. Point spherical balloon designs with advanced material designs were developed and the results are presented in Table 7.x. PBO film has yield strength of 150,000 psi at room temperature. If PBO film could be manufactured in large enough quantities, the design case used in this study would result in a 4.6-µm (0.18-mil) PBO balloon of 15,900 m^3 massing only 37 kg. If a lightweight scrim of PBO fiber could be combined with 2.5-µm (0.1 mil) polyester and polyethylene films, the resulting balloon would be 19,500 m^3 and weigh 52 kg.

Table 7.3 Advanced Material Sphere Designs*

Material	Material Strength† N/m	Material Mass g/m^2	Balloon Mass¥ kg	Balloon Volume m^3
4.6 µm PBO Film	4584	6.9	34.4	14,800
Scrim (20 denier PBO fiber at 15 yarns/inch) with 2.5 µm (0.1 mil) Mylar and PE films	4633	8.4	38.4	15,300

Notes: * - Both designs are for 180 kg to 30 km
† - 50% factor of safety
¥ - Includes 3.8 g/m seam tapes (60” gores), no adhesive, 2.6 g/m^2 scrim, 1.8 kg fittings

7.1.2 Multi-function Power Subsystem Integration

With any balloon, the system mass is essentially the mass of displaced air less the buoyancy gas. At 35 km altitude the air has a density of about 8.5 mg/m^3 which means it takes a lot of volume to carry even small payloads. For this reason it is important to explore possible mass savings of dual functional use of support subsystems like power.

7.1.2.1 Solar Array and Balloon Envelope Integration Issues

Considerable progress was made exploring the combination of thin-film solar array functions with the balloon envelope. Some options that were explored include:

- Make entire balloon film from thin film solar cells.
- Make only top hemisphere thin film solar cells.
- Make only selected gores from thin film solar cell material.
- Incorporate cells into central section of each gore, using compliant material for rest of gore near the seams.
- Incorporate cells into the load tapes

The last two options appear to be the most promising because they may be most amenable to low-cost fabrication processes. These options are illustrated in Figure 7.5.

Load tapes are narrow strips of material that are attached to the balloon, often at the gore seam, which help to carry loads along the gore direction. Tapes are sometimes used to carry loads and to attach the gores at the seams. At first, attachment or incorporation into the balloon load tapes sounds unreasonable due to the narrow width of the tapes. However, the number of gores (and thereby load tapes) for a large ULDB-type balloon can be over 100. If a 3-cm wide load tape and a balloon diameter of 48 meters are assumed then the load tape area exposed to the sun is about 2.5% of the projected balloon area facing the sun (1810 m^2) or about 45 m^2. Assuming a 20 % oblique area loss, there is an equivalent projected area of solar array of 36 m^2. At 10% conversion efficiency (expected within 10 years), this area will produce 4940 W (1372 W/m^2). Load tapes can be made to be very stiff and strong so they could have little deformation that could damage the solar cells. The array wiring could be incorporated on the back of the load tape.

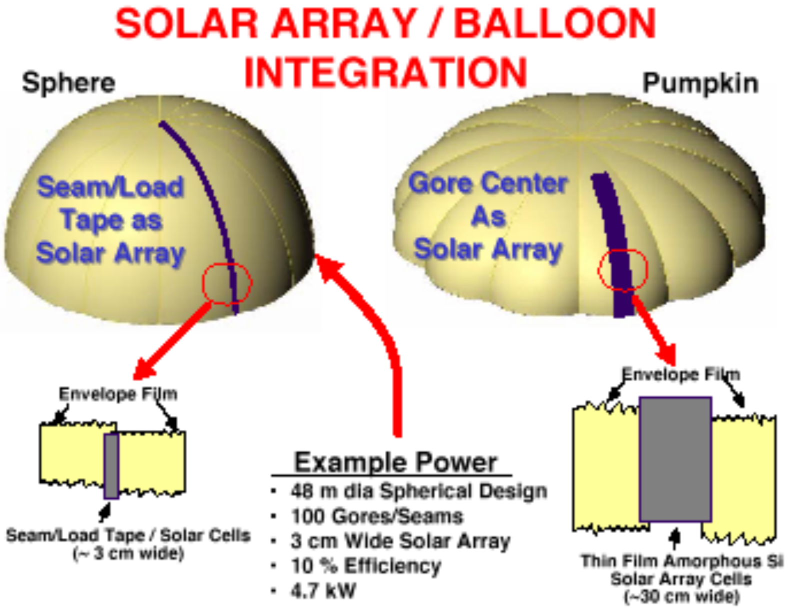


Figure 7.5 Solar array and balloon integration options

Attachment of a thin-film solar array to balloon gores is possible if provision is made to keep the strain in the array substrate to an acceptable level. This option is particularly amenable to a pumpkin design where the film stress is low. Kapton, a typical thin-film substrate, is significantly less compliant than polyethylene, a possible envelope film. This means that using the solar array as the skin of a balloon requires some careful design and new fabrication approaches. Second, array mounting, wiring and wire attachment will all have to be developed. The allowable strain is not yet well researched, but a load bearing scrim within the substrate could keep the mass penalty low. The thin cells currently being fabricated are made in long, continuous rolls each 12 inches wide. GAC currently has obtained samples of long segments that could be used in envelope fabrication experiments.

7.1.2.2 Battery Integration into StratoSat Subsystems

Two battery integration options were studied; to integrate the batteries into the balloon or gondola structure.

7.1.2.2.1 Integrate Batteries into Balloon

We have explored combining the battery function with an aspect of the balloon shell function. One idea was to combine Lithium polymer batteries with the balloon envelope load tapes that carry the longitudinal stress on the balloon envelope. This idea had promise because Lithium polymer cells are very thin and flexible and can be fabricated in a variety of shapes. However, the low temperatures during night are not compatible with lithium-ion polymer battery operation. Figures 5.X and 5.X, in Section 5 show typical lithium-ion cell performance at various temperatures and discharge rates. Significant performance loss result with temperatures below 0 C. Also, the lithium-ion battery is a fairly low rate battery with maximum recommended discharge rates of the order of 1 C (one times the battery capacity in Ah), and typical at C/2. More is being learned about future Lithium polymer technology from the manufactures, but for now the nominal plan is to make use of them as a thermal insulation and thermal inertia element in the gondola. We are planning to acquire sample battery cells in order to explore multiple uses for them.

7.1.2.2.2 Integrate Batteries into Gondola

The second concept was the integration of the batteries into the gondola structure. This option appears attractive although the analysis is not complete. The top of the gondola has been initially selected. The thermal requirement is not to exceed maximum battery temperature (60°C) in sunlight, and keep them above 0°C during night operation. Some solar energy will be absorbed during the day (during charge), although the main view is the cool (4 K) sky. At night, some of this energy will be retained, plus there will be some self heating and the power dissipated in the gondola will help maintain battery temperature. The gondola/battery thermal analysis is not complete at this time, and the location may change.

7.1.3 Telecommunications

7.1.3.1 Communications Studies

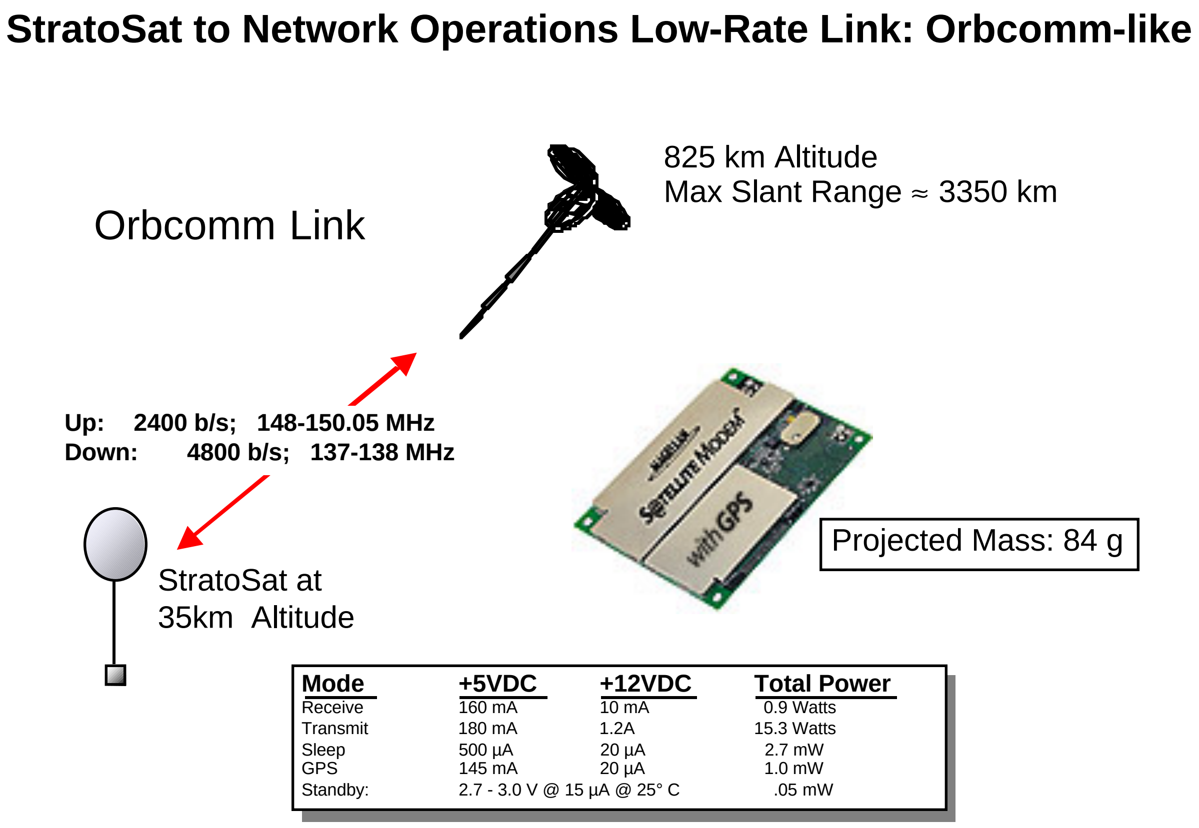
There were several studies of various communications options including two discussed in detail here:

- StratoSat-to-Operations Center Link
- Earth surface science pods-to-StratoSat Communications

7.1.3.2 StratoSat to Operations Center Link

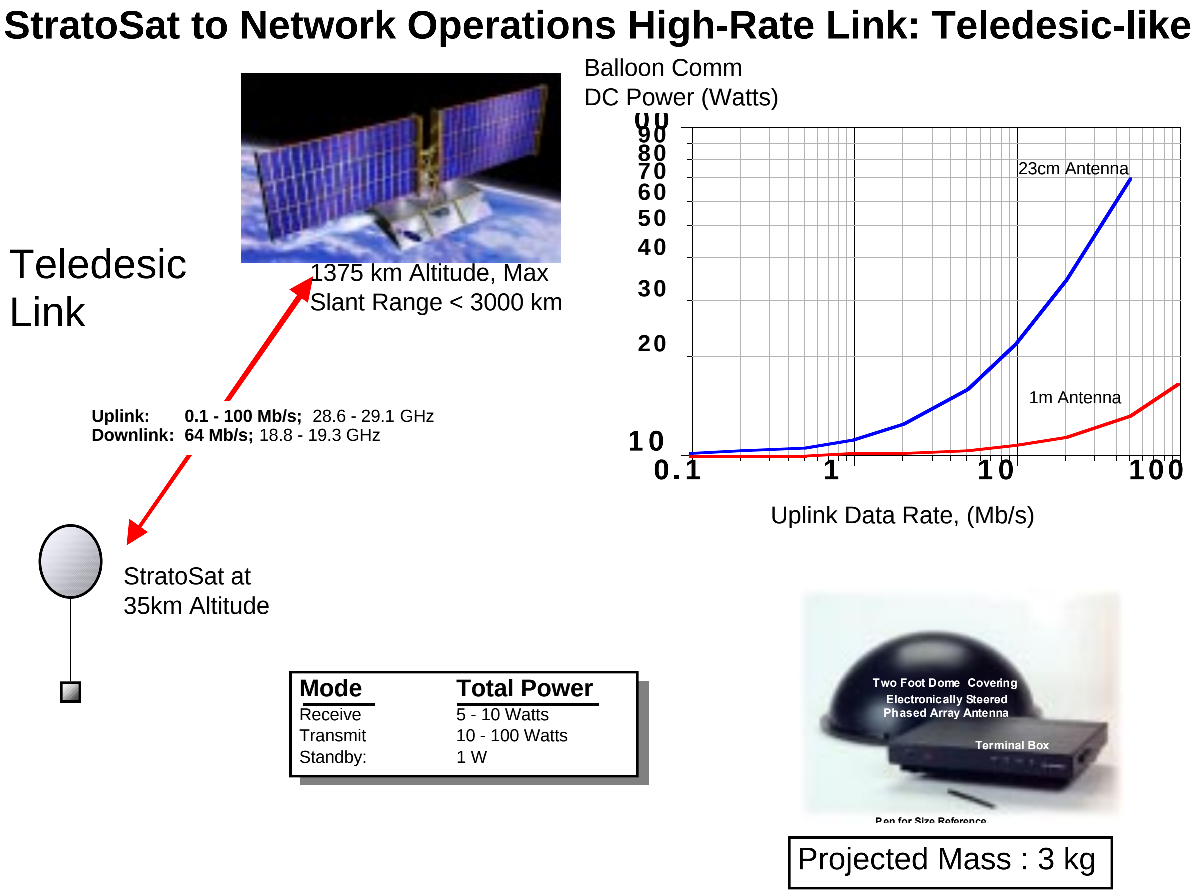
Two options for the StratoSat to Operations Center Link were considered. The first option considered was to use a satellite-based system for all low-rate data and storing all high-bandwidth data on board for playback to existing satellite ground stations when they are in view. The first option uses an Orbcomm-like system for balloon telemetry and control and for sampling low-rate science data or sending compressed/processed results or indicators of larger data sets (2.4kb/s uplink). Large volume science data, like imaging, is stored on disk or tape and played back when the balloon comes over ground station. If ground stations are encountered on the average of once every 5 days, a data storage capacity of 2.6 Tb/s is required. In general it would be expected that ground stations would be found more frequently while flying over land areas. Land areas are also more likely to be targets of high-resolution (spatial and spectral) imaging data would be desired.

The second option studied was to use an Orbcomm system for low-rate data (2.4kb/s uplink) and an expected future Teledesic-like system for the high bandwidth data at 2 Mb/s uplink. We have chosen a 2 Mb/s uplink to keep the antenna relatively simple and small. This rate is a 3:1 compression factor of the 6 Mb/s data requirement. Downlink data is expected to be very low duty cycle (low average rate) command and control information. The next two charts (Figure 7.6 and Figure 7.7 depict these two options.



Mode	+5VDC	+12VDC	Total Power
Receive	160 mA	10 mA	0.9 Watts
Transmit	180 mA	1.2A	15.3 Watts
Sleep	500 µA	20 µA	2.7 mW
GPS	145 mA	20 µA	1.0 mW
Standby:	2.7 - 3.0 V @ 15 µA @ 25° C		.05 mW

Figure 7.6 Orbcomm-example Low Rate Channel



Mode	Total Power
Receive	5 - 10 Watts
Transmit	10 - 100 Watts
Standby:	1 W

Figure 7.7 Teledesic-example High Rate Channel

Because high bandwidth satellite communications are quite likely in the future (perhaps driven by an expanding Internet and its use) we have decided to select the second option for communications between the StratoSat and its operations center.

7.1.3.3 Earth Surface Science Pods to StratoSat Relay Communications

Remote surface science pods could include systems that measure local meteorology and environmental pollution in very remote locations or track and monitor animals. Such systems can place a high premium on power either because they rely on very small solar arrays and secondary batteries or just primary batteries. Power to a transmitter tends to become a driver for size and mass of the system. Current methods of retrieving data from remote science packages include manual data retrieval, use of Argos polar LEO satellites, or use of current LEO communications constellations. Manual data retrieval has its obvious disadvantage of operations cost especially in very remote areas. For highly mobile animal systems, retrieval is not practical until the animal dies and even then it may be impossible. Argos systems (integrated with certain Sun synchronous, 850–km altitude NOAA satellites) allow very small messages (up to 32 bytes) to be transmitted but only when the satellite passes in view of the science package. Up to 7 Argos passes per day are available for data retrieval. Current Argos transmitters can be quite small (17 g for some bird systems) and can have up to a one year battery-limited life. A StratoSat-based data retrieval system could offer several advantages over Argos-like systems including 100-times higher data rates for similar RF transmitted power or 100-times less power for similar data rates and more frequent data retrieval to reduce data latency. The range benefit of a StratoSat is similar for a LEO communications network such as Orbcomm (at 785 km), but still 66-times shorter, a very significant advantage. Figure 7.8 illustrates the Orbcomm/StratoSat trade-off for uncoded DPSK data at a 5-deg minimum elevation angle. With less power, primary batteries could last longer, perhaps many years, before permanent loss of data. These advantages of two stage data relay using StratoSats could enable new science opportunities, e.g. the tracking of much smaller threatened species.

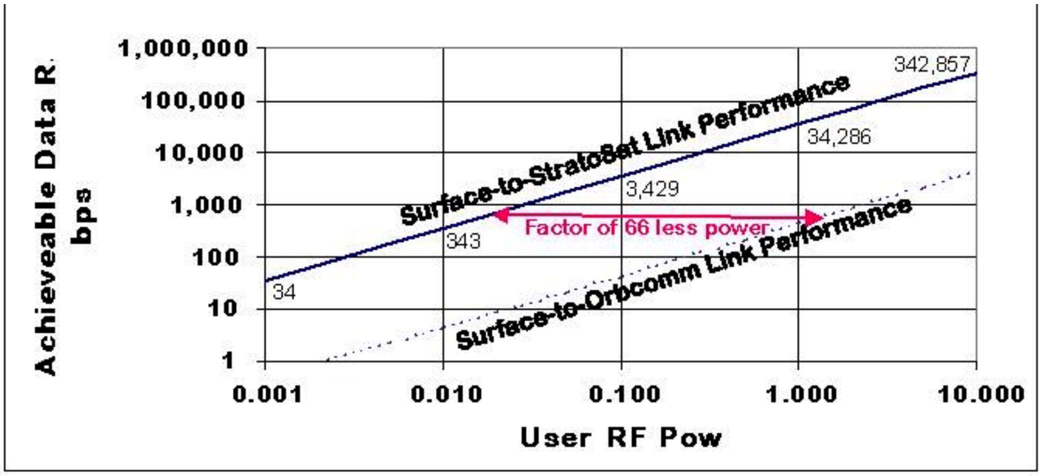


Figure 7.8 Comparison of Orbcomm and StratoSat (35-km) Surface Communications

7.2 Platform Subsystem Design Descriptions

The following sections describe each StratoSat subsystem function and preliminary design. Technology horizon for estimating masses of subsystems and components is 2010. Advanced design technology was 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 reduction 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 7.4.

Table 7.4 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

The science mass in this reference design is currently about 60% of the mass of the gondola, which is short of the 70% goal. Future studies will examine the high potential for mass reduction in most major components.

7.2.1 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 7.5.

Table 7.5 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

7.2.1.1 Shell, Load Tendons, and Miscellaneous Hardware

The balloon shell of the baseline balloon subsystem consists of the following components:

- Lobed Gores
- Tendons
- Inflation Tube
- Reefing Sleeve
- 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 under study for the ULDB Project, only thinner and 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. The pumpkin shape is displayed in Figure 7.9 on a relative scale.

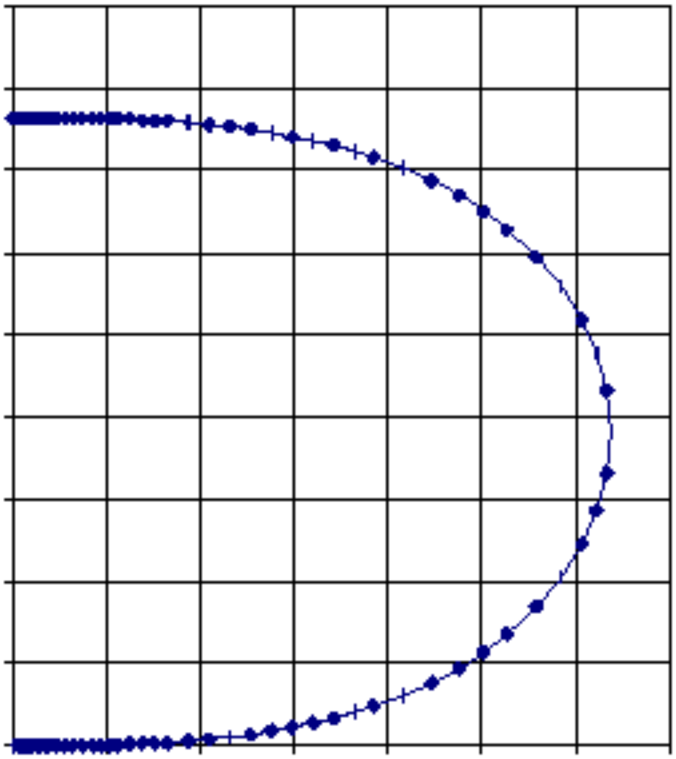


Figure 7.9 Euler Elastica “pumpkin” balloon shape

Along the seams would be an attachment system for the Zylon cord load tendon. Either the Zylon load tendon or its attachment system covering needs to be protected 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.

The inflation tube, which is affixed to the envelope, allows the inflation of the top of the balloon to begin even though the balloon is reefed (the balloon is reefed to minimize aerodynamic forces on the balloon during the launch operations). The buoyant gas is directed to the top of the balloon by the inflation tube and forced through a valve in the apex fitting at the top of the balloon. The inflation tube is 5 kg.

The reefing sleeve, which is integrated into one of the gore seams, keeps the envelope area minimized as it is being inflated. In this design the part of the balloon that is inflated is at the top and it is in a spherical shape, which minimizes aerodynamic forces. The rest of the envelope is contained inside the narrow reefing sleeve, which again minimizes the area of the balloon exposed to the winds. The balloon’s reefing sleeve essentially serves the same function of the reefing straps on the square-rigged sailing ships. The reefing sleeve is about 4.5 kg.

Finally, there is the termination hardware or rip line that rips open a small rip panel in the top of the balloon upon the receipt of a destruct command. This destruct rip line is about 1 kg of mass.

The following figure illustrates several of the balloon shell design features.

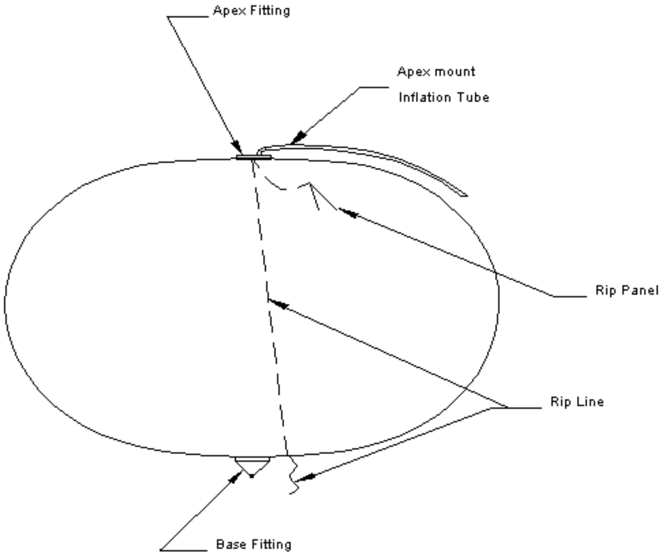


Figure 7.10 StratoSat balloon shell design features

7.2.1.2 Apex and Base Fittings

The balloon fittings include the apex fitting at the top of the balloon and the base fitting at the bottom of the balloon. The primary requirement of the apex fitting is to connect all the gores and load tendons at the top of the balloon. The apex fitting also supports the balloon health monitoring sensors, buoyant gas inflation and relief valves and buoyant gas replenishment components. The base fitting performs the same primary function of the apex fitting in addition to being the primary attachment point for the balloon payload. It is assumed that each fitting is a made of aluminum and estimated to mass about 20 kg each for a total mass of 40 kg.

7.2.1.3 Balloon Monitoring and Buoyancy Control

Additional balloon subsystem hardware is required to monitor balloon health (superpressure, temperatures, UV damage, and possibly envelope stress), to valve buoyant gas and to replenish buoyant gas if necessary. Expected loss of helium due to diffusion through the balloon envelope is only about 1.5 g/day at operational altitude, superpressure and temperature. At this rate there will be a loss of 2.7 kg of helium over the 5-year nominal StratoSat lifetime. The current concept for buoyancy gas replenishment is to electrolysis of water to extract hydrogen. Such a system requires about 10.8 kg of water to be carried in addition to the electrolysis system. Extracting water from the ambient atmosphere was considered, however it requires considerably more hardware mass than the simply carrying water along. In addition to carrying water, it may be prudent to overfill the balloon with helium by a small percentage with the understanding that if the extreme thermal environments are encountered (highest albedo surface during the day), the balloon will vent and therefore have somewhat less reserve gas remaining. The total mass of this hardware is estimated to be 15 kg.

7.2.1.4 Flight Train

The flight train includes the ladder cable structure between the balloon and the gondola. This support structure includes two tethers and a rigid “rungs” between them. The purpose of this structure is to tie the gondola and balloon dynamics together, i.e. if the balloon rotates so does the gondola. This design minimizes wrapping-up of the gondola support tether that could cause undesirable forces in the tether. The flight train also provides the mechanical interface between the balloon destruct device and the gondola. The flight train also provides the attachment point for the gondola parachute ripcord to be used in the event of balloon destruct or catastrophic failure. The flight train mass is estimated at about 1 kg.

7.2.2 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.

7.2.2.1 Functional Description – Functional block diagram of subsystem

The functional block diagram of the StratoSat Power Subsystem is shown in Figure 7.11. For this report, the block diagram and discussion will be done as if the major components (SSR, battery, charge controller) are single items. In reality, for this size power subsystem, multiple units would be used. There are some issues with multiple units (such as batteries in parallel), but in general, these have been accomplished before, and are not really important considerations for this report.

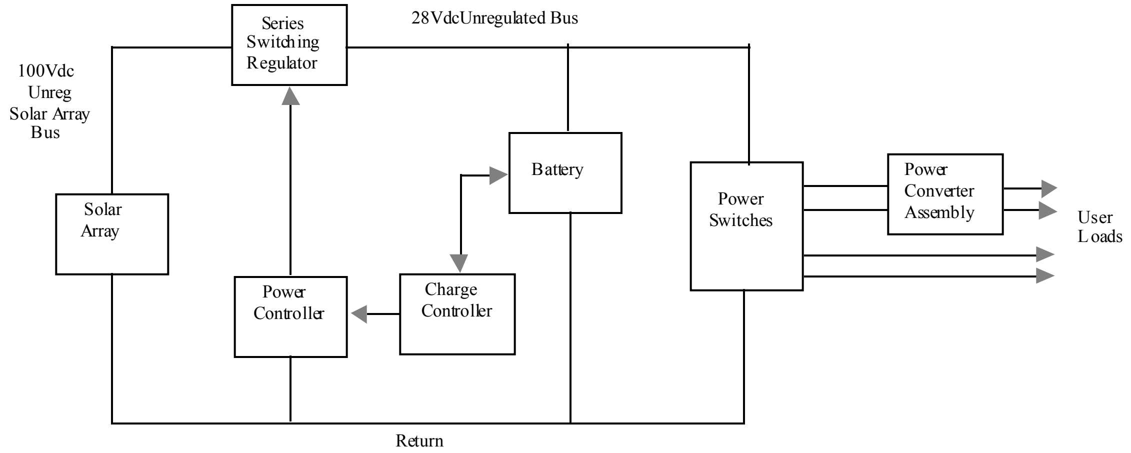


Figure 7.11 StratoSat Power Subsystem Functional Block Diagram

The solar array provides power at about 100 VDC to the power system. This voltage has been selected to reduce solar array wiring mass. This high voltage necessitates a buck type converter to drop the voltage to a more usable level such as 28VDC. This converter has been assumed to be a high efficiency non-isolated series-switching regulator (SSR). 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 which 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.

7.2.2.2 Subsystem Description

7.2.2.2.1 Solar Array

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.

7.2.2.2.2 Batteries

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.

7.2.2.2.3 PMAD

The solar array will provide power to the gondola at about 100 VDC. This voltage reduces the wiring mass on the array. However, most avionics systems, including StratoSat operate at a nominal bus voltage of 28 VDC. This voltage drop is accomplished by a high efficiency series-switching regulator (SSR), which has a wide input voltage range and provides an output at the desired 28VDC range. In sunlight the 28 VDC power bus voltage is controlled to provide proper charge control for the battery.

Charge control for the lithium-ion polymer battery consists of individual cell by pass circuits to prevent cell overcharge in case of cell imbalance. The Charge Controller also provides a control signal to the Power Controller to adjust the SSR duty cycle to set the bus voltage to the required level.

Power distribution is provided by solid state switching in the Power Switches block. The switches also provide overload protection for load faults. Switches can be used to switch either side or both sides of the line, and can be paralleled for higher power loads. The central computer performs monitoring and control of the switches.

Power conversion can be provided in the power subsystem, as shown in the block diagram, or can be located at or within a particular load. For a large system like StratoSat, the recommendation would be for power converters to be located at the using load to avoid the increased mass of low voltage wiring, and possible interference if multiple users share a central converter. It should be noted that, if there are very high power loads that require only daylight operation, an overall efficiency increase would result from powering these loads directly from the solar array bus at 100 VDC. That is, a wide range input high voltage converter would provide the power directly from the 100 VDC unregulated solar array power bus. The power switches would not provide switching and control of these loads.

Table 7.6 PMAD Component Characteristics

Component	Unit Mass	Capacity/Number	Mass
Power Conversion (SSR)	1.7 g/W	5000 W	8.5 kg (incl. Pwr. Cont.)
Switches	4 switches/25g	48 switches	0.30 kg
Charge controller	1.7 g/W	300 W	0.50 kg

7.2.3 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.

7.2.3.1 Functional Description – Functional block diagram of subsystem

Figure 7.12 illustrates a simplified functional block diagram of the entire telecommunications subsystem.

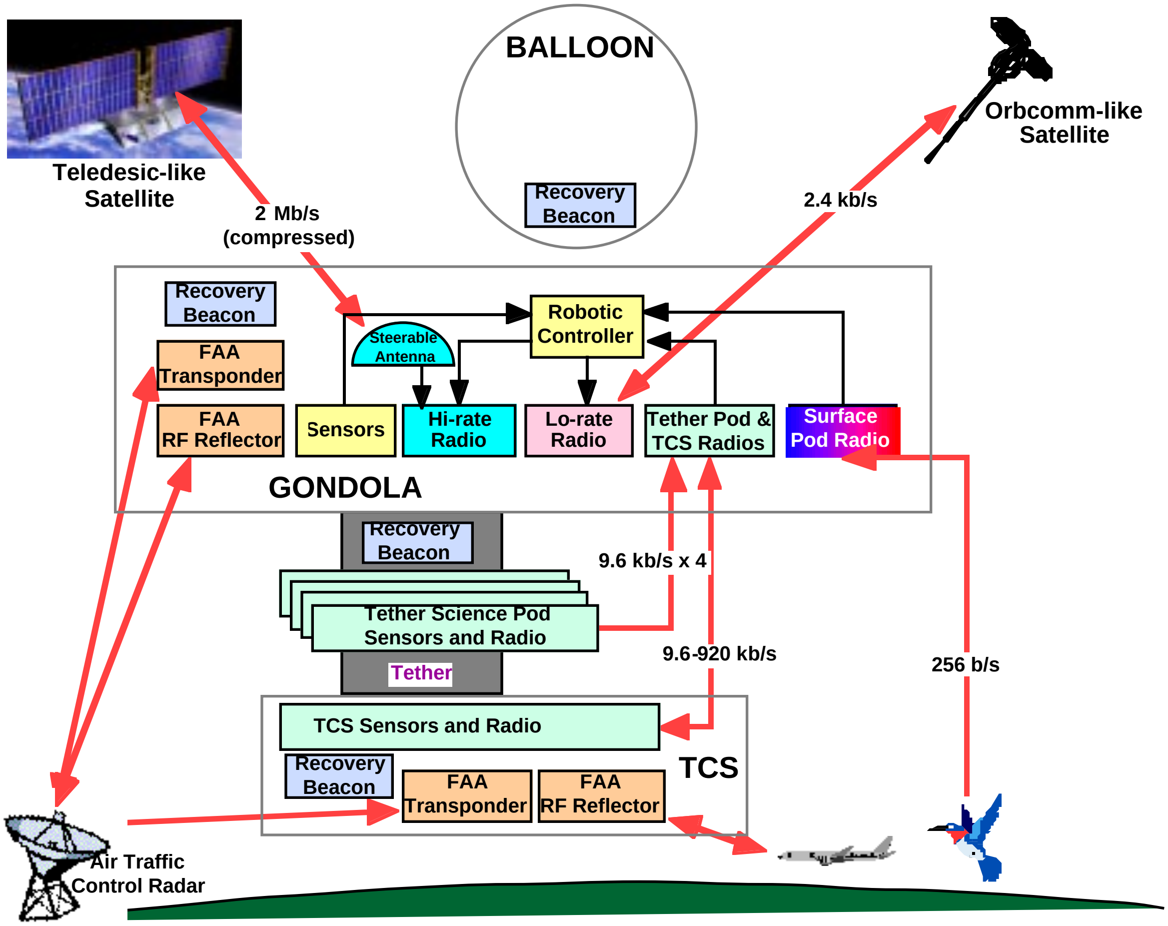


Figure 7.12 StratoSat Telecommunications Functional Block Diagram

7.2.3.2 Subsystem Description (to component level)

The following table summarizes the mass of the telecommunications subsystem.

Table 7.7 Telecommunications Subsystem Power and Mass Summary

Component	Average Power, W	Mass, kg
Low-rate science radio	1.5	0.218
High-rate science radio	0.7	2.600
High-rate science radio antenna		1.300
Surface science pod radio	1.2	0.130
TCS radio modem	0.2	0.105
Tether science pod radio	0.1	0.130
Transponder	2.0†	0.300
Radar Corner Reflector		0.150
Subtotal	3.7	4.933

† - Only operated on ascent or at termination

7.2.3.2.1 High Rate Link (6 Mb/s – equivalent uncompressed)

The high rate radio subsystem connects the balloon payload to the Teledesic-like 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 Teledesic systems 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 Teledesic spacecraft are not in geostationary orbits their apparent positions in the sky change and therefore the user terminal antenna must track them. Typical Teledesic 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 are performed automatically.

Quality of service is expected to be, “fiber-like”. Latency is only 20 ms for a single satellite hop link and round-trip communications time to the query balloon hardware is only 100 ms. Initial delay in establishing a 2 Mb/s link is only 50 ms.

The global coverage and inter-satellite connections used in the Teledesic-like system allow the balloon data to travel from any point around the world to any other. Connection from the downlink gateway site can be made to either a public network, like the Internet, or to a private network, like a T1 line.

Many of the details of the Teledesic communications hardware remain undefined or are proprietary.

7.2.3.2.2 Low Rate Link (2.4 kb/s)

The low rate data link uses hardware compatible with an Orbcomm-like satellite messaging system. 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.

The communicator can be programmed to report conditioned on various events, e.g., time schedule, if moved more than X km in T minutes, if latitude XX.XX or longitude YY.YY is crossed, if digital input has changed, etc. The result is efficient use of communications power.

Orbcomm does not provide 100% temporal coverage of every spot on the Earth. Therefore delays of many minutes to establish a connection or forward a message can occur. When data is downlinked to an Orbcomm gateway site, it is usually forwarded via a public or private network to the end user.

7.2.3.2.3 Gondola to TCS TWA

Link between the gondola and StratoSail™ TWA is used for the relay of TCS operational, environmental and scientific data to the gondola. The link range is only 15 km and can therefore employ relatively low-mass, low-power electronics. The radio technology uses frequency hopping spread spectrum communications in the 902-928 MHz ISM band to communicate at 2-way rates of 9.6 to 115 kb/s. CRC error checking and retransmission protocols are managed by the radio hardware and are used to ensure end-to-end data integrity. There are currently many manufacturers of applicable radio subsystems for this class of transceiver with mass numbers ranging from several grams, (ASH transceiver), to 70 grams, (Freewave Transceiver), and RF power outputs of 2mW to 1000mW. Current technology meets the Gondola to StratoSail™ TWA link requirements and future advancements should only improve radio performance and reduce mass and power.

7.2.3.2.4 Gondola to Surface and Tether Science Pods and Dropsondes

For very low data rate and very low power applications it is advantageous to use lower frequencies such as the 40.48–40.88 MHz ISM band. At these lower frequencies it is possible to transmit 100’s of b/s from the surface to the balloon gondola with only few milliWatts of RF power. (Check with link budgets). There are numerous manufacturers of spread spectrum transceivers at this frequency. In particular many of the smaller devices, used for covert electronic surveillance could be used directly or modified for use on science pods and dropsondes. Another alternative is to use Orbcomm type transceivers on the balloon and on the surface science pods. The 130–150 MHz frequencies are specified as multi-use and all transceiver equipment employs frequency hopping and an Aloha protocol that allows multiple users to share the same frequency. Typical performance on this type of link is given by the upper curve shown in figure 7.x (Comparison of Orbcomm and StratoSat relay Communications), 10-mW (RF) will enable a link capacity of 100’s of bits/s from the surface to the balloon gondola. Higher power units scale directly up in data rate performance. A third alternative is to use the 902–908 MHz ISM band and radio equipment used on the Gondola to StratoSail link. Here again the spectrum is designated as multi-use and the spread-spectrum signaling schemes and re-transmission protocols allow multiple links to co-exist in the same RF space while still maintaining full end-to-end data integrity on all the links.

7.2.3.2.5 Recovery Beacons

The low-rate radio equipment packaging will be designed to survive the landing. Thus after landing, the GPS receiver can immediately locate the landing site and the data can be relayed through and Orbcomm satellite to a recovery team. A backup short range beacon system could take on many different forms and its performance depends on location of the downed payload. In the open ocean, a small hand sized 25-mW radio, similar to those used to locate downed pilots, could communicate over a range of 40 miles. The same radio in a densely wooded area would have an effective range of only 15 miles. In an urban area the useful range would only be 2-3 miles. If GPS functionality is included in the recovery beacon, the downed payload position information could be included in the beacon signaling and location the payload would again be accelerated. [See http://www.ostgate.com/bugfrqQBPSK.html]

7.2.3.2.6 Radar Transponders

Radar transponders are used extensively on commercial aircraft to relay to radar operators the height and identity of the aircraft on their radar displays. A typical unit working is roughly palm size, weighs 300 grams and uses about 2 watts of power. [See http://www.gomicrosystems.com/pages/5WATT.HTM]

7.2.3.2.7 Radar Reflectors

Radar reflective surfaces are required so that worldwide air traffic control radar stations are able to see and track the StratoSat on its ascent and during any planned or inadvertent descent of the system. The requirement is that the balloon envelope is equipped with a radar reflective device(s) or material that will present an echo to surface radar operating in the 200 MHz to 2700 MHz frequency range. This hardware could amounts to a 1-m size corner reflector mounted on the system probably near the TCS.

7.2.4 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.

7.2.4.1 Gondola

The gondola main support structure is 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. A Styrofoam 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 the permit heat to escape. This is shown in the figure as a louvered radiator, similar to those used on spacecraft. However, since that figure was created, we have decided that 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 is that a motor is required to operate the door. 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 7.13 is a computer drawing of the StratoSat gondola along with the TCS hardware including the TCS Wing Assembly.

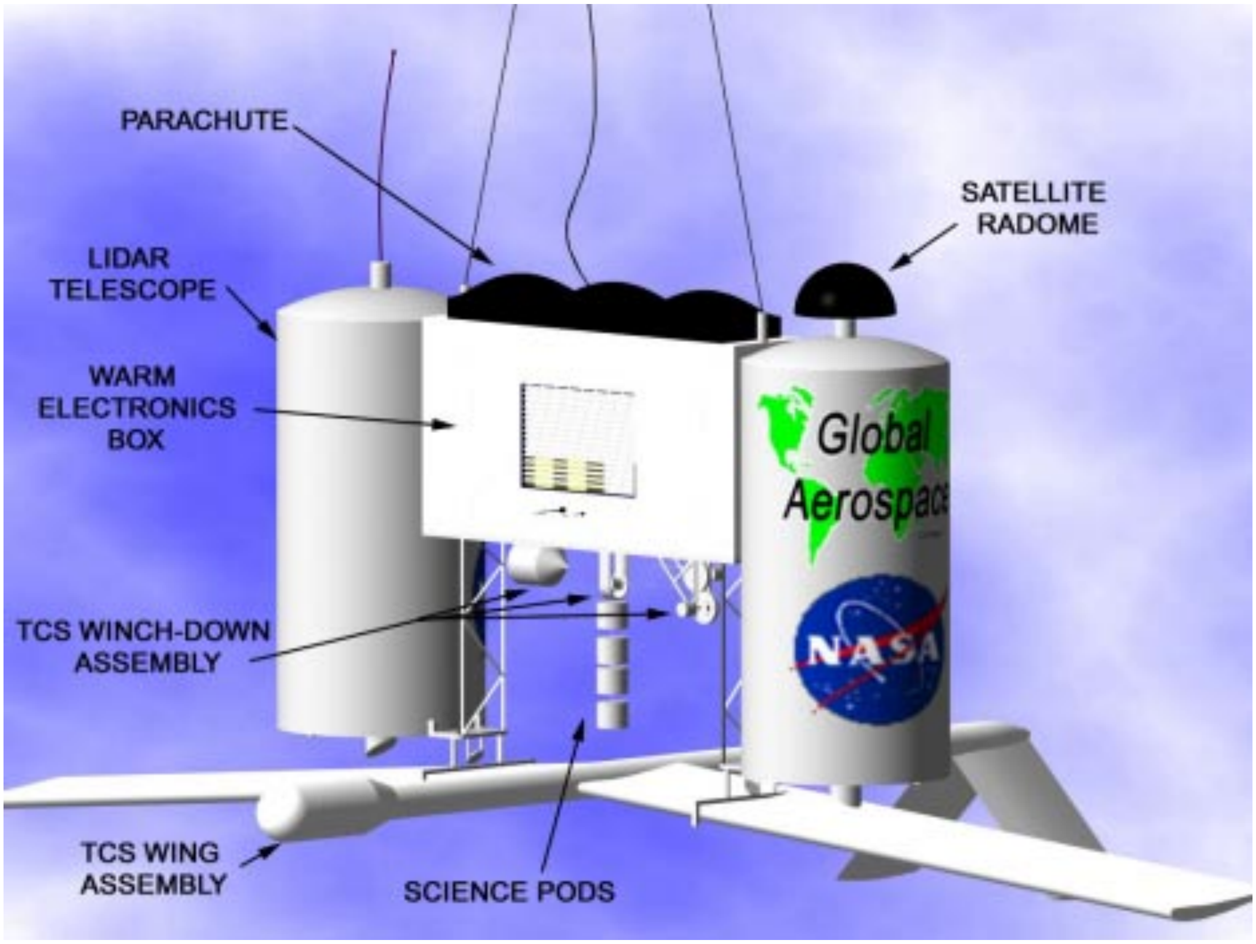


Figure 7.13 StratoSat Gondola and Trajectory Control Systems

7.2.5 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 300 g wind speed sensor, a 92 g rate gyro, a 63 g accelerometer and tilt sensor, a 375 g differential GPS unit, 375 g atmospheric pressure sensor and a 15 g temperature sensor. All of these components are available today in these masses and therefore mass reductions would be expected in the future. G&C average power requirements were estimated at 1.2 W.

7.2.6 Robotic Controller

The robotic controller performs many if not all on-board computational functions. It initiates autonomous activities of the StratoSat 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 from and to ground stations and other StratoSats (if cross-links are eventually) implemented. The robotic controller assesses StratoSat 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. Masses and average power requirements were estimated at 300 g and 3 W for the processor and 150 g and 1 W for the memory and interface electronics.

7.2.7 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 Trajectory Control System includes the TCS Wing Assembly (TWA) and the TCS Interface Package (TIP) the tether, a winch system, and an interface electronics and radios. The TWA has a wingspan of 8m and a chord of 1m. This is similar to hang gliders and suggests that the TWA could be constructed in a similar fashion. Most hang gliders depend on weight-shift of the pilot for control, so control surfaces and actuators would have to be designed. However, the baseline approach is to fabricate the TWA using lightweight composite ribs and spars covered with material similar to balloon envelope material. To help minimize weight, we have chosen to use a V-tail, but a conventional empennage would work also. The V-tail is constructed similar to the wing. 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 using a pitot-static tube. The following table describes the TCS components.

Table 7.8 TCS Mass Summary

Component	Mass, kg
TCS Interface Package (TIP)	32.4
TCS Wing Assembly (TWA)	48.4

7.2.7.1 TCS Interface Package (TIP)

The purpose of the winch assembly is to unwind the tether to lower the TWA following ascent of the balloon to altitude. The winch is a one-way device; it does not include the ability to raise the TWA, just to lower it. The extra weight and complexity to raise the TWA are not warranted here. While the TWA is reeling out, the tether turns a series of pulleys, which drive a pair of redundant generators. A bank of light bulbs acting as high temperature radiators dissipates the energy. The rate of descent is such that the power is kept to a very manageable level of about 100 W. This keeps the generator/brake system lightweight and allows the TWA to be fully deployed within 24 hours. Given the long duration of the mission, this delay is not an issue. While the TWA tether is extending, several small science pods are attached to the tether at intervals of a few kilometers. This provides the ability to take simultaneous measurements at several different altitudes. The following table describes the TIP components, including contingency.

Table 7.9 TIP Mass Summary

Component	Mass, kg
Structure	4.7
Winch-down Mechanism	11.7
Cutdown	0.3
Tether	15.7
Subtotal	32.4

7.2.7.2 TCS Wing Assembly (TWA)

The TCS Wing Assembly comprises a rigid wing and empennage attached to a boom. Specific construction techniques have not been selected at this early phase. Several candidates are available ranging from a sophisticated, albeit expensive, composite structure down to purchasing and modifying a hang glider. It is expected that the continuing evolution of hang gliders will lead to satisfactory options for the TWA over the next decade or so. The boom is a rigid element to mount the various elements of the TWA. A composite GFRP (graphite fiber reinforced plastic) tube will likely be available in a convenient size at a relatively low price and will provide a strong, stiff, lightweight mounting structure quite suitable to the requirements of the TWA. A housing attached to the forward end of the boom, which will house the TWA avionics and science instruments, acts as a counterbalance to set the position of the center of mass appropriately. The following table describes the TWA components, including contingency.

Table 7.10 TWA Mass Summary

Component	Mass, kg
Control Module	9.7
Wing Structure	38.4
Cutdown	0.3
Subtotal	48.4

7.2.8 Termination

The termination subsystem provides the means to reliably and safely terminate the mission of a StratoSat 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 which 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.

7.2.8.1 Emergency Termination

Emergency termination occurs automatically and essentially instantaneously following catastrophic failure of the balloon. Since the termination subsystem is not directly the subject of the advanced technologies being investigated in this effort, no specific suite of sensors has been selected. There are several quantities that could be measured to sense this condition: balloon pressure, payload altitude, support line tension, vertical relative wind velocity, rotation rate of platform, etc. To guard against accidental initiation of this emergency cut-down mode due to a sensor failure, one might require that at least two different sensors agree prior to execution of the command sequence.

Following detection of balloon rupture, several commands will be sent. The TWA will be commanded to separate itself from the bottom of the tether. Since the TWA is essentially a glider, it will be able to fly itself to a safe landing site. A database of safe landing sites may already be stored on board the TWA, or it may be commanded to a specific site as part of the termination command sequence. The science platform (gondola) will sever the top end of the TWA tether, allowing the small science instruments strung along the tether to fall with the tether. The drag of the tether is sufficient to prevent a high terminal velocity. However, the tether is expected to clump into a loose ball or series of clumps, rather than stringing out over many kilometers of terrain. The platform will command the ejection of a parachute or parafoil and sever itself from the support tether attached to the balloon. A parafoil provides significantly greater capability to descend to safer and more convenient landing sites for recovery. Each of the four separate elements will include a radio frequency recovery beacon, which will start emitting either as commanded during the cut-down sequence, or in response to a simple altimeter switch within the beacon. The four elements are the TWA, the tether, the science platform, and the balloon.

7.2.8.2 Nominal Termination

Although there are no specific life-limiting elements on board, it is recognized that the performance of various elements will eventually degrade to a level that continued operation would not be cost-effective. In this case, it is reasonable to expect remaining controllable lifetime so the mission will be commanded to follow a trajectory to a convenient landing site. Depending on the reason for the termination, actual cut-down may be delayed hours, days, or even weeks. Once the system is approaching a suitable landing site, the system will assume a configuration yielding the greatest probability of a safe and convenient recovery. After separation of the various elements, the TWA will be the most maneuverable, and will be able to guide itself to an appropriate landing site within a very large radius. The platform on its parafoil or parachute will potentially have some maneuvering capability. The balloon will tend to ball up and fall along a trajectory determined by the wind profile over the descent path. The tether will similarly fall along an uncontrolled, but somewhat predictable path. However, the tether constitutes a smaller threat to buildings and people on the ground since it is much lighter than the balloon. Therefore, it makes sense to maneuver the entire system, prior to separation, to a location that yields the safest projected landing site for the balloon. At this point, the sequence will be first to release the TWA and have it clear the tether. A delay of a few minutes should ensure this. Second, the tether will be released from the platform. It will fall quite rapidly at first being in a vertical orientation. Third, after a few minutes the platform will release itself from the balloon and begins its descent. Once the platform releases itself, the balloon will rise very rapidly. After it gains some altitude, it will rupture due to the pressure difference across the envelope. However, a timer will trigger a balloon destruct device a few minutes later to ensure that the balloon comes down predictably. This leisurely termination of the various elements will ensure a very low likelihood of the various elements interfering with one another.

7.2.8.3 Rapid Termination

Rapid termination is initiated in response to a sudden unexpected loss of system power. This situation differs from Nominal Termination in that much less controllable lifetime will be available to maneuver the system to a landing site. However, it also differs from Emergency Termination in that the system will not be in a catastrophic state requiring immediate action. The TWA and main platform have separate power systems and each will retain some autonomy in the event that the other fails. The sequence of events will depend on the nature of the power failure. Each will carry a battery to provide emergency power to either part of the system for enough time to assume a safe attitude for termination. If the power failure is localized such that normal communication between the TWA and gondola is not possible, each will follow a prescribed sequence of events. Both elements will try to transmit the state of the system to ground-based operators, using emergency transmitter options if necessary. Ground-based operators may override preloaded sequences if warranted.

The following subsections indicate possible courses of action of the system during power system failures of various kinds. The sequences described are not intended to be exhaustive, but rather to indicate the nature of rapid termination. A more comprehensive analysis would be performed during the actual design of such a system. The point is that for a large constellation, one must provide a reasonably robust set of sequences based on a number of failure scenarios.

7.2.8.3.1 Assumed Gondola Power Failure

If the gondola main power system fails, it will switch to emergency battery power. If the projected emergency battery power is sufficient to reach the next useful landing, the gondola will send a command to the TWA to maneuver the system towards the landing site. The TWA will then proceed autonomously towards the designated location in the absence of further commands. The gondola and TWA will both transmit the system state using normal and emergency communications channels as available. Provided the emergency power is sufficient, the termination will be essentially identical to the nominal termination sequence described above.

If the TWA notes insufficient emergency power, it will request the TWA to release itself. The gondola will then sever the tether, release itself from the balloon and descend by parachute or parafoil, and will issue a command to the balloon self-destruct system. The timing will not be as rapid as during emergency termination, but will not result in landing at a preferred site.

If the TWA receives no further instructions, it will proceed as long as possible towards the nearest reachable landing site based on its own database and its own knowledge of its position. At the appropriate location, it will broadcast its intent to separate and will then sever the supporting line. It will then proceed to land if possible. If the gondola is still functioning (perhaps with failed transmitters, for instance) it will detect the reduction in weight on the tether, either by direct measurement of tether tension, or indirectly through abnormal altitude gain. It may also be receiving the broadcast warning from the TWA if its receivers are still functioning. After a delay of a few minutes, the gondola will sever the tether, which will fall as during nominal cutdown. After a few more minutes, the gondola will sever the line to the balloon, and unfurl the descent parachute or parafoil and descend towards the landing site. The balloon will either rupture spontaneously as it ascends or will be terminated by command from the gondola or from operations, depending on available communications channels.

7.2.8.3.2 Assumed TWA Power Failure

If the TWA main power system fails, it will switch to emergency batteries. It will transmit its status to the gondola and to ground-based operators using normal and emergency channels as available. If no countermanding orders are received, the TWA will assume an attitude projected to maneuver the system to the closest attainable landing site at which point it will attempt to initiate a nominal cut-down. This will include broadcasting its intent so the gondola can follow the same procedure if it is receiving the TWA transmissions.

If the TWA detects imminent loss of emergency battery power, it will release itself from the tether and assume a gliding attitude with a planned slow descent rate. As long as emergency power remains, it will attempt to glide to a landing site. The gondola will note the loss of weight and project the flight path without the TWA. If the projection is towards more favorable sites (less populated regions, for instance) then it will delay the continuation of cut-down until more favorable circumstances exist. Eventually, the projection will be less favorable and it will release the tether, release the balloon, and descend by parachute or parafoil, and command balloon self-destruct.

If the gondola does not receive any status from the TWA, it will attempt to assess the probable status based on the trajectory behavior of the system. If the system appears to be targeting a reasonable landing site, the TWA will take no immediate termination action. It will communicate the status of the system to ground-based operators. If the TWA appears to be malfunctioning, as indicated by an apparent guided motion in an inappropriate direction (towards populated regions, for instance) then the gondola will assume a malfunction of the TWA and will release the balloon, deploy the parachute or parafoil and attempt to lower the TWA to the ground. After a reasonable delay, it will also initiate the balloon self-destruct system. Once the TWA is on the ground, the gondola will sense the reduced line tension (or it will assume the TWA is on the ground based on the gondola altitude and the known tether length), and the TWA will then sever the tether. The tether will fall to the ground still attached to the TWA. The gondola will then proceed to execute as safe a landing as possible.

7.2.9 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 in order to drive the StratoSat system design. The payload described below addresses the science objective of the understanding the water vapor and global circulation in the tropics (see Section 3.2.1)

At the gondola:

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

Along the tether (2, 4, and 6 and 10 kilometers above the StratoSail™ TCS):

- Water vapor and ozone infrared absorption instruments
- Temperature

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

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.

7.2.9.1 Gondola Science

Science experiments at the gondola will take advantage of the 30-45 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. The following table describes the science mass (includes contingency mass) and average power assumptions. All of the science reserve is bookkept in the gondola science mass.

Table 7.11 Gondola Science Power and Mass Summary

Experiment	Ave.	Mass, kg
Ozone LIDAR	34	24.0
Water Vapor LIDAR	34	24.0
Temperature & Pressure	See G&C	See G&C
Science Reserve	22	21.5
Subtotal	90	69.5

7.2.9.2 Tether Science Pods

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. For the example science payload the science pods (4 each) each consists of the following hardware.

Table 7.12 Science Pod Power and Mass Summary

Experiment/Component	Ave.	Mass, g
Water/O_3 TDL IR Absorption Cell	125	375
Temperature	10	8
Microcontroller	100	40
Radio Modem	100	116
Battery		113
Solar array		15
PMAD		38
Subtotal	335	700

7.2.9.3 TCS Science

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. The example TCS science is described in the following table

Table 7.13 TCS Science Power and Mass Summary

Experiment	Ave.	Mass, kg
Microwave Temperature Profiler	2.0	3.0
Water/O_3 TDL IR Absorption Cell	0.5	0.4
Temperature & Pressure	See TCS	See TCS
CO2 Cavity Ringdown Laser	1.0	1.5
Subtotal	3.5	4.9

7.2.9.4 Dropsonde Science

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.

7.3 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 7.14 shows the operations system schematic.

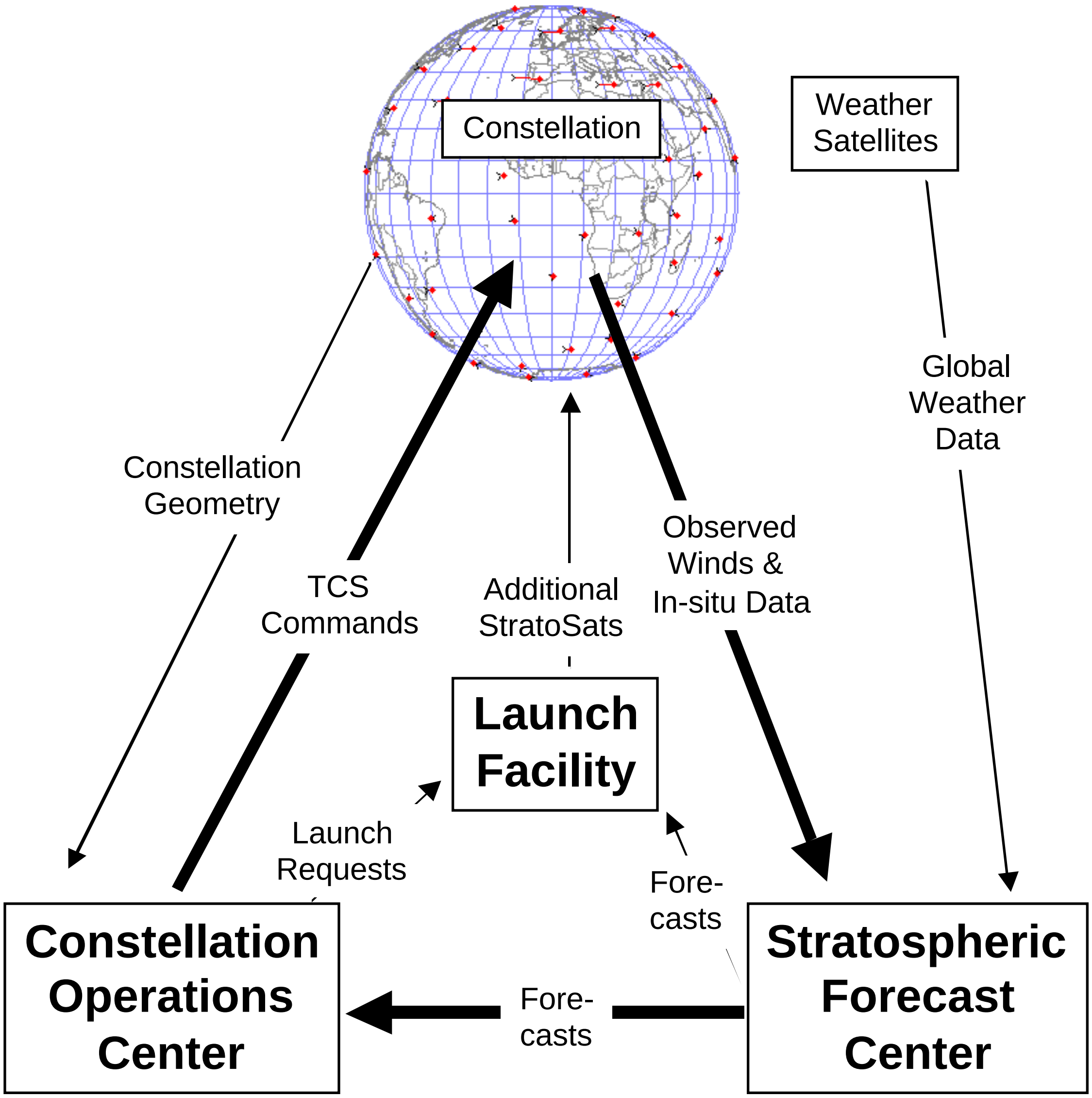


Figure 7.14 Operations System Schematic.

7.3.1 Operations Center Description

The Operation Center receives, processes, distributes and archives data from and sends command updates to platforms in the constellation. The Operations Center receives data by means of direct radio contact with balloons themselves, satellites, and other commercial ground stations that have been in contact with the network.

In addition, the Operations Center receives world stratospheric environmental data and predictions from the weather forecast center. The Operations Center will process all position and velocity data from all platforms of the network, combine these data with wind predictions, and simulate the evolution of the network into the future. Computer analysis of these data will result in updates of TCS control algorithms for all affected platforms in order to maintain optimum network configuration.

The Operations Center will autonomously assess platform health and call in humans when intervention may be required, i. e. subsystem or instrument major state modification or termination.

7.3.2 Launch Facility Description

An entire constellation of StratoSats can be launch from a single facility because of trajectory control capability. The launch facility initially will be used to launch the entire network over a specified time period, e.g. months. This facility includes all necessary infrastructure to launch a network of the appropriate size including operations, storage and assembly and test buildings, local surface and altitude wind measurement capability and inflation and launch equipment. Once the network is in operation, the Launch Facility will launch replenishment platforms as required to maintain constellation coverage or configuration.

7.3.3 Weather Forecast Center Description

The weather forecast center will provide periodic stratospheric weather forecasts to the operations center. Input data for the assimilation and forecasting activity will come from several sources, including the worldwide radiosonde network, weather satellites, ground stations, and the stratospheric constellation itself. The forecast center will use all these data to develop assimilations (snapshots of the state of the atmosphere) and forecasts (predictions of the evolution of the atmosphere). These outputs will be used by the operations center to command the individual StratoSats in the network.

The environment data provided by the forecast center will be highly accurate compared to what is produced today because of the inclusion of *in-situ* data from the constellation.

8 Cost Analysis

8.1 Introduction

The section provides a preliminary estimate of costs for a StratoSat network. This cost estimate needs to be evaluated in comparison to costs for conventional satellite systems. We begin by discussing space systems costs and thereafter we present global StratoSat constellation cost estimates and compare them with space system costs.

8.2 Space Systems Costs

We first indicate some of the high cost elements necessary to operating science experiments or Earth monitoring systems in earth orbit.

8.2.1 Launch Costs

Space launch costs and specific launch costs ($/kg) are shown in the next figure for operational and soon-to-be-operational launch vehicles. These specific costs were calculated for placing payloads into low-inclination (28 degrees), 200-km altitude orbits. The NASA ULDB estimated cost of $2M per launch (probably a factor of twice eventual cost) of 1000 kg science payload is shown for reference since its “orbit” is only 35 km, which is still above 99% of the Earth’s atmosphere. Note that most specific launch costs are between $10k and $20k per kilogram, except for the more expensive Pegasus, Taurus and Athena launch vehicles. Although these launchers have low total cost, the specific launch costs are high. In addition, these small launchers only have payload capabilities between 470-720 kg to these low inclination orbits.

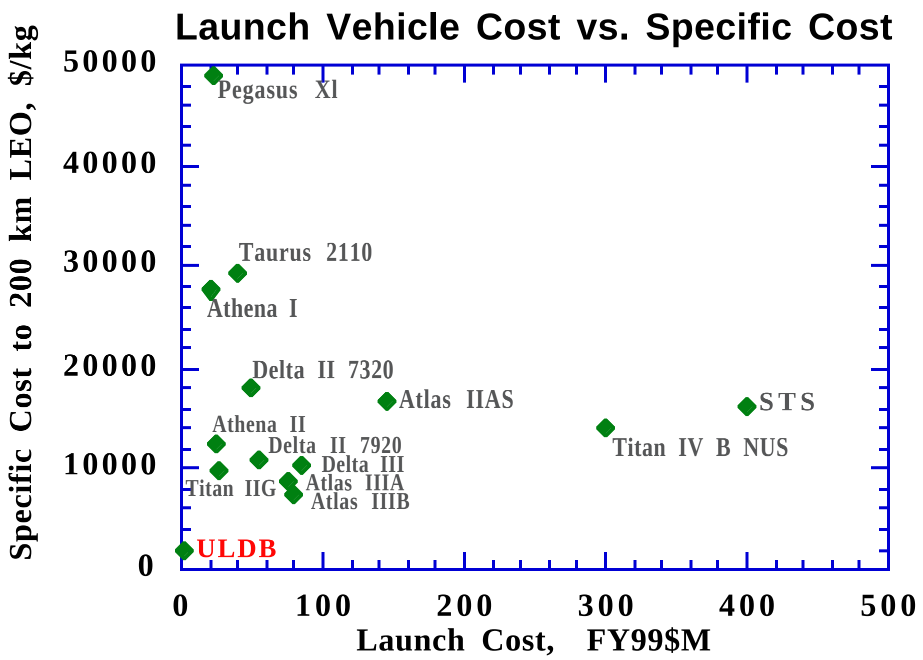


Figure 8.1 Launch Vehicle and Specific Launch Costs

The next figure shows the range of specific cost for a variety of space launch vehicles capable of placing payloads between 200-km altitude, low-inclination orbits and 1000-km altitude, sun synchronous orbits. Since Sun synchronous orbits are at near polar inclinations, thus they require more launch energy to reach and hence reduced payload mass for the same launch cost. The STS and ULDB are shown only for reference since the STS cannot achieve sun synchronous orbits by itself and the ULDB is only at 35-km altitude. The lower end of the bars represent specific launch costs for 200-km, low-inclination orbits while the high end of the bar represents the near-polar orbits. These data indicate that, especially for expensive launchers like Pegasus, Taurus and Athena, the specific launch cost climbs dramatically when global, near-polar orbits are desired.

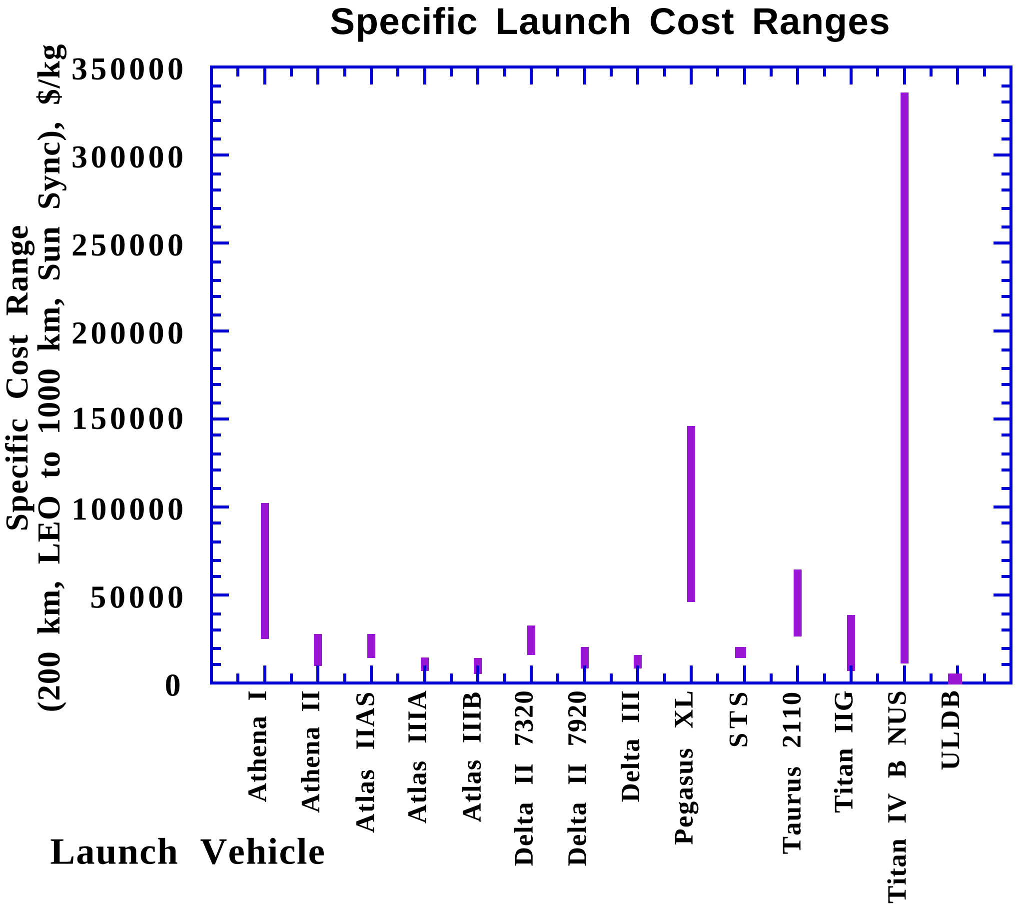


Figure 8.2 Specific Launch Cost Ranges as a Function of Orbit

8.2.2 Earth Science Satellite Costs

At this time it does not make sense to launch satellites that cost significantly less than the launch cost investment, unless several satellites can be launch at the same time (as is done with some communications satellite constellations). Thus for large operational flight systems, the costs will be comparable to the launcher costs. This means that, unless there is an order of magnitude reduction in launch costs, satellite costs are expected to be between about $25M and $100M or higher depending on satellite mass and complexity.

8.3 Global StratoSat Constellation Costing Assumptions

There are a number of assumptions relating to the following cost estimates including:

- FY99$
- 100 StratoSat constellation
- 133 StratoSats initially fabricated and assembled
- 10-year StratoSat lifetime
- 3% per year StratoSat mortality rate
- Commercial telecom providers for data return at 5 MB for $1
- Balloon costs are function of material costs (proportional to envelope area) and fabrication labor (proportional to total gore seam length)
- Upgrade of stratospheric environmental data providers assimilation and forecast systems
- Constellation development costs include StratoSat flight and operations systems design
- Emplacement requires one year
- Constellation emplacement costs include StratoSat flight systems procurement, launch and operations costs
- Constellation maintenance costs include StratoSat flight systems replenishment and operations costs

8.4 Global StratoSat Constellation Development Phases

Several phases characterize the development of a global constellation of stratospheric scientific platforms. These phases include Conceptual Design, Technology Development, System Development, System Emplacement and Operations and Maintenance Phases. These are described in more detail below.

8.4.1 Conceptual Design

The conceptual design phase is the current phase of the global constellation of stratospheric scientific platform concept. It is in this phase that the basic feasibility of an advanced concept is established. This period is currently being funded by NIAC as a Phase 1 advanced concept study and, hopefully later, a Phase 2 advanced concept study. The goal of the conceptual design phase is to obtain a fundamental technical understanding of the concept, to verify its application and user need and to interest future sponsors (NASA) to fund follow-on development activities.

8.4.2 Technology Development

In the technology development phase the key technologies are supported to insure technical feasibility. NASA Technology Readiness Levels have been established to measure the progress of technology development and to assess technology readiness levels. In the global constellation of stratospheric scientific platform concept there are currently several candidate areas for future technology development including constellation maintenance, balloon design, trajectory control modeling and analysis and science experiment developments.

The ULDB technology development AND system development is estimated to cost about $12M up to the first full-scale demonstration flight. For the ULDB Project, the key technology was the balloon design and fabrication. To a lesser extent there has been development of gondola subsystems, termination subsystems and the ULDB trajectory simulation and prediction system. Assuming that (1) the ULDB development is successful and (2) taking into account the larger scope of StratoSat technology development activities, StratoSat constellation technology development is estimated to be about $10-15M.

8.4.3 System Development

The system development phase includes the system design and prototyping of both hardware and software. The system development and the technology development phases may actually overlap in time similar to the ULDB development.

Many of the technologies, and perhaps some of the experiments, may need to be verified on low-cost proof-of-concept flights prior to large investment of development resources. StratoSat constellation system development is estimated to be about $10M. These resources include work on specific: balloon material designs, production and testing, balloon design, analysis and testing, and balloon fabrication development and testing; constellation management systems design and testing (including hardware infrastructure and environmental data requirements); gondola and trajectory control systems design and testing; design of systems interface with global communications providers and science instrument and sensor design development directed at specific proof-of-concept flight experiments.

8.4.4 System Emplacement

System emplacement cost includes the cost of producing 133 StratoSats and launching 100 within one year. StratoSat costs include the major hardware the elements of balloon envelope, gondola, science payload, and StratoSail™ TCS. In addition, system emplacement costs include the cost of an operations center for the one year.

8.4.4.1 Balloon

Balloon costs were developed from analogy with one current ULDB balloon type and cost estimate. The ULDB Project has estimated the cost of a PE pumpkin balloon, of 11 million cubic feet volume, at about $130,000. For the purposes of the costing we have assumed that the StratoSat balloon is also a pumpkin balloon of similar construction. The cost of envelope materials is about $11 per kg, the cost of tendon cord is about $2.30 per liner meter, and seam cost is about $4 per linear meter of total seam length. Scaling the ULDB reference balloon discussed above with these fabrication numbers yields a StratoSat balloon cost of about $69,000 each. This cost is conservative because future balloon design and fabrication technology should serve to further reduce this cost.

8.4.4.2 Gondola

Most of the non-science hardware described above can currently be purchased for under $1000 per component, and in many cases below $500. A major exception to this is the solar array that could cost about $9,000 for the 4.9kW array at today’s prices and technology. Additional costs are estimated in the following table. Future advancements in subsystem technology is expected to both reduce cost as well as mass.

Table 8.1 Gondola Cost Estimate per StratoSat

Subsystem	Cost Estimate, k$
Power	18
Telecom	5
Mechanical	3
Avionics	4
Subtotal	30

8.4.4.3 Science

The science hardware is estimate assuming all 133 units (532 science pods) are fabricated at about the same time in an assembly line process. The following table summarizes these estimates.

Table 8.2 Science Cost Estimate per StratoSat

Experiment	Cost Estimate, k$
Water & O_3 LIDARs	50
Science Pods (4)	8
Microwave Temperature Profiler	5
Water/O_3 IR Absorption Cell	1
CO_2 Cavity Ringdown Laser	5
Subtotal	69

8.4.4.4 Trajectory Control

We estimate the cost of the TCS components for a StratoSat as follows: TWA, $40k; Tether, $10k; TIP, $10k; for a total TCS cost estimate of about $60k.

8.4.4.5 StratoSat Flight System Cost

Table 8.3 StratoSat Flight System Unit Cost Estimate

Element	Cost Estimate, k$
Balloon	69
Gondola	30
Science	69
TCS	60
Assembly &Test†	15
Subtotal	243

† – 15% of gondola and science costs

8.4.4.6 Operations System

The Operations System costs include the cost of equipment, facilities and personnel for the Operation Center plus the additional cost for the initial emplacement launch operations. We estimate the operations personnel costs at 20 people for one year at an average of ~$150k/person, for a cost of $3M. The facility and equipment costs are estimated at $0.3M and $0.7M, respectively, in the first year of operations. Due to the importance of accurate stratospheric assimilations and forecasts, a major effort is assumed in this area including the development and/or modification of GCMs and the incorporation of StratoSat data into the assimilation process. Launch operations also include equipment, facilities and personnel. It is assumed that a commercial facility will be leased and the launch operations done under contract. We assume a 10-person crew launching about 2 StratoSats per week for a personnel cost of $1M. Facility and equipment lease are estimated at another $1M total.

Table 8.4 Operations Costs for Emplacement

Element	Cost Estimate, M$
Ops Center personnel	3
Ops Center Facilities & Equipment	1
Stratospheric Environmental Data	1
Launch Ops	2
Subtotal	7

8.4.5 Operations and Maintenance

Constellation maintenance costs include the costs of the replenishment launch operations at a rate of 3 per year, the operation system and the data recovery costs paid to global communications providers. Data cost assume 5 MB cost about $1. The total data returned from the constellation is the assumed low-rate data at 2.4 kb/s for one year for 100 StratoSats. This low rate data cost is only about $0.2M. High rate data is assumed at 2Mb/s for an average of about 3 hours per day for a cost $0.8M per year.

8.5 Total Estimated Costs

8.5.1 Constellation Emplacement

Table 8.5 Estimated Constellation Emplacement Costs

Element	Estimated Cost, M$
Flight Systems, 133 each	32
Operations (1 year)	7
Total	39

8.5.2 Constellation Operations

The yearly estimated operations and constellation maintenance costs are shown in the following table.

Table 8.6 Estimated Operations and Maintenance Costs

Element	Estimated Cost, M$
Operations Center	3
Launch Ops (3 per year)	1
Data	1
Total	4

8.6 Cost Summary

These total costs, though conservative, are obviously very low relative to typical space launcher and spacecraft costs. These numbers indicate that for those applications where global StratoSat constellations make sense, the costs are very reasonable compared to space program costs. In fact, the constellation emplacement cost by itself is less than 75% of all the launch vehicles listed in Figure 8.1; and in the case of the space systems, the spacecraft is not even considered. Table 8.7 illustrates an example cost comparison between the deployment of a StratoSat constellation and one Earth science satellite using typical costs.

Table 8.7 Cost Comparison of StratoSat Constellation with One Earth Science Satellite

	100 StratoSat Constellation	One Earth Science Satellite
Hardware	$32M	$50M
Launch	$7M	$50M
Total	$39M	$100M

This cost comparison confirms the potential economy of StratoSat constellations relative to space infrastructure and point to the benefits of developing this concept further.

9 International Considerations

9.1 Overflight Issues

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 to impossible to receive. The overflight issue can be exacerbated if down-looking imaging is carried and/or if scientists from the 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. National sovereignty usually applies to airspace but not outer space. It has been determined that the end of airspace and the beginning of outer space is between the upper flight height of aircraft and the lower orbit of spacecraft [John Kish, *The Law of International Spaces*, A.W. Sijthoff, 1973, p. 44]. Thus it appears that functional factors determined the historical delimitation of airspace and outer space. 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.

The Open Skies Treaty (see below) is a positive step toward building confidence and security in the arms control and verification process ongoing between signatory nations.

9.2 Open Skies Treaty

On March 24, 1992, 25 nations signed the Open Skies Treaty (OST) in Helsinki, Finland (See http://www.acda.gov/treaties/openski1.htm). When fully implemented, the treaty will establish a regime of unarmed military observation flights over the entire territory of its signatory nations. The OST was originally negotiated between members of NATO and the former Warsaw Pact as a confidence building measure in arms control.

Some of the key statements in the OST 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 OST: 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 OST enters into force after ratification by at least 20 nations.

The OST 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 OST 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."*

10 Future Work Plan

10.1 Introduction

A number of areas in the understanding of global constellations of stratospheric platforms need further work beyond what is possible under a Phase 1 NIAC study including constellation management, science application development, balloon design, trajectory control, and international overflight.

10.2 Constellation Geometry Management

In this report, we discussed several constellation geometry management strategies and algorithms. We have made significant progress in understanding what is required for managing StratoSat constellations, and we have identified several areas where improvements could be made. In this area several future activities need to be pursued in the future.

10.2.1 Control of Distributed Systems in Chaotic Environments Research

When developing future advanced constellation geometry strategies and algorithms, we will gain insight from a new field of mathematics built around the control of systems in chaotic environments. We will evaluate the new field of Weak Stability Boundary Theory to obtain maximal control of StratoSat trajectories with limited control authority. We will investigate extending these theories to the control of distributed systems in chaotic environment and apply them to the task of constellation management.

10.2.2 Develop Advanced Constellation Geometry Control Algorithms

The previous sections have discussed several constellation management strategies and algorithms. We have made significant progress in understanding what is required for managing StratoSat constellations, and we have identified several areas where improvements could be made.

At this point, the constellation management algorithm that shows the most promise is a combination of molecular and macro control strategies, namely the Paired N-S/Zonal control algorithm. However, there are significant improvements that could be made. First, the use of forecast data for “look-ahead” network control strategies could provide significant advances in the capabiltiy to control constellation geometry by identifying (a) those StratoSats that should not be moved (because they will move into a better position later) and (b) those StratoSats that will require significant trajectory control in the future. In the first case, use of a look-ahead capability will simplify the control of individual StratoSats by minimizing the amount of control commands. In the second case, less control authority will be needed if it is applied earlier.

10.2.3 Integrate Balloon Model, Environment and Advanced TCS Models and Control Algorithms in Constellation Simulations and Analysis

During the Phase 1 activity, we reduced computing requirements by simplifying the TCS model. For future work, higher fidelity TCS models should used that fully describe all available control options. The use of enhanced environment information, including forecasts needs to be considered. The use of forecasts will provide the opportunity for “look-ahead” control strategies that may have a dramatic effect on constellation geometry management .

10.2.4 Control of Distributed Systems in Chaotic Environments Research

When developing future advanced constellation geometry strategies and algorithms, we will gain insight from a new field of mathematics built around the control of systems in chaotic environments. We will evaluate the new field of Weak Stability Boundary Theory to obtain maximal control of StratoSat trajectories with limited control authority. We will investigate extending these theories to the control of distributed systems in chaotic environment and apply them to the task of constellation management.

10.3 Science Applications Development

10.3.1 Proof-of-Concept Flight Definition - A Logical Next Step

An obvious step in the direction of global constellations of stratospheric platforms is the definition of possible proof-of-concept flight missions. Such a mission must be defined in enough detail that program managers can assess the cost and value of future global constellations. The key uncertain elements, which need future definition, are the choice and the cost of proof-of-concept science experiments. Assuming the ULDB systems are operational in the next two years, these systems provide a unique opportunity to fly low-cost constellation-like science experiments for long duration; 100 days or more.

10.3.2 Broaden Search for New Earth Science Concepts

The purpose of the work on science applications was to illustrate how balloon-born *in situ* instrumentation on advanced global stratospheric balloon constellations can be used help answer some of the key questions we face regarding global change. We summarized in this report and in more detail in our report on *Earth Science Rationale and Mission Scenarios* [GAC Report 510-02511-006, October 31, 1999] 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 presented 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. There is a need to expand on this work both in depth and breadth across the Earth science community. We hope and anticipate the *Earth Science Rationale and Mission Scenarios Report* will be a living document, providing impetus and focus for input and development from the broader scientific community.

10.4 Advanced Balloon System Design

Much can be done in the area of balloon design to optimize the StratoSat and to provide more science mass, achieve higher altitudes, or longer mission duration. It is clear that much needs to be done in the area of balloon design. Every kilogram of mass removed from the balloon is mass available to improve science capability. Balloon system design efforts should be focused in (a) advanced research in new and innovative polymer materials that can be fabricated in commercial quantities and at low cost, (b) balloon design and analysis models in order to quickly compare the performance and cost of design options, and (c) research into the envelope design and fabrication processes necessary to construct high strength, low mass, and low cost balloon envelopes.

10.5 Advanced Trajectory Control

Global Aerospace Corporation has initially selected an advanced TCS Wing Assembly (TWA) option that uses a symmetric, dual wing design. Given this basic design, dynamic and aerodynamic models need to be developed in order to characterize and optimize this design. In addition, aerodynamic control strategies need to be developed that can feed directly into the constellation management. Once the design is optimized and control strategies defined, preliminary system requirements can be determined and design studies can proceed.

10.6 International Overflight

Overflight issues need to be understood and developed further. The degree to which opportunities exist for further diplomacy should be explored with appropriate U.S. and international institutions. The current open literature regarding international affairs indicates a strong interest in the application of global technologies to the improvement of life. With NIAC and NASA cognizance technical details of global stratospheric constellation concepts and technologies could be shared with policy makers and their staffs.

11 Summary

This report describes the work accomplished and results obtained during Phase I of the development of an innovative and new concept for a Global Constellation of Stratospheric Scientific Platforms in support of the NASA Institute for Advanced Concepts. During Phase 1, we demonstrated the feasibility of the concept by

- verifying the strong Earth science appeal of global stratospheric constellations
- showing that the trajectory of stratospheric balloons can be controlled and global constellations can be managed by such control,
- illustrating the scientific value of an example payload and using it to carry out a point design of a StratoSat flight system, and
- demonstrating that the cost of deploying a network of 100 StratoSats is less than putting one satellite into orbit

There were five tasks during Phase I:

- Task 1 Define Preliminary System Requirements
- Task 2 Science Observations Development
- Task 3 Conceptual System Design
- Task 4 Estimate System Costs
- Task 5 Reporting

During Phase I, we met 100% of the objectives by completing all the tasks. This document includes reports on the first four tasks. Its submission completes the fifth task.