Development of a Preliminary Technology Roadmap for Stratospheric Balloon Platforms Dedicated to Earth Science Applications

Report A:

Summary of Science Requirements, v. 0.1

Global Aerospace Corporation

April 29, 2002

Jet Propulsion Laboratory Purchase Order No. 1235768

GAC Report 140-76811-01

Global Aerospace
Corporation
711 W. Woodbury Road, Suite H
Altadena, CA 91001-5327 USA
Telephones: +1 (626) 345-1200
(626) 303-9500, Fax (626) 296-0929
Email: global@gaerospace.com
Web: http://www.gaerospace.com

Table of Contents

Development of a Preliminary Technology Roadmap for Stratospheric Balloon Platforms Dedicated to Earth Science Applications

Report A

Summary of Science Requirements

1 Introduction

1.1 ESTO Effort Overview

Part of the "Vision" activity of NASA's Earth Science Enterprise (ESE) is to develop concepts and plans for platform technologies to be pursued and developed in the future. One potential platform for Earth Science is very long life, guided stratospheric balloons. The NASA Earth Science Technology Office (ESTO) has solicited input from Earth scientists via a small study activity that seeks to identify technology requirements for future stratospheric observing platforms. Global Aerospace Corporation (GAC) is leading this study to

- Explore Earth science applications for ultra long life stratospheric balloons,
- Develop a set of driving Earth science requirements for stratospheric balloons,
- Identify technology needs for stratospheric balloon platforms to meet these requirements, and
- Develop a preliminary roadmap for such technology development including technology readiness levels (TRLs) and need dates.

The new class of stratospheric balloons being developed by NASA offers new potential science capabilities and extends capabilities of the existing observing platforms. Some of these potential capabilities include:

- Regional or global measurements;
- A few to many years of flight duration;
- Trajectory control;
- Remote and in-situ sensing throughout the atmosphere; and
- Adaptive sampling.

These new systems may have potential applications in many research areas: global climate change, Earth radiation balance, atmospheric chemistry, global circulation, solid Earth monitoring, enhancement of weather prediction, global ocean productivity, and hazard detection and monitoring.

One aspect of this study is to obtain science input from potential users of balloon platforms - scientists. For this purpose ESTO and GAC organized an informal workshop where scientists were presented with a summary of current state of the art in balloon technology and potential future capabilities of stratospheric balloons. Scientists were then asked to outline a potential earth science application for future balloon platform and to list science and instrument requirements that would drive the development of the platform.

1.2 Purpose of this Report

The purpose of this report is to summarize the results of the workshop, to summarize science applications and requirements suggested at the workshop, and to identify driving science requirements for technology development based on these applications and science requirements.

1.3 Organization of this Report

The remainder of the report is organized in the following way. In Section 2 we give an overview of the workshop organization and give the list of participants. Section 3 describes potential mission concepts developed during the workshop, their relationship to NASA's goals, and measurement and instrument technology requirements for these concepts. Section 4 lists technology requirements for stratospheric balloon platforms arising from the distilled science requirements.

2 Science Workshop Summary

To obtain the users input on potential science applications and requirements for the proposed long duration stratospheric observing platform, GAC hosted an ad-hoc Earth science workshop at GAC facilities at Altadena, CA on January 7, 2002. A number of prominent scientists from NASA's Jet Propulsion Laboratory (JPL), NASA Goddard Space Flight Center (GSFC), NASA Langley Research Center (LaRC) and from the Virginia Polytechnic Institute and State University (Virginia Tech) attended the workshop. Loren Lemmerman (ESTO/JPL) and Matthew Heun, Alexey Pankine, and Kerry Nock (GAC) attended plenary and group sessions. Matt Heun and Alexey Pankine organized the sessions and gave scientists their charter for the meeting. The list of participants was generated jointly by GAC and ESTO/JPL that had as broad a representation as possible with respect to Earth science disciplines and instrument classes (See Figure 1), and were deemed likely be able to attend in person or by telecon. Finally, ESTO/JPL approved the final list of attendees and sent invitations. A majority of the invitees were able to attend the workshop.

	Atmospheric Chemistry	Geophysics	Ocean, Ice	Hazards	ERB	Climate (global change)	Weather
Radar		**Ali Safaeinili, Rolando Jordan, (subsurface ice, MARSIS/JPL)**	**Ali Safaeinili, Rolando Jordan (ice, MARSIS/JPL)**				
Microwave	**Bob Stachnik (SLS/JPL)**						
LIDAR							
Radiometer					**Bob Mahan, Amie Nester (Virginia Tech)** **Tom Charlock** **Wenying Su (LaRC)**		
Magnetometers		**Carol Raymond (JPL)**					
GPS		**Carol Raymond (JPL)**	**Carol Raymond (ice, JPL)**				
Spectrometry	**Randy Friedl (JPL)**						
In situ methods	**Randy Friedl (JPL)** **Jim Margitan (JPL)** **Paul Newman (GSFC)**		**Frank Carsey (ice, JPL)**	**Paul Newman (stratospheric plume dynamics, GSFC)**			**Paul Newman (GSFC)**
Theory/Modeling	**Ross Salawitch (JPL)** **Paul Newman (GSFC)**				**Warren Wiscombe (GSFC)** **Paul Newman (GSFC)**	**Warren Wiscombe (GSFC)**	**Paul Newman (GSFC)**

Figure 1 Matrix of Science Participation versus Disciplines and Instruments

During the meeting, GAC presented an outline of the meeting and the context of the ESTO effort (see Appendix A). GAC then presented an overview of scientific ballooning and the possible future capabilities of the platform (see Appendix B: Present & Future Scientific Ballooning). This briefing was followed by Dr. Pankine who charged the science group with the task of generating science requirements and provided the group with a process for developing them (See

Appendix C). The rationale behind technology requirements development is illustrated on Figure 2. First, the scientists were asked to discuss potential mission scenarios and applications utilizing the capabilities of stratospheric balloons that would help to answer key questions outlined in the NASA Earth Science Enterprise (ESE) Strategic Plan (See Appendix D). The scientists were then asked to describe the measurements and instrumental approaches for these missions and applications, and to outline the requirements that these measurements and instrumental approaches impose on the observational platform. The sets of requirements developed in this way were recorded in the Data Capture Questionnaires (DCQs) developed for this purpose (see also Appendix D for a sample DCQ and Appendix E for the actual DCQs filled at the workshop). The DCQs are the starting point for the development of the ESTO technology requirements for future guided stratospheric balloon platforms. The science requirements distilled from the completed and submitted DCQs will drive the technology requirements. The analysis of the technology requirements, of the interrelationship between the technologies and an assessment of the technology readiness levels will be summarized in a technology development roadmap.

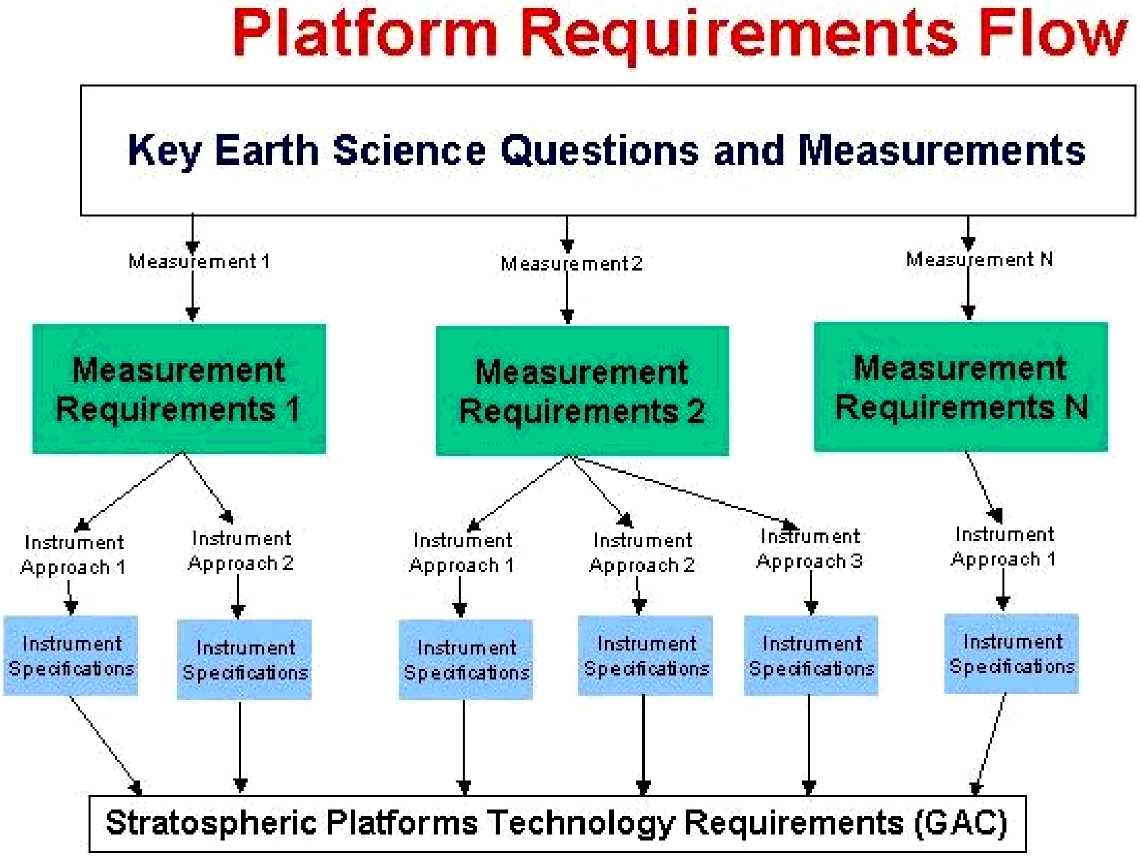


Figure 2 Rationale behind technology requirements development

After Dr. Pankine's charge to the group, the attendees broke into three subgroups to discuss requirements for future science missions. The three subgroups were:

- **Surface Science:**
  Frank Carsey (JPL)
  Rolando Jordan (JPL)
  Carol Raymond (JPL)
  Ali Safaeinili (JPL)

- **Atmospheric Radiation:**
  Tom Charlock (LaRC) (via teleconference)
  Bob Mahan (Virginia Tech)
  Amie Smith Nestor (Virginia Tech)
  Bob Stachnik (JPL)
  Wenying Su (LaRC) (via teleconference)
  Warren Wiscombe (GSFC) (via teleconference)

- **Atmospheric Chemistry:**
  Randy Friedl (JPL)
  Jim Margitan (JPL)
  Paul Newman (GSFC) (via teleconference)
  Ross Salawitch (JPL)

The following section describes the potential missions and requirements developed by the scientists in each group.

3 Potential Mission Scenarios, Approaches and Requirements

This section summarizes the science requirements input received from the scientists during the workshop and during the follow up process.

3.1 Surface Science

The Surface Science group focused on the following two general questions (A and B) and three more specific questions (1, 2, and 3) from the NASA's ESE Strategic Plan:

A) How is the global Earth system changing?

1. What changes are occurring in the mass of the Earth's ice cover?
2. What are the motions of the Earth and the Earth's interior, and what information can be inferred about Earth's internal processes?

B) What are the primary forcings of the Earth system?

3. How is the Earth's surface being transformed and how can such information be used to predict future changes?

In addition, even more detailed questions were addressed for all three of these specific questions. For question 1, the following detailed questions were suggested:

1a. What is the spatial and temporal character of ice accumulation?

1b. What is the topography of the Antarctic ice sheet bed?

For question 2, the following question was suggested:

2a. What are the dynamics of the magnetic (and gravity) fields at regional geological scales and what process drive the variations?

Finally, for question 3 above, the following more detailed question was suggested:

3a. What are the spatial (on a 100 km scale) and temporal (daily) characteristics of the transient strain accumulation and release?

These more detailed questions serve as a starting point in the definitions of the required measurements and instrument approaches for surface science applications of the future potential stratospheric balloon platforms. Each of these detailed questions can be addressed by a separate approach or concept that employs stratospheric balloons. These concepts are described below. The description follows the DCQ layout in that it starts with required measurement and corresponding requirements, followed by instrument approach with corresponding requirements. For convenience, the names of the concepts refer to proposed measurements.

3.1.1 SS1 Height changes of the ice sheet surface.

The concept, which addresses the question 1a, is to measure the changes in the height of the ice sheet surface from stratospheric altitudes. The candidate regions for this mission are the Antarctic ice sheet, the Greenland ice sheet, or any other ice cap. Current approaches to the ice topography measurements include spacecraft (for example, ICEsat/GLAS, CryoSat, MOLA), aircraft (NASA's Airborne Topographic Mapper (ATM)), and surface measurements. Stratospheric balloons offer an inexpensive alternative to these approaches. Balloon measurements can also be used to bridge the gap between the resolution of aircraft and satellite measurements and to continuously validate the satellite measurements.

Changes in the ice sheet height at a particular point are due to the snowfall changes and to changes in ice horizontal velocity (see Figure 3 for schematic of ice sheet dynamics. West Antarctica is a tightly coupled, dynamic environment. The size of the ice sheet depends on snow accumulation, wind-driven ablation, and subglacial melting and freezing. Under the floating ice shelves, circulating waters can drive melt rates in excess of 10 meters per year. The shape of the ice sheet depends on ice-flow that varies more than two orders of magnitude from the slow interior to the rapidly sliding ice streams. Subglacial water and till properties are strong influences on where faster motion occurs. Ice domes and divides are the most stable locations for deposition and englacial archiving of past atmospheric samples. Records of past ice-sheet extents are found in the isolated mountains high enough to emerge from the ice-sheet surface, and on the floor of the seas surrounding the ice sheet. The picture and the explanation are from NASA's West Antarctic Ice Sheet Initiative web page, http://igloo.gsfc.nasa.gov/wais/). Snow is deposited on the surface, but also is removed towards the edge of the ice cap by horizontal movement of the glacier. This horizontal stretching causes thinning of the ice. The rate of spreading varies with time. As geothermal heat warms the base of the ice sheet, the ice sheet starts to stretch under its weight and the upper surface of the ice descends. In time, this causes the thermal gradient within the ice sheet to sharpen and stops the outward stretching. The thickness of the ice sheets starts to increase again and the cycle repeats itself.

Measurements of the ice sheet height changes will be used to estimate changes in its volume and mass. This, in turn, would allow assessing the impact of this changes on global sea level, and, ultimately, on climate variability.

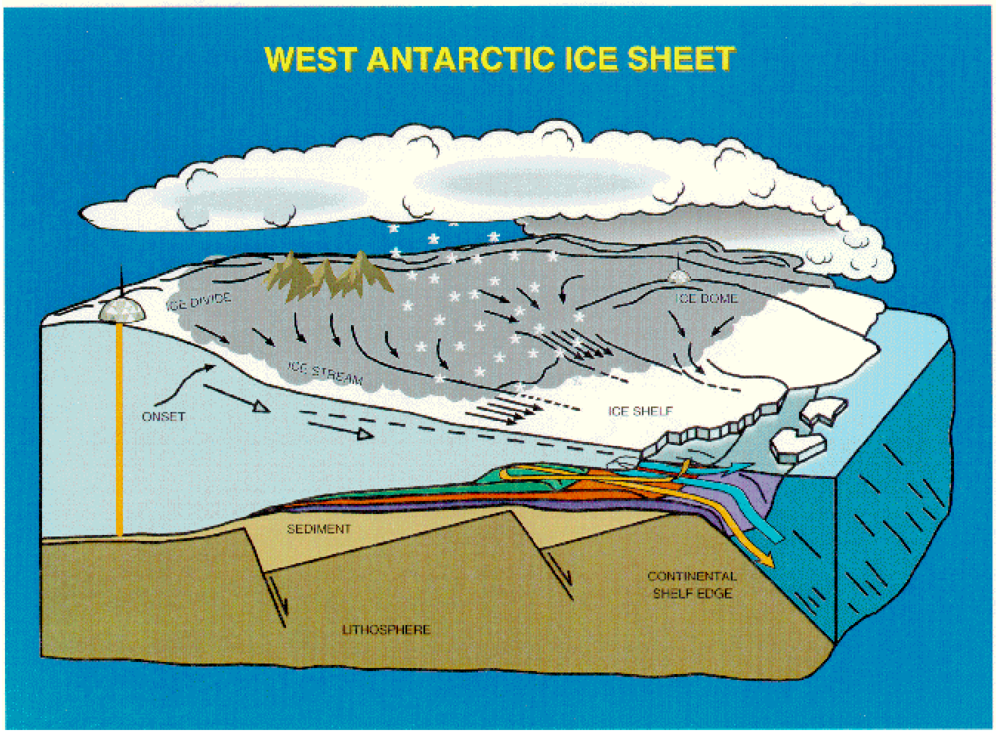


Figure 3 West Antarctica dynamic environment.

The changes in the snowfall occur on shorter time scales (daily) than the changes in the ice sheet height due to spreading (yearly). A tradeoff between the coverage and the length of observations suggests that the stratospheric balloon observations should focus on long-term changes, because they are more important and snowfall timescales are too short for the height changes to be captured over the entire region with a reasonable number (dozens) of balloons. Revisit times of less than 5 years of locations within the ice cap would be sufficient too assess changes of height due to movement of the glacier. Constellations of balloons would be able to provide the needed large-scale coverage over shorter campaign durations. Constellations may also be able to provide sufficient temporal and spatial coverage over sections of an ice cap to study snowfall rates.

The measurements are sought over an irregular grid with several kilometers of separation between the grid points to resolve the typical width of the ice stream flow within the glacier, which is of the order of tens of kilometers. Figure 4 shows schematics of the measurement. Observations should be roughly uniform over a region to minimize interpolation errors. It is important to have a substantial number of zonal trajectories because they are more likely to capture the radial changes in spreading velocity of the glacier. The range measurements are made with the nadir looking LIDAR. LIDAR sends a laser pulse and determines the distance by timing the return of the pulse. The required accuracy of the height determination is 2 cm (the expected change in topography is of the order of 10 cm/year). Instruments currently flown on satellites achieve this accuracy. Instruments flown on aircraft (ATM) achieve accuracy of about 10 cm with the use GPS technology.

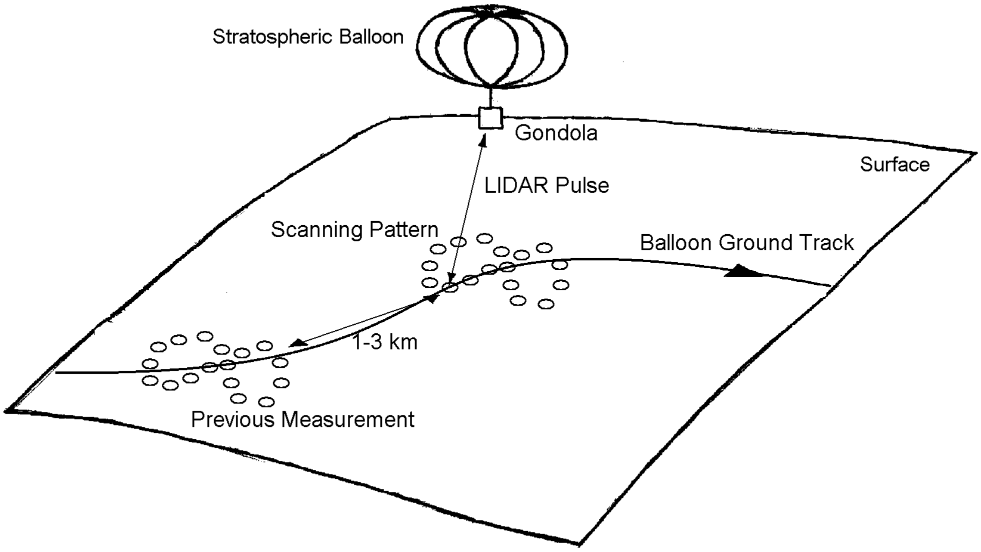


Figure 4 Schematics of a balloon LIDAR surface topography measurements

A MOLA-type LIDAR (Mars Orbiter Laser Altimeter, currently around MARS on Mars Global Surveyor) seems to be appropriate instrument for this concept. MOLA mass is 26 kg with power consumption of 34 W. The spot size of the laser pulse on the ground depends on the altitude of the platform. For a typical angular size of tenths of milliradians (ATM – Airborne Topographic Mapper, MOLA, GLAS - Geoscience Laser Altimeter System) the laser spot on the ground for a balloon instrument at 35 km altitude would be 10 to 30 m. Along the track spacing between the measurements depends on the speed of the platform and the frequency of the observations. For a typical frequency of 10 Hz and a typical balloon speed during Antarctic summer of 1 m/s the along the tracks separation would be of the order of 0.1 m. During winter balloon speeds can rise up to 50 m/s, which would increase the separation to 5 m. Thus a balloon would be able to achieve better horizontal resolution than the needed one (several km).

The LIDAR would operate in a scanning mode. As clouds and haze are abundant in the Polar Regions it is important to be able to find a clearing in the cloud cover to acquire the surface. Scanning would allow making measurements when the surface is partially covered by clouds. The scan pattern is not important. Figure 4 shows the figure eight scanning pattern. The radius of the scanning pattern that maximizes the chances of acquiring the surface would need to be determined (roughly, several kilometers wide).

Typically LIDARs' temperatures must be maintained in the range of 10° to 25° C, so thermal control of the instrument is necessary.

Pointing control and knowledge are required to operate a LIDAR. For example, GLAS instrument has pointing control accuracy of 30 arc seconds, and the required post processing pointing knowledge is 1.5 arc seconds. Achieving required pointing accuracy on a balloon-based instrument would be the biggest challenge of the concept. For instruments flown on satellites, a star-tracking camera is used to determine the attitude with the required accuracy. Pointing control accuracy may be smaller for a stratospheric balloon due to lower speed and altitude. This star-tracking approach can potentially be implemented on a stratospheric balloon, too, because at this altitude the balloon is above the 99% of the atmosphere, at the “edge of space” environment, and stars are clearly visible even during the day.

Inflight calibration of a LIDAR can be accomplished by flying over open sea surface or target areas with known topography. Another way to calibrate the instrument is with surface corner-reflectors at designated surface stations. Calibration is required infrequently, - 1-2 times per year.

Balloon LIDAR operation can be coordinated with satellite observations for mutual validation. Balloon data sets can compliment satellite data sets where satellite coverage is sparse due to cloudiness.

Data rate of the typical LIDAR instrument operating at 10 Hz pulse rate is several hundreds of bytes per second.

A number of other observations can be made in conjunction with the primary measurement. Seasonal changes of snow albedo can be measured by measuring the energy in the returned laser signal. These measurements are important for atmospheric radiation, snow hydrology and sea ice heat budget calculations. By turning the LIDAR to look more obliquely, it is possible to estimate winds by measuring the Doppler shift of the returned signal.

The following tables summarize the measurement and the instrument requirements.

Table 1 Measurement requirements

Spatial requirements:	
Horizontal coverage	Antarctic, Greenland ice sheets; other ice caps
Horizontal resolution	Several km (1-3)
Temporal requirements:	
Length of observations	Sufficient for full coverage of desired area, up to 5 years
Frequency of observations	1-10 Hz

Table 2 Instrument specifications

Mass	30 kg
Power consumption	34 W continuous
Thermal regime	10° to 25° C
Pointing and position accuracy	Attitude control to better than 30 arc seconds Attitude knowledge to better than 1.5 arc seconds Vertical position knowledge to better than 2 cm
Configuration	Nadir looking; scanning
Calibration	Infrequent, 3-4 times per campaign; over sea surface, corner reflectors
Data handling	100s bps
Coordination	Coordination with satellites for validation, complimenting data sets.

3.1.2 SS2 Topography of the ice sheet bed.

The concept, which addresses the question 1b, is to measure the topography of the surface underlying the ice sheets in Antarctica, Greenland, or any other ice laden region, with a radar from stratospheric balloons. Knowledge of the ice bed topography is needed to determine the speed with which the glaciers move (see previous section). For example, the bed of the West Antarctic Ice Sheet lies largely below sea level. The ice sheet could potentially, in the future, become unstable, - and suddenly discharge ice from its interior into the ocean causing substantial (one meter) rise in global sea level. Presently, rapidly moving bands called ice streams are responsible for most of the ice discharge from the West Antarctic ice sheet (see Figure 3). It is thus important to understand what determines the dynamics of the ice streams. Measuring the ice bed topography can lead to better understanding of the ice streams. Radar techniques also map internal stratigraphy of the ice sheet and thus can provide information about the past history of the flow.

Currently, measurements of the ice bed topography are made from the surface, aircraft or space. Balloon measurements would provide better coverage than the surface and aircraft observations, and better resolution than the satellite observations. Balloon observations are not affected by surface or tropospheric weather and are not limited in range, as are surface and aircraft observations. In addition, long duration balloon operations are much less expensive than the satellite operations, and are less expensive than aircraft operations.

It is desired to cover the whole region occupied by the ice sheet. The flight length should be sufficient to provide the desired coverage. Repeated or returned observations are not required as no changes in ice sheet bed topography are expected. The instrument for this concept (Radar Sounder or Ice Penetration Radar) operates by sending a signal and registering an echo. The ground footprint of the instrument is 500 by 500 m if operated from 35 km (see Figure 5). As the balloon moves, it sweeps a 500 m wide corridor on the ground. Ideally, it is desired to have these tracks to cover the whole surface of the studied region without any gaps. However, this would require either constellations with a large number of balloons operating for long times (100 balloons for 20 years, assuming summer wind speeds of 1 m/s and no overlaps between the tracks) or continuous operations during polar night (50 balloons for 2 years, assuming wind speeds of 20 m/s during polar night and no overlaps between the tracks). It is not clear at the moment what level of the track separation would be sufficient for scientific purposes, but several kilometers (the current ground flight track separation in airborne experiments) would probably suffice. The number of balloons required in the above estimates would then be reduced by an order of magnitude. In general, more platforms in the area would provide higher resolution. Balloon trajectory control and constellation topography management would allow for more uniform coverage.

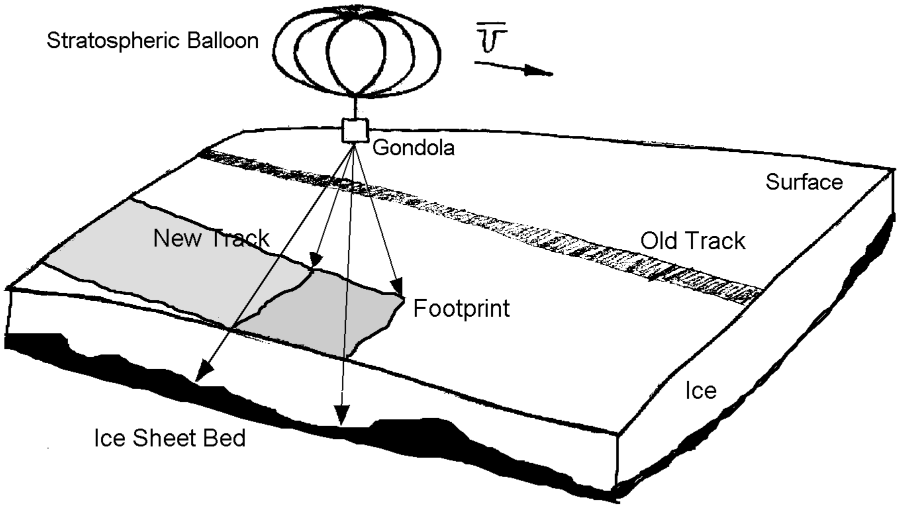


Figure 5 Ice sheet bed topography measurement schematics

As mentioned above, these observations could be performed either with a Radar Sounder or Ice Penetration Radar . The Sounder mass is 1 to 5 kg plus antenna. The maximum consumed power is 30 W, which includes data processing. The Sounder can operate at ambient temperatures between –50° and +50° C. The instrument does not require precise angular pointing (~0.5 radians), since the antenna has almost uniform response in all directions. Knowledge of the balloon position is required to better than 1 m. The instrument would be configured in such a way, so that the antenna is on the nadir side of the payload. The Sounder would be immobile (with respect to the platform) and require only infrequent calibration. Calibration of radar would require ground transmitter and receivers. Estimated datarate for this mission would be of the order of 50 bytes/sec or 5 Mbytes/day.

The Ice Penetration Radar weighs 30 kg and requires 100 W of power at peak consumption. The Penetration Radar operates at temperatures between –20° and +40° C with the preferred temperature of 25° C. Platform attitude and instrument pointing knowledge are needed to an accuracy of few degrees. Data flow may require short-term on board storage with subsequent downlink to ground station. The platform would be operating autonomously with infrequent command uplinks. The instrument would require infrequent calibration. Calibration of radar would require ground transmitter and receivers. An innovative solution for the antenna may include embedding the antenna into the balloon envelope material. Embedding antenna into the envelope may be beneficial because HF radars need long wires (tens of meters) and the balloon envelope can provide a good substrate.

The following tables summarize the measurement and the instrument requirements for both instruments.

Table 3 Measurement requirements

Spatial requirements:	
Horizontal coverage	Antarctic, Greenland ice sheets; other ice caps
Horizontal resolution	Several km track separation; ideally - overlapping 500 m wide tracks (assuming 35 km altitude)
Temporal requirements:	
Length of observations	Sufficient for coverage; one-time observation
Frequency of observations	1 Hz
Simultaneity	Simultaneous with satellites

Table 4 Instrument specifications for Radar Sounder

Mass	1 to 5 kg plus antenna
Power consumption	30 W max (includes data processing)
Thermal regime	-50° to 50° C
Pointing and position accuracy	Attitude control to better than 0.5 radian Position knowledge to 1 m
Configuration	Nadir looking
Calibration	Infrequent via ground transmitter/receiver
Data handling	50 bytes/sec; 5Mbytes/day onboard processing
Coordination	Coordination with satellites for validation; within constellation to achieve required resolution and coverage

Table 5 Instrument specifications for Ice Penetration Radar

Mass	30 kg
Power consumption	100 W peak; battery use at night.
Thermal regime	From -20° to 40° C, 25° C preferred.
Pointing and position accuracy	Platform attitude knowledge, instrument pointing knowledge and instrument pointing control to better than few degrees. Platform position knowledge to better than 1 m
Calibration	Infrequent via ground transmitters/receivers
Data handling	Onboard processing; 10Kbytes/sec
Coordination	Coordination with satellites for validation; within constellation to achieve required resolution and coverage

3.1.3 SS3 Vector magnetic (scalar gravity) field.

The concept, which addresses the question 2a, is to measure Earth’s magnetic and gravity fields from the stratosphere. Measuring the Earth’s magnetic field from stratospheric balloon platforms offers several advantages over surface, aircraft, and satellite measurements. Even though surface measurements are made around the world by magnetic observatories, they only cover a small fraction of the Earth’s surface. Systematic observations are lacking over oceans, Antarctica, Africa, South America, Siberia and other places (see Figure 6).

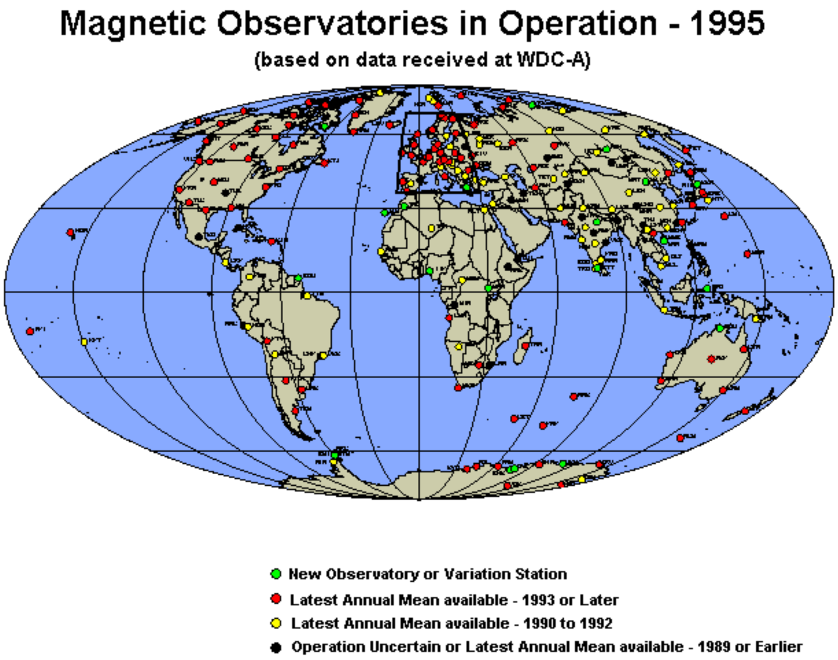


Figure 6 Magnetic observatories.

Aircraft observations lack sufficient range, cannot provide global coverage and are relatively expensive. Measurements from oceanic vessels are slow and expensive. Satellite measurements are noisy due to ionospheric influence and require very high instrument sensitivity due to the weak field at orbital altitudes (the decrease of magnetic field with distance is inversely proportional to the square of the distance). The high orbital speed of the satellites also reduces the resolution of the measurements.

All these factors make stratospheric balloon magnetic field measurements very attractive. The balloon measurements would bridge the gap between the surface and satellite measurements; provide observations with high resolution and high signal-to-noise ratio; provide global and regional coverage; provide measurements over different time scales; and lead to development of three-dimensional maps of the Earth’s magnetic field and it’s sources. Balloon measurements also offer an unprecedented capability to measure globally the vertical gradients of the magnetic field, which provides an opportunity to determine not only the direction to, but also the location of the source. High-spatial-resolution measurements would allow investigators to distinguish magnetic sources in the crust with applications in geology, paleogeology, geophysics, oil and mineral exploration, and archeology. It may even be possible, with sufficiently improved instrument sensitivity, to detect underground terrorist installations and hideouts. Observations of magnetic field variations over long time scales (years) would help to detect magma displacements in the Earth mantle and potentially lead to forecasts of earthquake and volcanic eruptions.

Systematic observations are required globally to distinguish magnetic field variations over various spatial and temporal scales, and to separate the effects of the external component of the magnetic field (arising from interactions of the solar wind with magnetosphere), the crustal component, and the internal component of the field (due to Earth's dynamo). However there are also several focus regions that include Antarctica, active tectonic areas and costal areas. Due to nature of the observed quantity, surface "footprint" is roughly equivalent to altitude of a stratospheric balloon (35 km). Because of this, maximum attainable altitude is preferred to provide maximum coverage. The footprint form a stratospheric platform is much smaller than from a satellite, but it is possible to provide global coverage from a constellation of stratospheric balloons in a reasonable period of time. For example: simple back-of-the-envelope calculations indicate that a constellation of 25 balloons can cover an area equal to the surface area of the Earth in a year (assuming no overlaps of the balloon tracks and balloons moving with stratospheric winds at representative velocity of 20 m/s).

Figure 7 illustrates the concept. The cartoon shows a balloon flying over a region of the Earth. The dashed circle on the surface below the balloon indicates approximate area that contributes to the magnetic signal at the balloon altitude *h* at any given moment. Subsurface sources underneath this area contribute to the signal as well. As the balloon passes over the surface, the sampled area on the ground forms a "corridor" of the width roughly equal to the balloon altitude *h*. This corridor is labeled as "New Track" on the figure. The instrument – a magnetometer - can be positioned on the gondola or on a tether below the gondola. Several magnetometers (at least two) would be needed for gradient measurements. They can be positioned on a tether, as is shown on the picture. A vertical separation between the sensors from 1 to 10 km is desired, with larger separation increasing the sensitivity and the resolution of the measurements.

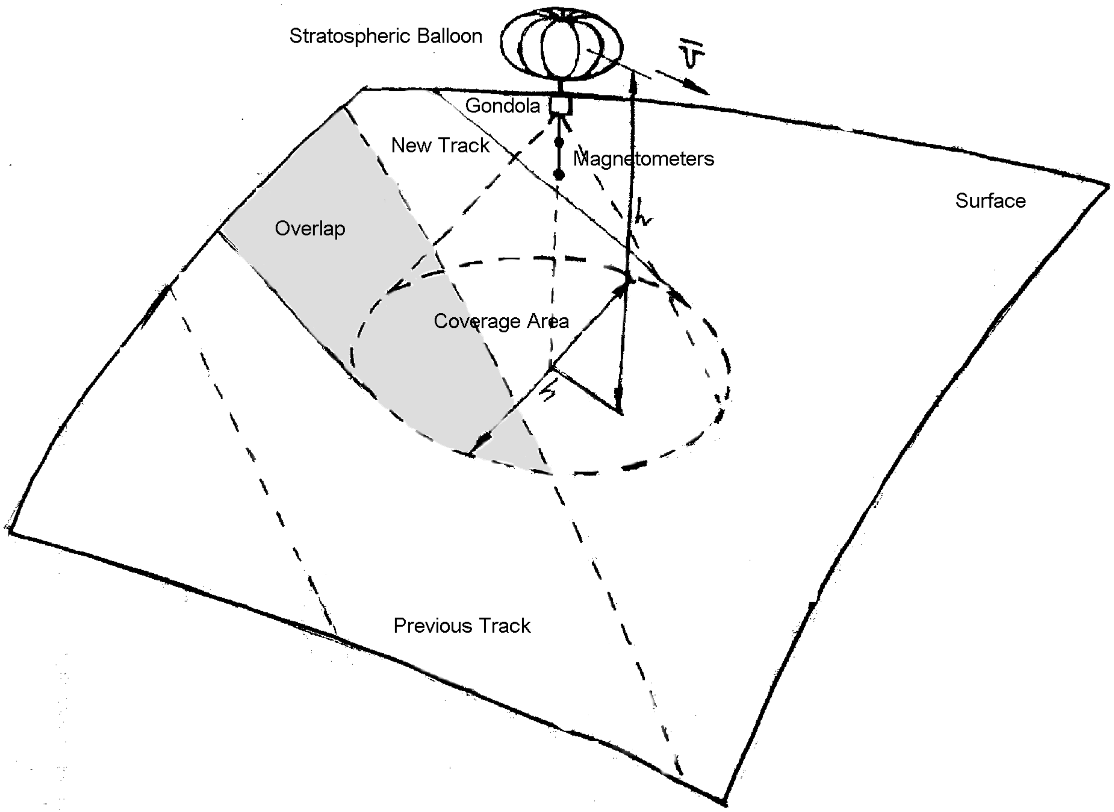


Figure 7 Magnetic field measurement schematics

To determine the distribution of sources that produce the measured magnetic field more accurately, observations of the same areas from different (orthogonal) directions are needed. This can be accomplished by a single balloon revisiting it’s previous tracks on the ground, a constellation of balloon flying in close formation, or horizontally distributed magnetometers (on a long mast or a boom) on one balloon. The horizontal separation of balloons in a constellation observing the same area must less than a float altitude to achieve an overlap of the ground tracks. Similarly, a single balloon revisiting the study region must closely follow its previous track or cross it often enough to provide useful data. The needed horizontal separation of magnetometers on a single balloon is unknown at the time.

The desired length of flight is from months to years. Increasing the length of flight would provide more opportunities to revisit or to cross previous tracks (which would increase resolution of the observations), to maneuver the balloon towards the areas of interest, provide larger coverage, to separate the components of the field, and to capture long term variability of the internal magnetic field. This consideration applies to both single balloons and constellations of balloons. The frequency of the observations during a flight is 1-10 Hz, which would allow observation fluctuations of the external field.

The instrument of choice for these observations is vector magnetometer (or gradiometer, when used to measure gradients). Magnetometer measurements are simple, low-mass, low-power, and low-datarate. The magnetometer mass is 1 kg, with continuous power consumption of 2 W. The desired thermal regime is between –55° and 40° C. However, the instrument is sensitive to EMI (electro-magnetic interference). Thus, the instrument environment must be magnetically clean, which would probably require placing instruments located on the gondola on a short boom (0.3–1 meters). Tethered instruments would not require placement on the boom. Knowledge of the uncertainty of the instrument attitude is required to be less than 10 arc seconds. For instruments flown on satellites, a star-tracking camera is used to determine the attitude with the required accuracy. This approach can be implemented on a stratospheric balloon too, since at this altitude the balloon is above the 99% of the atmosphere in “edge of space” environment and stars are clearly visible even during a day. The attitude knowledge is required for vector measurements. Note, however that it is not required for the measurements of the magnetic field strength, which would be useful by themselves. The magnetometer can be calibrated by flying over a control area where the field is known from surface and satellite measurements. An alternative calibration method is to recover and calibrate the magnetometer after the flight termination. Position knowledge is required within the limits of the current GPS technology. The data flow rate is estimated at 1-2 Mbytes per day. For constellation of platforms, coordination would depend on the goals of the campaign. For field monitoring campaign, coordination that maintains a uniform distribution of platforms may be needed. On the other hand, it may be desired to have “clumps” of balloons in coordinated flight for high-resolution observations of crustal sources.

It may be beneficial to perform gravity and gravity gradient measurements simultaneously with measurements of the magnetic field. The requirements for the measurement and the instrument are essentially the same as for the magnetic field concept, except the gravimeter is a heavier (several kilograms) and a more precise instrument. Accurate knowledge of the velocities and accelerations of the balloon platform would be required.

The following tables summarize the measurement and the instrument requirements.

Table 6 Measurement requirements

Spatial requirements:	
Horizontal coverage	Global; focus areas are Antarctica, active tectonic areas, coastal regions
Horizontal resolution	Overlap in ground track (35 km wide).
Vertical coverage	Maximum balloon altitude to maximize surface footprint
Vertical resolution	From 1 to 10 km for vertical gradient measurements
Temporal requirements:	
Length of observations	Continuous; from months to years
Frequency of observations	1-10 Hz (to capture external field fluctuations)
Simultaneity	Instantaneous measurements along the vertical gradient

Table 7 Instrument specifications

Mass	1 kg
Power consumption	2 W continuous
Thermal regime	–55° to 40° C
Environmental regime	Sensitive to EMI, requires magnetically clean platform (0.3-1 m boom)
Pointing and position accuracy	Attitude knowledge to better than 10 arc seconds Position knowledge within GPS technology limits
Configuration	May require positioning sensors on a tether or on a long boom (mast)
Calibration	Infrequent; over control areas, or after flight termination
Data handling	1-2 Mbytes/day. Latency not an issue.
Coordination	Coordination to achieve surface “footprint” overlap may be required for high-resolution observations.

3.1.4 SS4 3-D displacement maps

The concept, which addresses the question 3a, is to measure Earth’s surface topography using radar interferometry from stratospheric balloons. Three-dimensional deformation maps created in this way can be used to monitor strain in tectonically active regions or assess topography changes associated with floods and fires. Accessibility to globally distributed focus regions would be required from a balloon or a constellation of balloons. The length of flight depends on the ability to revisit the imaged region (see below) and also on the time scale of the changes that are to be observed. From general considerations, flight durations from months to years would be required. Certain events would require rapid response times. For example, to detect changes due to fires and floods, a platform must reach the site in a matter of days or weeks after the event. Earthquake sites can be visited in a matter of months after the event.

Two images of the same region at different viewing angles are needed to produce an interferogram and extract topography. Because of this, the subsequent ground tracks of the instrument platforms must come very close to each other, and images must overlap. Current data processing techniques require that the overflight tracks be straight lines at a constant offset from each other. The required offset is of the order of 1 km (up to 10 km).

The concept relies on the use of a radar (such as ScanSAR or SAR – Synthetic Aperture Radar). Figure 8 shows a schematic of the concept. The radar is side looking (20-50°) and scanning. The balloon is shown with the ScanSAR antenna (15 by 1.5 m). Images are obtained by scanning the surface with different regimes that produce various coverages and resolutions. For a ScanSAR sized antenna and a balloon at 35 km, the maximum swath width is about 20 km. Smaller antenna would produce larger swath width, since the beam width is inversely proportional to the antenna size.

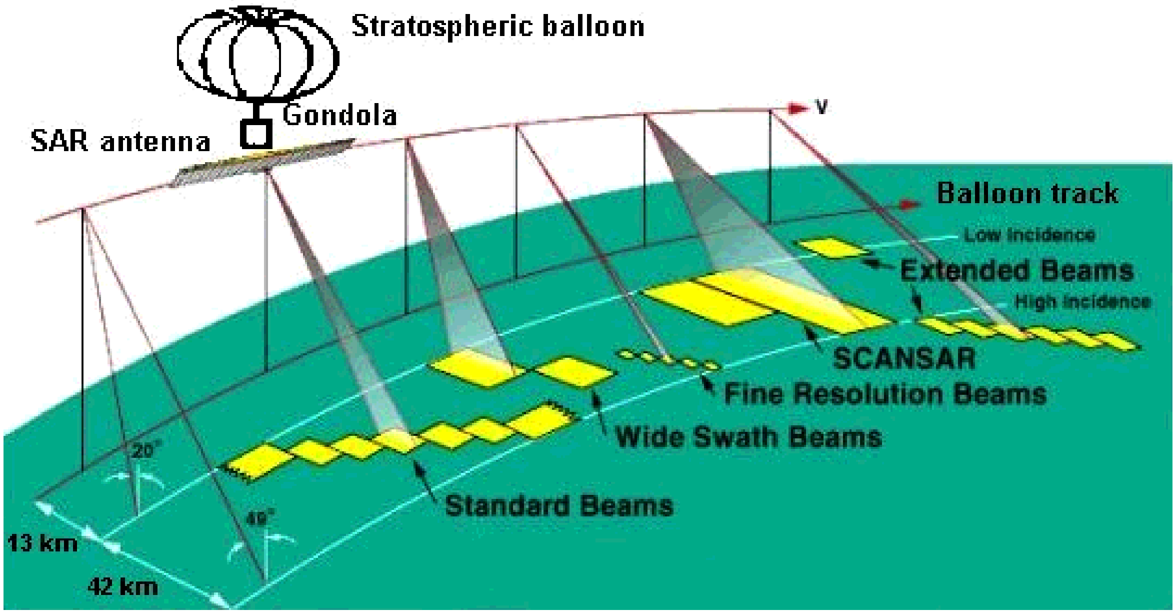


Figure 8 Schematics of SAR observations with different regimes from a stratospheric balloon

The radar's weight is about 50 kg and power consumption is 10 to 20 W. Interferometry requires very precise attitude knowledge (for example, 1 arc second for 500 km-altitude spacecraft illuminating at an angle of 30° – to achieve height accuracy of 2 m). For a given height accuracy the attitude knowledge precision scales proportional to altitude, thus for a balloon altitude of 35 km the attitude would need to be known to 20 arc seconds to achieve height accuracy of 2 m. Surface control sites can be used to calibrate absolute height estimates even in the absence of arc-second attitude information. Data handling may present a challenge – each image would contain Gbytes of information. Finally, the radar would require a C-band or L-band 50-cm antenna.

Balloon platforms would meet significant challenges in trying to achieve straight-line trajectories and overfly small targets with the required accuracy. Hence, in the discussions of this concept with the scientist after the workshop, an opinion was formed that this concept may not be well suited for a balloon platform. However, if two horizontally separated antennas can be flown on a single platform, the concept may still make sense for a balloon platform. The length of the mast would probably need to be of the order of meters or tens of meters. Antennas can also be separated vertically, with one antenna at the gondola and the other one hanging on a tether below the balloon. Another option is to fly balloons in tandem, but the straight-line trajectory problem still remains.

The following tables summarize the measurement and the instrument requirements.

Table 8 Measurement requirements

Spatial requirements:	
Horizontal coverage	Access to globally distributed locales
Horizontal resolution	Constant separation (1-10 km) of ground tracks (30 km wide)
Temporal requirements:	
Length of observations	Continuous; from months to years
Frequency of observations	Continuous

Table 9 Instrument specifications

Mass	50 kg
Power consumption	10-20 W
Thermal regime	10 to 25° C
Pointing and position accuracy	Attitude knowledge to better than 1 arc seconds Position knowledge within GPS technology limits
Configuration	May require positioning instruments on a tether or on a long boom (mast)
Calibration	Via ground truth
Data handling	Gbytes/day.
Coordination	Coordination to achieve surface “footprint” overlap or constant separation (1-10 km) and straight-line trajectories is required.

3.2 Atmospheric Radiation

The Atmospheric Radiation group focused on the following general (A) and a more specific (1) question from the NASA ESE Strategic Plan:

A) What are the primary forcings of the Earth system?

1. What trends in atmospheric constituents and solar radiation are driving global climate?

In particular, the question of interest to the atmospheric radiation group was:

1a. How do top-of-the-atmosphere (TOA) fluxes deduced from CERES (-type) measurements agree with *in situ* measured TOA fluxes?

The corresponding measurements and requirements are described in detail in the following section.

3.2.1 AR1 Fluxes at TOA.

The concept is to measure radiative fluxes at the TOA from an *in situ* location with stratospheric balloon platforms. As question 1a suggests, these measurements can be used to validate radiative flux estimates based on satellite measurements or they can be used for long-term monitoring and observation of the dynamics of radiative fluxes. At present, the CERES (Clouds and Earth Radiant Energy System) instruments on EOS Terra satellite make continuous measurements of outgoing short and long-wave radiation from the Earth. However, CERES instruments measure radiances, directionally dependent radiation from a source location on the Earth. These radiance measurements must be converted to fluxes at the top of the atmosphere to estimate the Earth's energy budget. Knowing the Earth's energy budget is necessary for predicting long-term climate variability, interannual and seasonal changes on different spatial scales and effects of natural disasters, such as floods, fires and volcanic eruptions. The conversion process introduces 4% uncertainties into flux estimation, which can be large enough to affect the interpretation of the measured data. For example, 4% error in long wave flux estimation corresponds to an error of about 10 Wm^{-2}. Even 1 Wm^{-2} change in radiative forcing is important for climate change, and variability of 4 Wm^{-2} could drive a major climatic change. Stratospheric balloons can measure the TOA fluxes directly, thereby eliminating the conversion error and providing a significantly better estimate of the earth radiation budget.

Knowledge of the Earth's radiative budget (the amount of energy received from the Sun, the amount of energy emitted into space, and their difference) is crucial for determining (a) weather or not the global climate is changing and (b) what is the direction of the changes, if they are occurring.

Besides being used for validation of satellite data, stratospheric balloons can be used as a complimentary platform providing measurements that are not obtainable with satellites. There are a number of advantages in measuring fluxes from constellations of stratospheric balloons. Balloons may prove to be a less expensive alternative to satellites for the radiative flux measurements, if they can provide continuous, global observations over time periods comparable to satellite lifetimes (5 years). Even more importantly, balloons can provide observations with higher accuracy and relatively high spatial and temporal resolution. For a radiometer instrument at a typical satellite altitude of 700 km the ground footprint is of the order of 1000 km. For a balloon at 35 km the corresponding footprint is about 50 km. This higher spatial resolution could be used to resolve clouds in the instrument's field of view and to study small-scale structure of the radiative fields. In addition, fluxes measured from stratospheric balloons will not have diurnal and sun-angle biases known to exist in satellite measurements. All times of day would be sampled. The slow speed of the balloons (1% of satellite speed) also would allow observations of diurnal variations over areas with characteristic spatial scale of ~1000 km (a balloon moving with characteristic speed of 20 ms^{-1} would cover a distance of about 1,800 km during a 24-hour period). A sufficiently large constellation of balloons can provide nearly global coverage (see Figure 9). Smaller regional constellations can be used to validate satellite measurements and to test the feasibility of a global constellation.

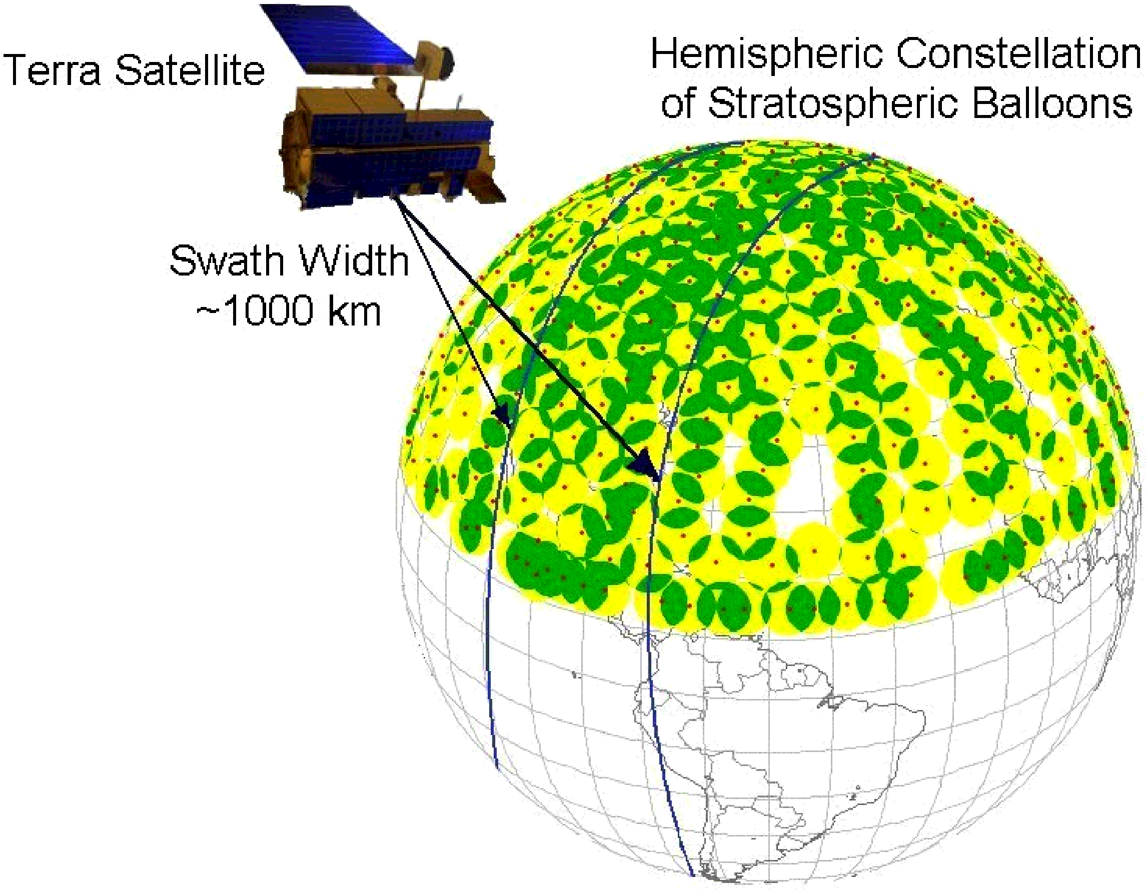


Figure 9 Hemispheric constellation of 395 stratospheric balloons. Red dots represent balloons, yellow circles - the limb-to-limb viewing areas of balloons, green regions - overlaps of viewing areas. Also shown for comparison a single track of CERES instrument. The satellite swath width is of the order of 1000 km.

Development of operational systems for this concept could begin with just 3 balloons in tropics for a proof of concept mission phase. This approach would allow investigators to study angular variations of the radiative fields over a scene, make repeated measurements of the same quantity to reduce errors, and make observations at different spatial resolutions by converging (diverging) the balloons. Note that the constellation geometry control requirements for this proof of concept phase with a small number of balloons could be quite different (possibly more stringent) than the requirements for the working, global constellation phase. We do not address requirements for the proof of concept mission here.

In this concept, measurements over two spectral regions are made:

- A total (0.2→20 μm) flux measurement (downlooking);

- A “visible” (0→5 μm, solar) flux measurement (downlooking).

The long wave flux (5→20 μm) is obtained by differencing the total and short-wave measurements. Active Cavity Radiometers (ACRs) are proposed for the flux measurements. Both the short wave and total measurements would be made with the similar instruments, except that the short wave instrument will have a filter dome.

The preferred coverage for this observation is global, however, regional coverage (for example, tropics) is acceptable at early stages of constellation deployment or for proof of concept mission. The minimum length of observations is 2 weeks with continuous observations reported every 2 minutes. Longer flight durations are desired. The measurements must be performed simultaneously with the overpassing CERES instrument for satellite data validation with temporal accuracy of 1 minute. The CERES instruments on the Terra satellite are on a near-polar sun-synchronous orbit at 705 km altitude with orbital period of about 100 minutes. The limb-to-limb scan width is about 5600 km at this altitude, and subsequent ground tracks overlap by about 50% at the equator. Overlap is larger near the poles. Because of this, the slow-moving balloons will always be overflown by CERES instrument at least twice a day, no matter where they are on the Earth surface.

Observations can be made with 2π-space (hemispherical) filed of view or with narrow (several degrees) field of view. In the former case the footprint on the ground would be of the order of 1000 km from 35 km altitude, and in the latter case the footprint would be of the order of 50 km. Advantages and disadvantages of having measurements of different resolutions would need to be explored. Fields of view limiters cannot be changed in flight on an ACR without developing a new device. The simplest solution seems to be to have a separate instrument for every different field of view and spectral range measurement, thus having both wide and narrow fields of view on board would require total of 4 ACR instruments.

The Active Cavity Radiometer proposed for these measurements weighs 0.5 kg and consumes 0.5 W of power.. The ACR must be heated to 300°±10° K. The wide field instrument would be insensitive to pointing (within reason) because it measures hemispheric flux (from 2π-space below the balloon). The narrow view instrument would need accurate knowledge of pointing (less than a degree). The instrument can be mounted on a tilting bench to allow for direct solar observations for calibration (a few times during a 2 week flight period) or have a rotating mirror exposing the instrument sequentially to sun and space. Depending on the stability of the instrument calibration, it may not require onboard calibration at all: the instrument would be precalibrated before the flight and verified upon payload recovery after mission termination. Position knowledge of the platform is required to correlate balloon measurements with the satellite measurements and with the map. The data would be stored on board and then downlinked to the ground station. The maximum data rate is 1 byte per second or 84 Kbytes per day (assuming 4 channels). Trajectory control may be required to position the platform over target regions.

The following tables summarize the measurement and the instrument requirements.

Table 10 Measurement requirements

Spatial requirements:	
Horizontal coverage	Global or regional (tropics)
Temporal requirements:	
Length of observations	Minimum 2 weeks
Frequency of observations	Every 2 min
Simultaneity	With overpassing CERES instrument

Table 11 Instrument specifications

Mass	0.5kg
Power consumption	0.5 W
Thermal regime	25±10° C (needs to be heated)
Pointing and position accuracy	Wide filed insensitive to pointing; narrow filed – within a degree or better
Mobility	May require tilting for solar calibration
Calibration	Few times in 2 weeks
Data handling	84 Kbytes/day
Coordination	Coordinate observations with CERES overflight.

3.3 Atmospheric Chemistry

The Atmospheric Chemistry group focused on the following three general questions (A, B and C) and three more specific questions (1, 2 and 3) from the NASA ESE Strategic Plan:

A) How is the global earth system changing?

1. How is stratospheric ozone changing, as the abundance of ozone-destroying chemicals decreases and new substitutes increases?

B) What are the primary causes of the earth system variability?

2. What trends in atmospheric constituents and solar radiation are driving global climate?

C) How does the earth system respond to natural and human-induced changes?

3. How do stratospheric trace constituents respond to change in climate and atmospheric composition?

The above questions can be addressed by remote and *in-situ* measurements of vertical profiles of temperature, pressure, ozone, water vapor, and tracer elements (such as CO_2, CO, CH_4, N_2O, etc.). A combination of three payloads was discussed for these measurements: a fixed *in situ* payload on a tether and (or) vertically-translating gondola, a remote sensing payload on a gondola, and meteorological dropsondes. Different payloads can be carried on different platforms, or each platform can carry the same combined payload.

3.3.1 AC1 Vertical profiles of ozone and trace constituents.

The tropical region plays an important role in global climate system and in ozone chemistry. It is currently understood that troposphere air enters the stratosphere in tropics. This region of the tropical atmosphere, where tropospheric air enters the stratosphere and remains substantially unmixed with midlatitude stratospheric air is usually referred to as the “tropical pipe”. The low temperature of the tropical tropopause limits the amount of water that enters the stratosphere. Water vapor can significantly affect global energy balance by (a) blocking the long wave emission from escaping the Earth and (b) by increasing the number of stratospheric clouds that reflect solar radiation. Troposphere air entering the stratosphere also carries with it antropogenically produced elements (such as CFC’s) that affect ozone chemistry. The concept is to measure vertical profiles of ozone and tracer elements, together with temperature, pressure and water vapor profiles in tropics. These measurements would help to characterize tropospheric-stratospheric exchange and “tropical pipe” boundaries.

3.3.1.1 AC1.1 *In situ* payload for vertical profiles of ozone and trace constituents.

The *in situ* payload would measure vertical profiles of ozone and tracer elements, together with temperature, pressure and water vapor profiles with *in situ* sensors at altitudes between 15 and 30 km. on seasonal and interannual scales. Three balloons would circumnavigate the globe in the equatorial region (within 14° S and 14° N latitudinal band). The balloons are not required to fly in formation. The desire is to get more or less uniform coverage within the band (see Figure 10). The minimal requirement on flight duration is to complete one orbit (about 20 days at 20 ms^1 at the equator). The observations would be repeated every 2 or 3 month. This flight sequence must be continued for several years to capture interannual variability (for example, 5 years to capture two cycles of QBO - Quasi-Biennial Oscillation). Alternatively, a single balloon flight of very long duration would be sufficient. It is desired to make observations continuously during a flight. The typical time for a single *in situ* measurement is between 10 to 100 seconds. The required vertical coverage is between 15 km and the altitude of the balloon (25-35 km). Although observations at higher altitudes are desirable, observations up to 35 km are acceptable. The required vertical resolution of the measured profiles is from 100 to 500 m. The *in situ* observations are required to coincide in space and time with the remote observations (see below). Due to the nature of the proposed remote instrument (FTIR, see below) that employ a solar occultation technique, simultaneous observations are required twice a day, during sunrise and sunset.

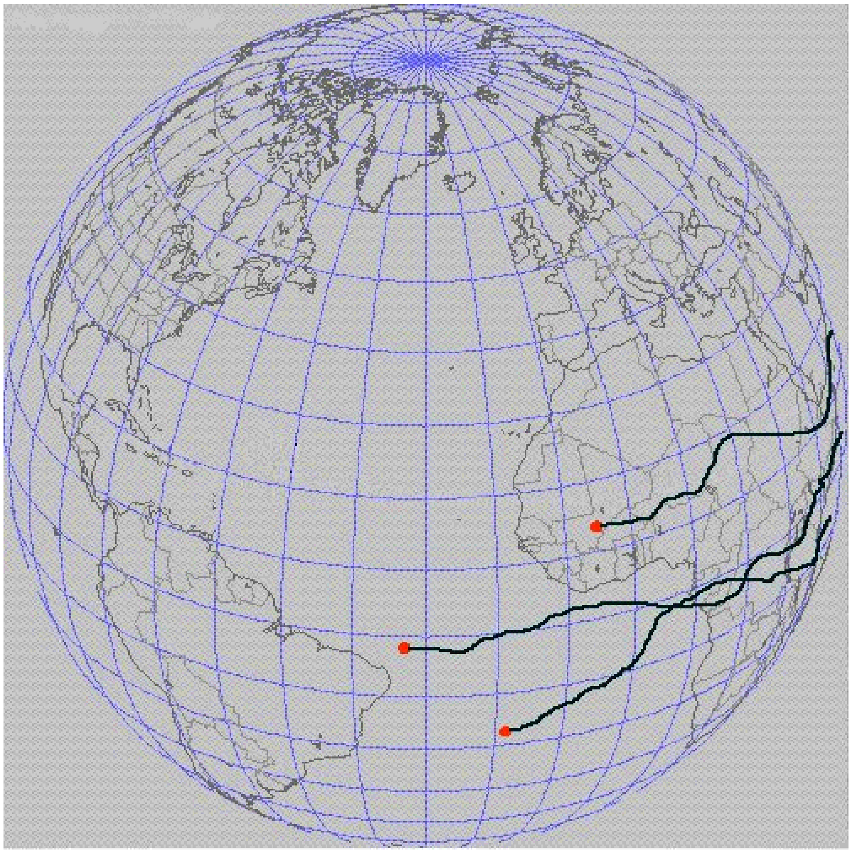


Figure 10 Schematics of the Atmospheric Chemistry constellation. Red dots indicate balloons and black trails indicate balloon trajectories.

The in situ instruments could be positioned on a tether and reeled up and down to provide measurements over the required height of the atmosphere. Another option is an ascending/descending (with vertical velocity of 3-5 m/s) balloon platform with a fixed instrument suite on the gondola. Another implementation option for the *in situ* payload is multiple instruments positioned along the tether.

The *in situ* instruments for the proposed concept already exist. The total mass of the suite of *in situ* instruments is estimated at ~200 kg (potentially 100 kg, assuming advancements in technology). Some in situ instruments would require consumables, namely – calibration gases. Care must be taken to avoid balloon contamination of the sensors, so the sample inlets are usually located outside the boundary layer of the balloon gondola. The power consumption of the instrument suite is about 800 W. The instruments need to be heated to room temperature, and also must be able to dissipate heat. Heat dissipation is usually done by radiators on the instruments. Some instruments of the in situ suit require frequent calibration (every measurement). The sampled air is delivered to the instruments by pumps. The data can be stored onboard and then downlinked to the ground control.

The following tables summarize the measurement and the instrument requirements.

Table 12 Measurement requirements

Spatial requirements:	
Horizontal coverage	Tropics, between 10±4° S and 10±4° N
Vertical coverage	From 15 km up to ceiling altitude
Vertical resolution	100-500 m
Temporal requirements:	
Length of observations	1 orbit flight duration (20 days), every 2 to 3 months, for 5 years.
Frequency of observations	Continuous during a flight (every 10-100s)
Simultaneity	Simultaneous with FTIR measurements during sunset/sunrise

Table 13 Instrument specifications

Mass	200 kg
Power consumption	800 W
Thermal regime	20±5° C
Consumables	Calibration gases
Pointing and position accuracy	Knowledge of position
Calibration	Some instruments on the payload require frequent calibration
Coordination	Simultaneous in situ, remote and meteorological measurements

3.3.1.2 AC1.2 Remote sensing payload for measurements of the vertical profiles of ozone and trace constituents.

The concept for remote sensing observations is similar to that for *in situ* observations. 3 circumnavigating balloons are suggested in the equatorial region. The desired vertical coverage for the remote sensing instrument is from tropopause (15 km) to 35 km. The instrument is positioned at 35 km.

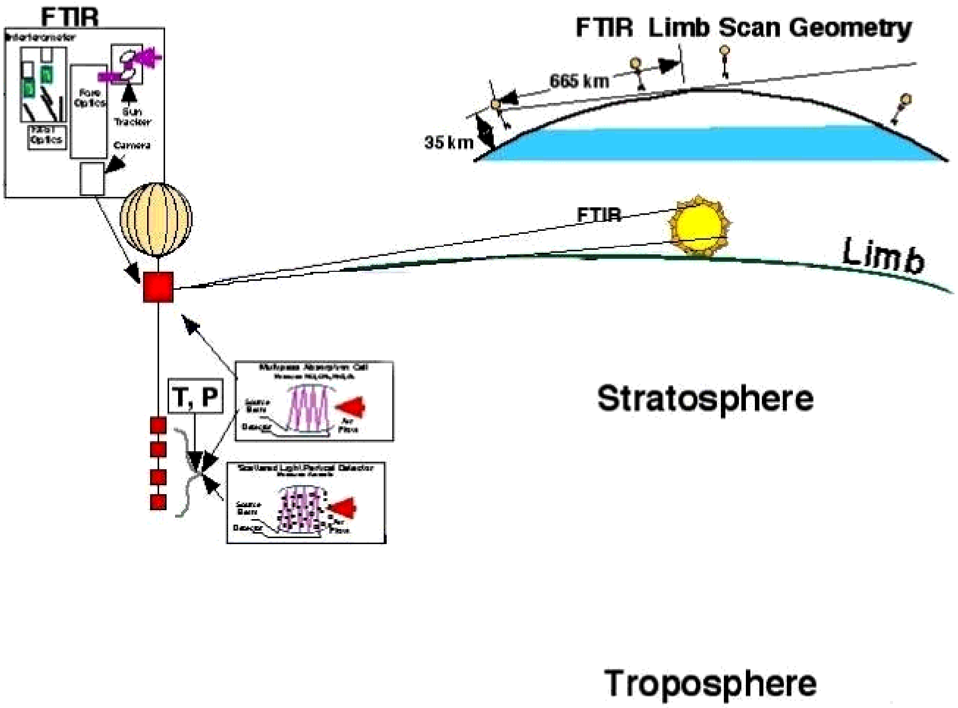


Figure 11 Schematics of the *in situ* and remote sensing payloads operations on a stratospheric balloon

The proposed instrument is a modified JPL Fourier Transform Infrared Radiometer (FTIR) MkIV. The FTIR is a solar occultation instrument; it makes measurements of the atmospheric abundances by measuring the absorption of the sunlight (see Figure 11). It requires a suntracer to track the sun at sunset and sunrise. The FTIR measures abundances of H_2O, CO_2, O_3, N_2O, CO, CH_4, NO, NO_2, NH_3, HNO_3, HF, HCl, OCS, H_2CO, $ClNO_3$, HCN, CFC-12, COF_2, C_2H_6, C_2H_2, N_2, HCFC-22, HDO, and SF_6. MkIV was successfully flown on a stratospheric balloon during NASA SOLVE mission. The MkIV FTIR mass is 350 kg. It is desired to reduce the mass of the FTIR to 200 kg to lighten the payload mass, thereby enabling flights on smaller and less-expensive balloons. The power consumption of the FTIR is 250 W. The instrument configuration is side-looking and it operates in a limb-scanning mode. The datarate at sunset and sunrise is estimated at 350 kbps for 1 hour.

The following tables summarize the measurement and the instrument requirements.

Table 14 Measurement requirements

Spatial requirements:	
Horizontal coverage	Tropics, between 10±4° S and 10±4° N
Vertical coverage	From 15 km up to ceiling altitude
Vertical resolution	2 km
Temporal requirements:	
Length of observations	1 orbit flight duration (20 days), every 2 to 3 months, for 5 years.
Frequency of observations	1 hour during sunset and sunrise.
Simultaneity	Simultaneous with in situ measurements during sunset/sunrise

Table 15 Instrument specifications

Mass	350 kg
Power consumption	250 W
Data handling	350 kbps for 1 hour during sunset/sunrise
Coordination	Simultaneous in situ, remote and meteorological measurements

3.3.1.3 AC1.3 Meteorological dropsondes for vertical profiles of ozone and trace constituents.

The meteorological measurements, valuable by themselves, will compliment the *in situ* and remote measurements. The measurements would cover an atmospheric column from the altitude of the balloon (35 km) to the surface. The required vertical resolution of these observations is 0.5-1 km.

The concept assumes the use of dropsondes. Between 0 and 5 drops per day are required. GPS dropsondes currently used for meteorological measurements weigh 400 g and are designed to operate in a temperature range between -90° to +60° C. Dropsonde draws power from an 18-volt lithium battery pack.

The following tables summarize the measurement and the instrument requirements.

Table 16 Measurement requirements

Spatial requirements:	
Horizontal coverage	Tropics, between 10±4° S and 10±4° N
Vertical coverage	From the balloon altitude down to the surface
Vertical resolution	1-2 km
Temporal requirements:	
Length of observations	1 orbit flight duration (20 days), every 2 to 3 months, for 5 years.
Frequency of observations	Up to 5 drops a day.
Simultaneity	Compliment in situ and remote measurements

Table 17 Instrument specifications

Mass	400 g
Power consumption	18 V battery
Thermal regime	-90° to +60° C

4 Summary of Science Requirements

4.1 Summary of Requirements.

The following tables summarize the requirements described in the previous section. Table 18 summarizes science requirements, while Table 19 summarizes instrument requirements.

4.2 Review of Relevant Platform Technology Areas

In the sections above, we discuss the mission requirements and instrumentation specifications that drive platform design. In this section, we discuss several technology areas and the performance capabilities needed to enable the Earth science mission concepts. We discuss the range of performance capabilities and highlight those mission concepts that have the most stringent performance requirements in each technology area.

4.2.1 Power

Power is required for all applications – to power the instruments, for communication and “housekeeping” needs, to provide mobility for the instruments (for example, in reeling the instruments on a tether), and sometimes to maintain the required thermal requirement. The most power intensive concept is *in situ* atmospheric chemistry, which requires 800 W for the suite of instruments. Individual instrument’s power consumption in this suite is of the order of 100 W. Other concepts can be realized with power consumption level below 40 W.

4.2.2 Trajectory Control

Trajectory control can significantly expand capabilities of a balloon platform. The 3D Deformation Maps concept has the most stringent requirements for trajectory control amongst the reviewed concepts. Trajectories need to follow straight lines and have a constant separation of 1 to 10 km. Because of this stringent requirement the concept seems to be unsuitable for balloon implementation.

The trajectory requirements for other concepts are less stringent. The several kilometers required separation between the subsequent tracks required in the Ice topography and Ice bed topography concepts can probably be achieved with minimal trajectory control due to the small coverage area of the target regions (ice caps). Balloons in the zonal flow in Polar Regions exhibit short revisit times. A sufficient number of balloons (ten) making observations for about a year (assuming continuous operation during polar night) theoretically would be able to achieve the required coverage (assuming no overlap between the tracks). Trajectory control in this case would be necessary to avoid “clumping” of balloons and to maximize coverage by moving balloons apart.

(continued on p. 33)

Table 18 Measurement Requirements

Measurement Parameters	**SS1 Ice Surface Topography**	**SS2 Ice Bed Topography**	**SS3 Magnetic (gravity) fields**	**SS4 Deformation Maps**	**AR1 TOA Fluxes**	**AC1 Ozone and tracers profiles**
Horizontal coverage	Antarctic, Greenland ice sheets; other ice caps	Antarctic, Greenland ice sheets; other ice caps	Global; focus areas are Antarctica, active tectonic areas, coastal regions	Access to globally distributed locales	Global or regional (tropics)	Tropics, between 10±4° S and 10±4° N
Horizontal resolution	Several km (1-3)	Several km track separation; ideally - overlapping 500 m wide tracks	Overlap in ground track (35 km wide).	Constant separation (1-10 km) of ground tracks (30 km wide)		
Vertical coverage			Maximum balloon altitude to maximize surface footprint			From 15 km up to balloon altitude (AC1.1, AC1.2); From the balloon altitude down to the surface (AC1.3)
Vertical resolution			From 1 to 10 km for vertical gradient measurements			100-500 m (AC1.1); 2 km (AC1.2); 1-2 km (AC1.3)
Length of observations	Sufficient for full coverage of desired area, up to 5 years	Sufficient for coverage; one-time observation	Continuous; from months to years	Continuous; from months to years	Minimum 2 weeks	1 orbit flight duration (20 days), every 2 to 3 months, for 5 years.
Frequency of observations	1-10 Hz	1 Hz	1-10 Hz (to capture external field fluctuations)	Continuous	Every 2 min	Continuous (every 10-100s) (AC1.1); 1 hour during sunset and sunrise (AC1.2); Up to 5 drops a day (AC1.3)
Simultaneity		Simultaneous with satellites	Instantaneous measurements along the vertical gradient		With overpassing CERES instrument	Simultaneous FTIR/in situ measurements during sunset/sunrise

Table 19 Instrument Specifications

Instrument Parameters	**SS1 Ice Surface Topography**	**SS2 Ice Bed Topography**	**SS3 Magnetic (gravity) fields**	**SS4 Deformation Maps**	**AR1 TOA Fluxes**	**AC1 Ozone and tracers profiles**
Mass	30 kg	1 to 5 kg plus antenna (Sounder); 30 kg (Radar)	1 kg	50 kg	0.5kg	200 kg (AC1.1); 350 kg (AC1.2); 40 kg (AC1.3)
Power consumption	34 W continuous	30 W max (includes processing)(Sounder); 100 W peak; battery use at night (Radar).	2 W continuous	10-20 W	0.5 W	800 W (AC1.1); 250 W (AC1.2); 400 18 V batteries (AC1.3)
Consumables						Calibration gases
Thermal regime	10° to 25° C	-50° to 50° C (Sounder); From –20° to 40° C, 25° C preferred (Radar)	–55° to 40° C	10 to 25° C	25±10° C (needs to be heated)	20±5° C (AC1.1); -90° to +60° C (AC1.3)
Environmental regime			Sensitive to EMI, requires magnetically clean platform (0.3-1 m boom)			Avoid contamination by balloon (AC1.1)
Pointing and position accuracy	Attitude control to better than 30 arc seconds Attitude knowledge to better than 1.5 arc seconds Vertical position knowledge to better than 2 cm	Attitude control to better than 0.5 radian Position knowledge to 1 m (Sounder); Platform attitude knowledge, instrument pointing knowledge and instrument pointing control to better than few degrees (Radar).	Attitude knowledge to better than 10 arc seconds Position knowledge within GPS technology limits	Attitude knowledge to better than 1 arc seconds Position knowledge within GPS technology limits	Wide filed insensitive to pointing; narrow filed – within a degree or better	Knowledge of position within GPS technology limits
Mobility					May require tilting for solar calibration	Reel down on a tether (AC1.1); scanning (AC1.2).
Configuration	Nadir looking; scanning	Nadir looking	May require positioning sensors on a tether or on a long boom (mast)	May require positioning instruments on a tether or on a long boom (mast)		Side-looking (AC1.2)

Table 19 continued

Calibration	Infrequent, 3-4 times per campaign; over sea surface, corner reflectors	Infrequent via ground transmitter/receiver	Infrequent; over control areas, or after flight termination	Via ground truth	Few times in 2 weeks; by looking at sun/space; or after flight termination on recovery	Some instrument require frequent calibration (AC1.1)
Data handling	100s bps	50 bytes/sec; 5Mbytes/day onboard processing (Sounder); Onboard processing; 10Kbytes/sec (Radar)	1-2 Mbytes/day. Latency not an issue	Gbytes/day	84 Kbytes/day	350 kbps for 1 hour during sunset/sunrise (AC1.2)
Coordination	Coordination with satellites for validation, complimenting data sets.	Coordination with satellites for validation; within constellation to achieve track overlap	Coordination to achieve surface “footprint” overlap may be required for high-resolution observations.	Coordination to achieve surface “footprint” overlap or constant separation (1-10 km) and straight-line trajectories is required.	Coordinate observations with CERES overflight.	Simultaneous in situ, remote and meteorological measurements

The magnetic field measurements concept requires overlap of 35 km wide ground tracks to resolve field sources. This would probably be easy to achieve in Antarctica for reasons outlined in the previous paragraph. Trajectory control would need to be more precise or the number of balloon significantly increased for measurements over other locales. Note, however, that magnetic field measurements offer exciting science even without resolving the sources from directionally varying measurements.

Trajectory control technology needs to be developed to achieve required resolution and coverage for all concepts.

4.2.3 Constellation Management

Global coverage, such as desired in TOA fluxes and magnetic field measurement concepts, or even large-scale regional coverage, as in the Ozone and tracer profile concept, requires deployment of balloon constellations. Numerical simulations indicate that without trajectory control, balloons in the stratosphere tend to clump together or get trapped in vortices (see Figure 12; nomenclature is the same as on Figure 9).

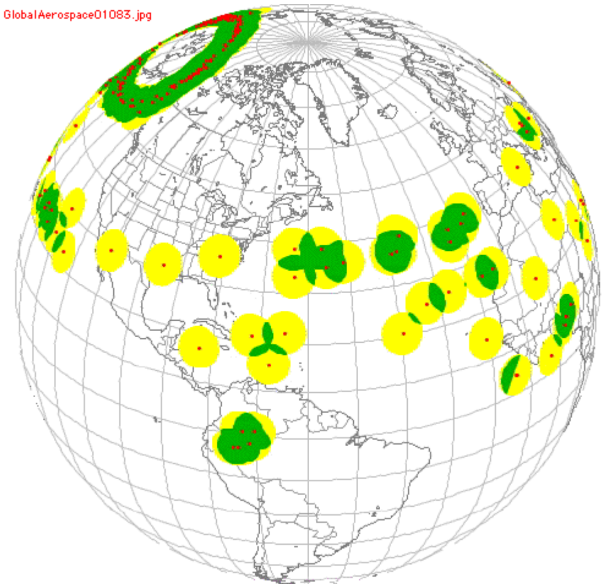


Figure 12 Clumping of balloons in uncontrolled constellation during winter in Northern Hemisphere

Trajectory control within a constellation would avoid the situation shown in Figure 12 and potentially achieve the desired degree of constellation uniformity. Constellation geometry management technology that provides the desired constellation topologies by employing autonomous control methodologies needs to be developed.

4.2.4 Trajectory Prediction

Trajectory prediction of individual balloons or balloons in a constellation is needed for mission planning, mission forecasting and safety. Balloon behavior in the atmosphere needs to be examined to develop mission scenarios, to choose launch sites and times most appropriate for meeting mission objectives. During a flight, balloon trajectories need to be forecasted several days ahead to allow for trajectory control, if needed. Safety risk calculations can be run parallel to the trajectory forecast calculations, so that safe operation of stratospheric balloons can be accomplished. Technology that allows for accurate trajectory prediction needs to be developed.

4.2.5 Platform and Instrument Position and Orientation (knowledge and control)

Knowledge and control of position and attitude of both the platform and instrumentation are required with various levels of accuracy for the different mission concepts. There is a difference between knowledge and control accuracy. Knowledge only may be required, for example, to correlate observations with other databases. However, accurate control of an instrument may be required for pointing to small target areas or to receive a reflected signal.

Most of the concepts require position knowledge within GPS technology limits, while two concepts (Ice surface topography, Ice bed topography) require vertical position knowledge to better than 2 cm and 1 m, respectively. Achieving knowledge of balloon altitude to better than 2 cm presents a challenge.

In addition three of the concepts (namely Vector Magnetic field, Ice surface topography, and 3D Deformation Maps) require quite accurate knowledge of the instrument attitude – to better than 10 arc seconds (note that scalar magnetic field measurement do not require attitude knowledge). On satellite-based instruments pointing knowledge is achieved via star tracking. This approach can be potentially implemented on balloon platforms too.

Attitude control is required for two concepts (Ice surface topography, Ice bed topography). The required accuracy is better than 30 arc seconds and better than 0.5 radian, respectively. This requirement necessitates development of the balloon attitude control technology.

4.2.6 Tethered instrument technology (reeling and fixed)

Positioning instruments on a tether below a balloon allows adding vertical profile measurements to measurements from the gondola. Tethered instruments can be used to measure vertical gradients of magnetic and gravity fields and atmospheric constituents. Tethered instruments can be fixed at constant depth below the balloon or they can be reeled up and down and sample the atmospheric column below the balloon at different depths. The instruments need to be light enough to be supported by the tether. In addition, deployment, retrieval and reeling technologies need to be developed.

4.2.7 Data storage technology

Depending on the number of balloons in a constellation, availability of ground stations or communication satellites, and communication scheme, there would be situations when data would need to be stored onboard for an extended period of time. The largest datarate amongst the concepts is of the order of Gbytes per day (Radar penetrator for Ice bed topography and 3D Deformation Maps). Lightweight, compact, low-power data storage technology would need to be developed to allow storage of Gbytes of data onboard.

4.2.8 Communications (within balloons in constellation)

Balloons within a constellation would need to communicate with a ground station (either directly or via a communication satellite) to receive commands and send data and telemetry. Balloons would also need to communicate with each other if autonomous control of constellation topology is desired. Internal communications within a constellation can also be beneficial in the case where only a few or one balloon is communicating with a ground station or a satellite. The other balloons would then be able to relay their data to the command center via links to the only balloon communicating with the ground station. Figure 13 illustrates the idea of these distributed and centralized communication schemes. In the first case (A) constellation platforms communicate only with neighbors. In the second case (B) the ground station sends information, which is relayed to the constellation objects via the communication satellite.

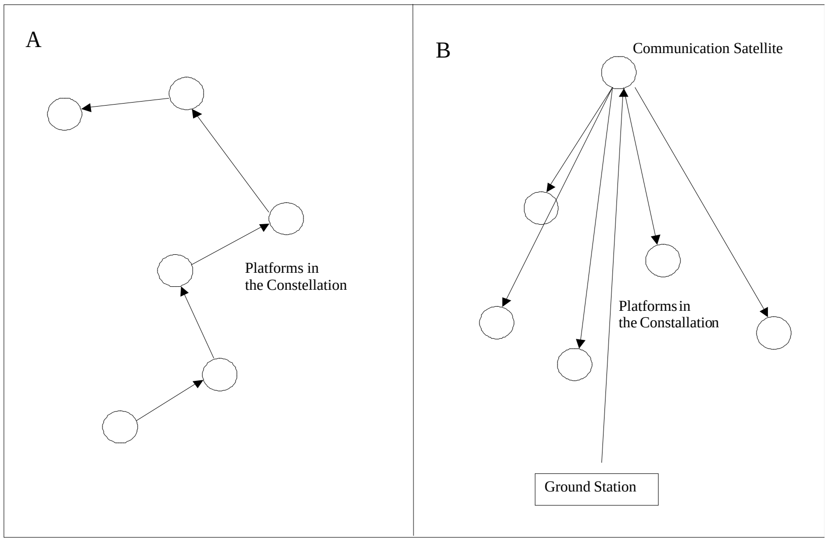


Figure 13 Distributed and centralized communications

Technology would need to be developed that supports communication of balloons within a constellation for the purposes of autonomous control, information relay, etc.

4.2.9 Technology for dropsondes and *in situ* profilers

Dropsondes and *in situ* profilers deployed from balloons can provide a wealth of data not otherwise accessible or at a much lower cost. To maximize the number of drops during a flight it would be beneficial to reduce the mass of the dropsondes (currently 400 g). Any increase in the number of drops possible during a single flight would significantly reduce the cost of data, because the cost of dropsondes is lower than the cost of a balloon and its launch.

Currently available GPS dropsondes measure temperature, pressure and water vapor content. Wind speeds can be retrieved from GPS descent altimetry. It would be beneficial for atmospheric chemistry applications to develop a lightweight dropsonde that would be able to measure concentration of the other atmospheric constituents, such as ozone, methane and NO_2.

4.2.10 Thermal control (gondola and science)

Balloon platforms can experience quite extreme temperature changes during ascent and descent: – from +20° C at the surface to –80° C at the tropopause. Atmospheric temperatures at the balloon ceiling altitude (35 km) can vary from –40° to –60° C, but balloon platform component temperatures are determined by radiative energy balance at flight altitudes because there is little convective heat transfer in the near-space environment. This thermal environment needs to be taken into account when considering various instruments for deployment on a balloon platform. Most of the instruments the above table require temperatures in the range of 20°±10° C. Because of these requirements, heating equipment would probably be required on a balloon platform, although during a day instruments may be heated by direct sunlight, if their surfaces are dark enough. Some instruments in the *in situ* atmospheric chemistry concept require heat dissipation, which is usually accomplished by coupling instruments to radiators.

4.2.11 Multi-platform multi-site launching technology

At the present time, balloon-launching technology is designed to efficiently launch single balloons for one- or two-flight campaigns. Emplacement of a large constellation of balloons or rapid replacement of disabled balloons will require development of launching technology that speeds up the launching process and reduces the cost of repeated launches. The technology would allow rapid deployment of personnel to multiple launch sites and launch of multiple platforms in rapid sequence.

4.2.12 Payload recovery technology

One of the advantages of stratospheric balloon technology as compared to satellite technology is that a payload can often be recovered and the instruments reused. Technology needs to be developed that would allow for rapid long-range reliable recovery of terminated payloads from the ground (or even sea surface). This technology could include guided descent systems for landing in areas where recovery is highly probable.

4.2.13 Safety systems

Because flights require overflight of moderately populated zones, safety system technology is necessary to avoid casualties on the ground and in the air due to descending elements. Safety systems would be responsible for reducing the momentum of the falling elements. Parachuting or gliding systems need to be developed. Flight termination systems technology also needs to be developed that would allow to terminate a flight if it presents a safety risk to a populated area or stopped responding to commands.

4.2.14 Mass lifting capability

The mass lifting capability of a balloon platform affects the mass of instrumentation that can be deployed and also the flight duration for concepts that require to carry consumables. The heaviest payloads for the mission concepts studied herein are the *in situ* and remote (FTIR) atmospheric chemistry payloads – 200 kg and 300 kg respectively. Other concepts can be realized with the payload mass not exceeding 50 kg. Much heavier payload masses are routinely carried for space science applications of stratospheric balloons.

4.2.15 Polar winter power

Several concepts (Ice topography and Ice bed topography, probably magnetic field) can benefit from development of a power source that can operate during polar winter. Summer months in Polar Regions is characterized by weak winds (1 m/s). This circumstance limits the coverage achievable by balloons. On the contrary, polar winters are characterized by extremely strong winds (50 m/s). The ability to operate balloons and balloon instrumentation during polar nights would increase the amount of coverage by a factor of 50. This can lead to either a reduction in the number of the balloons in a constellation, or a significant reduction of time required to accomplish a mission.

5 Summary

This document summarizes the results of the ad-hoc science workshop held in January 2002. Furthermore, we identify driving science requirements for stratospheric balloon platform technology development.

These science requirements will be used to develop a preliminary stratospheric balloon platform technology development roadmap. Figure 14 shows the process by which we are moving from key Earth science questions and measurements to a balloon platform technology roadmap. Figure 15 shows details of the Analysis Process box in Figure 14.

For the remainder of this activity, we will be developing preliminary roadmaps for each technology area and combining them into an overall stratospheric balloon platform technology development roadmap.

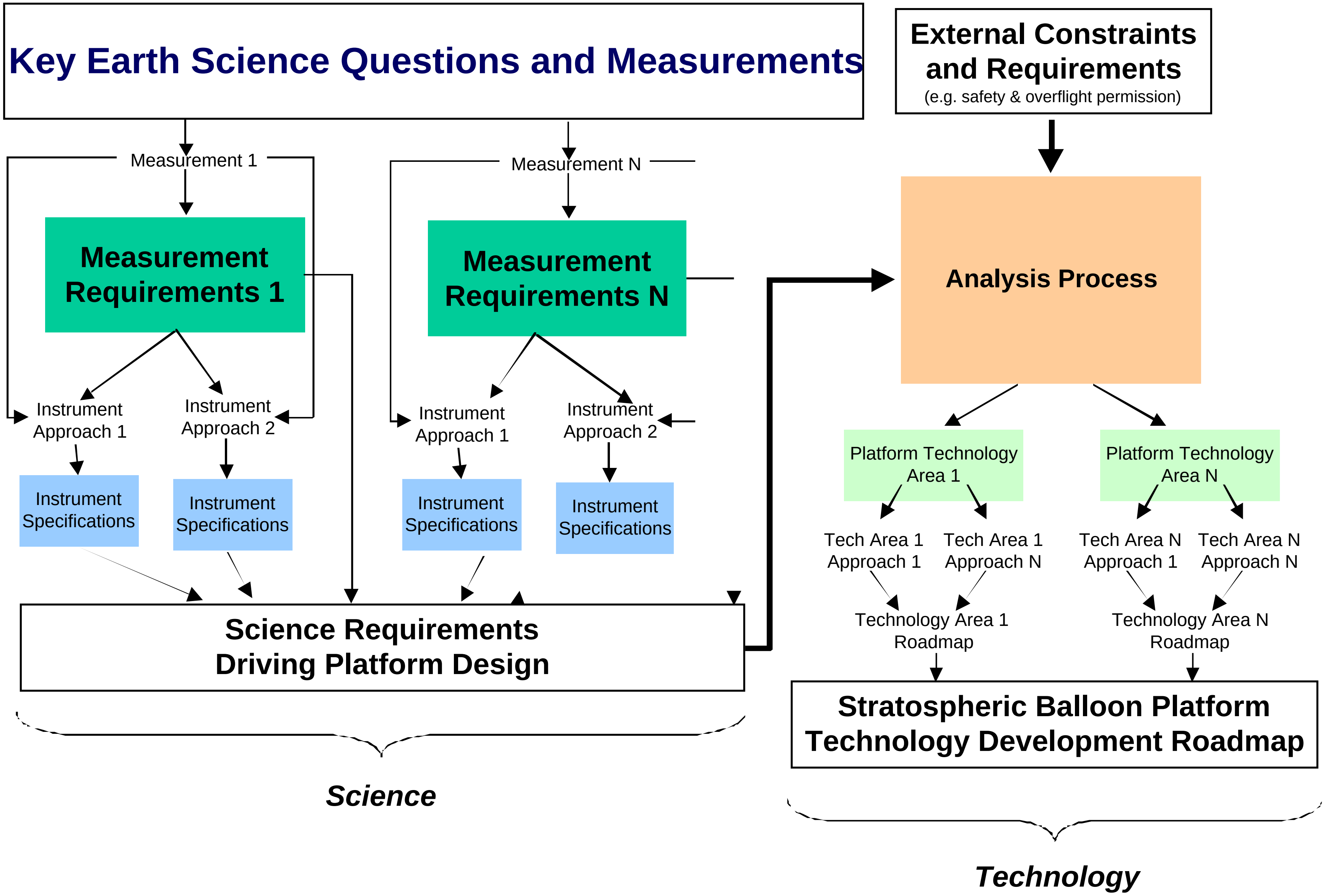


Figure 14 Stratospheric Balloon Platform Technology Development Roadmap Process

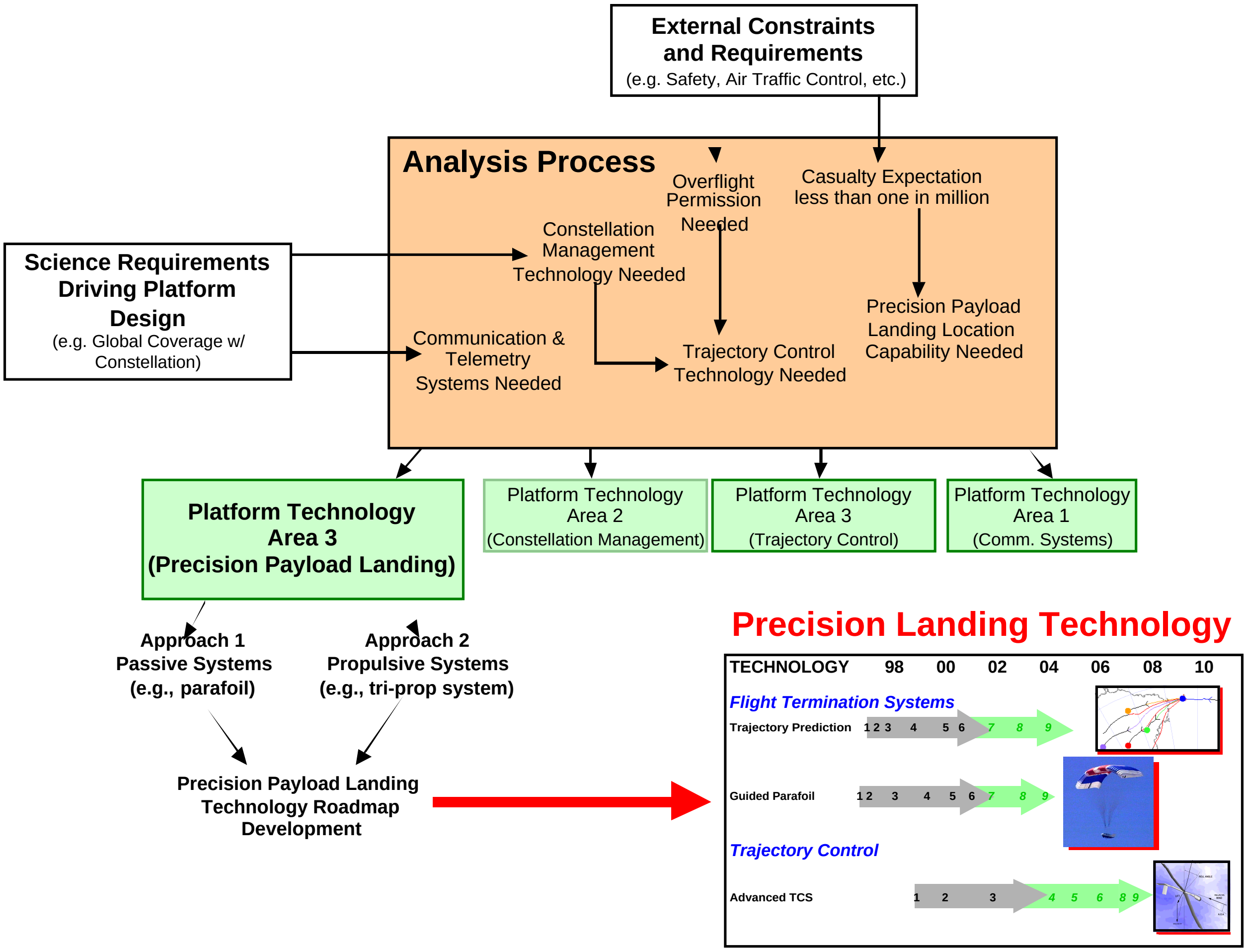


Figure 15 Example Detail of Analysis Process

Appendix A: Meeting Plan, by Dr. Matthew Heun

ESTO Ad-Hoc
Earth Science
Stratospheric Balloon Workshop
Meeting Plan

Presentation to
ESTO Ad Hoc Science Workshop

By Dr. Matthew Kuperus Heun
Global Aerospace Corporation
http://www.gaerospace.com/

7 January 2002

Global
Aerospace
Corporation

Agenda

- **9:00–9:05 Welcome (Kerry Nock, GAC)**
- **9:05–9:15 Introduction (Loren Lemmerman, ESTO)**
- **9:15–9:25 Plan for the study and meeting (GAC)**
- **9:25–10:10 Present & future of scientific ballooning (GAC)**
- **10:10–10:25 Instructions for breakout sessions (GAC)**
- **10:25–10:35 Break**
- **10:35–11:20 Breakout sessions (all)**
- **11:20–12:00 Prepare breakout group reports (all)**
- **12:00–12:45 Working lunch: review of reports (all)**
- **12:45–13:00 Meeting wrap-up**

Context for Study

- **NASA balloon program focus on astrophysics missions in the last decade**
- **Increased interest within NASA for Earth science from stratospheric balloons**
- **New technologies being developed that will extend capabilities of stratospheric platforms for Earth science**
  - **Longer-duration superpressure balloons**
  - **Trajectory control**
  - **Stratospheric balloon constellations**
- **Revolutionary Aerospace Systems Concepts (RASC) activity will evaluate stratospheric platforms and will affect FY 2005 funding and beyond**

Motivation for Study

- Desire greater utilization of NASA Scientific Balloon Program capabilities for Earth science
- Need reference requirements for stratospheric Earth science platform technology
- Want requirements in place for near-term platform technology funding decisions

Objective of Study

Develop a roadmap for stratospheric balloon platform technology development that provides guidance to ESTO for FY 2003 platform technology funding

Study Tasks & Scope

Ad-hoc ES workshop → **Distill driving requirements for strat. balloons for ES** → **Identify preliminary balloon platform technology requirements for ES** → **Develop roadmap**

- Assist JPL in organizing ad hoc Earth Science (ES) workshop
- Distill set of driving requirements for stratospheric balloons
- Identify preliminary balloon platform technology requirements
- Develop a preliminary stratospheric balloon technology roadmap
- Final presentation

- Completion Date: 30 April 2002

Agenda

- 9:00–9:05 Welcome (Kerry Nock, GAC)
- 9:05–9:15 Introduction (Loren Lemmerman, ESTO)
- 9:15–9:25 Plan for the study and meeting (GAC)
- **9:25–10:10 Present & future of scientific ballooning (GAC)**
- **10:10–10:25 Instructions for breakout sessions (GAC)**
- **10:25–10:35 Break**
- **10:35–11:20 Breakout sessions (all)**
- **11:20–12:00 Prepare breakout group reports (all)**
- **12:00–12:45 Working lunch: review of reports (all)**
- **12:45–13:00 Meeting wrap-up**

Appendix B: Present & Future Scientific Ballooning, Presentation to ESTO Ad Hoc Science Workshop, by Dr. Matthew Heun

Present & Future Scientific Ballooning

Presentation to
ESTO Ad Hoc Science Workshop

By Dr. Matthew Kuperus Heun
Global Aerospace Corporation
http://www.gaerospace.com/

7 January 2002

TOPICS

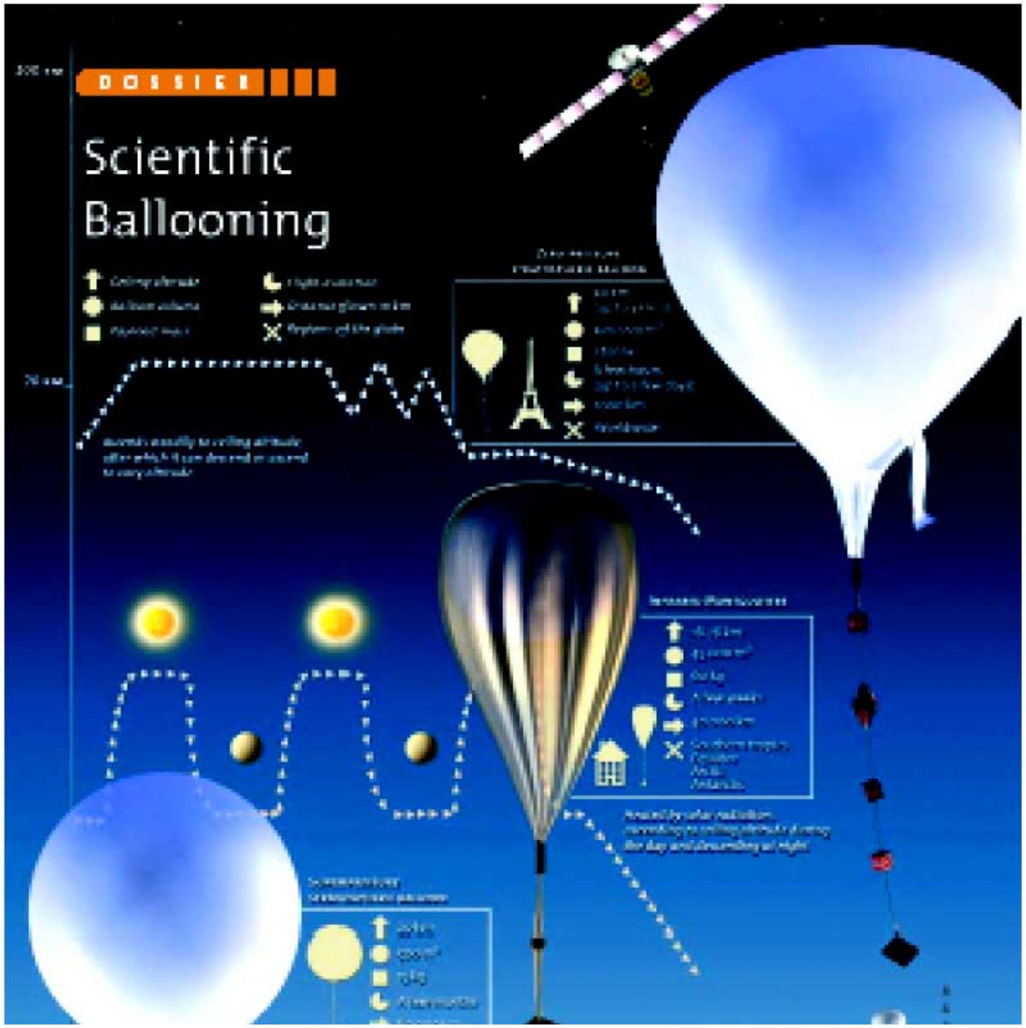
Overview of Scientific Ballooning

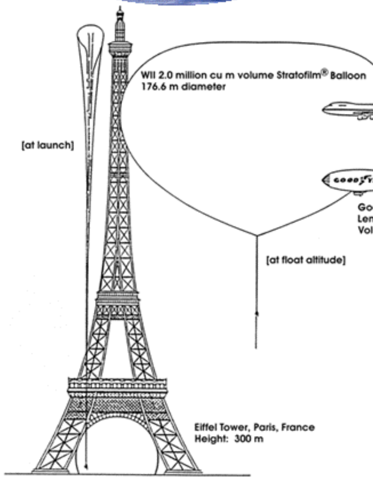
Present and Future Capabilities

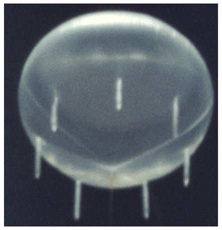
Conclusion

Overview of Scientific Ballooning

Balloon Types

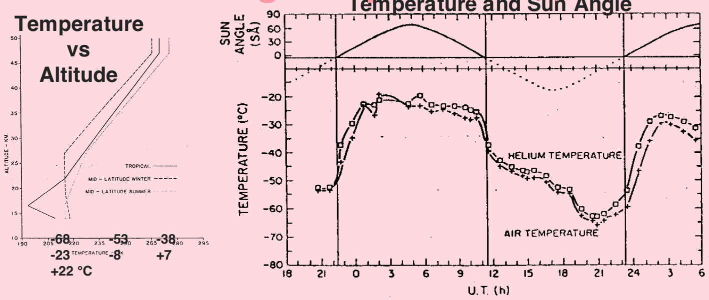






NASA balloon size

RACOON Flight:Equator, Fall, 1980*



* - Lally, V. E., The Radiation Controlled Balloon (RACOON), ASR 1983

Balloon Payloads

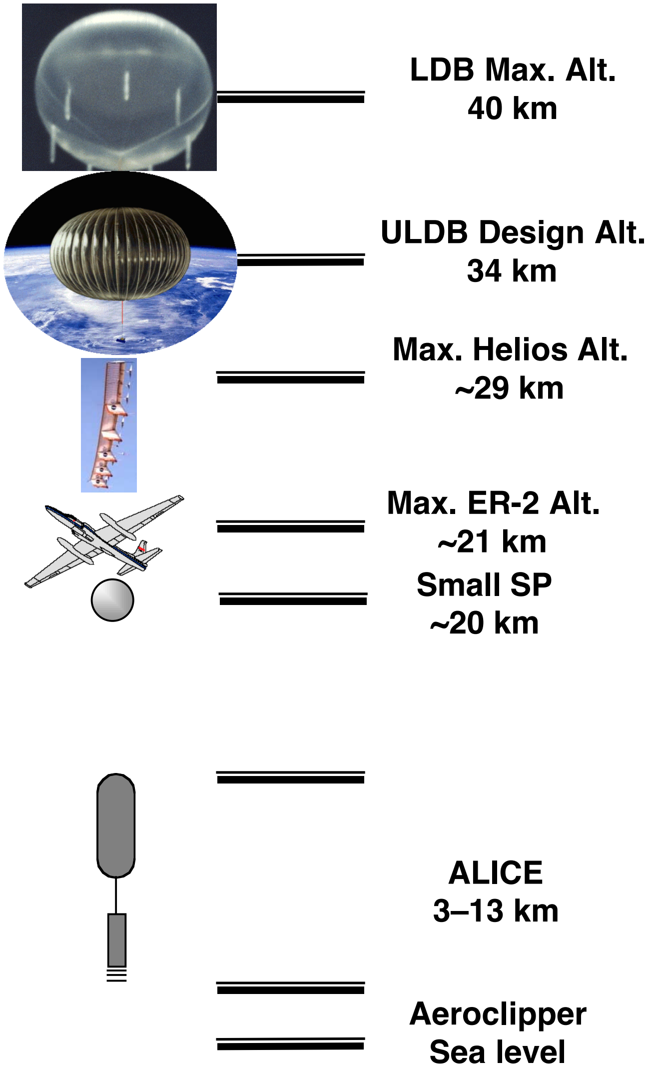
- Various Sizes:
  - Few kg
  - Few thousands of kg
- Designed for recovery
- Science variety
  - Chemistry
  - Astrophysics
  - Weather & climate
  - Radiation
- Stable platform
- Pointed instruments
- Benign launch environment

HIREGS (UCB & UCSD)
1994–95, Antarctica LDB

NightGlow (U. Utah, NMSU)
Feb 2001 ULDB payload

Earth Science Balloon Altitudes

- Variety of altitudes available based on balloon type
- "Edge of space" with large zero-pressure or superpressure
  - Less than 1% of atmosphere above
  - 99% of atmosphere below
- Stratosphere/troposphere interface (20 km) with small superpressure
- Variable altitude with ALICE or Racoon Anchor balloons
- At sea-level with "Aeroclipper" balloons



LDB Max. Alt.
40 km

ULDB Design Alt.
34 km

Max. Helios Alt.
~29 km

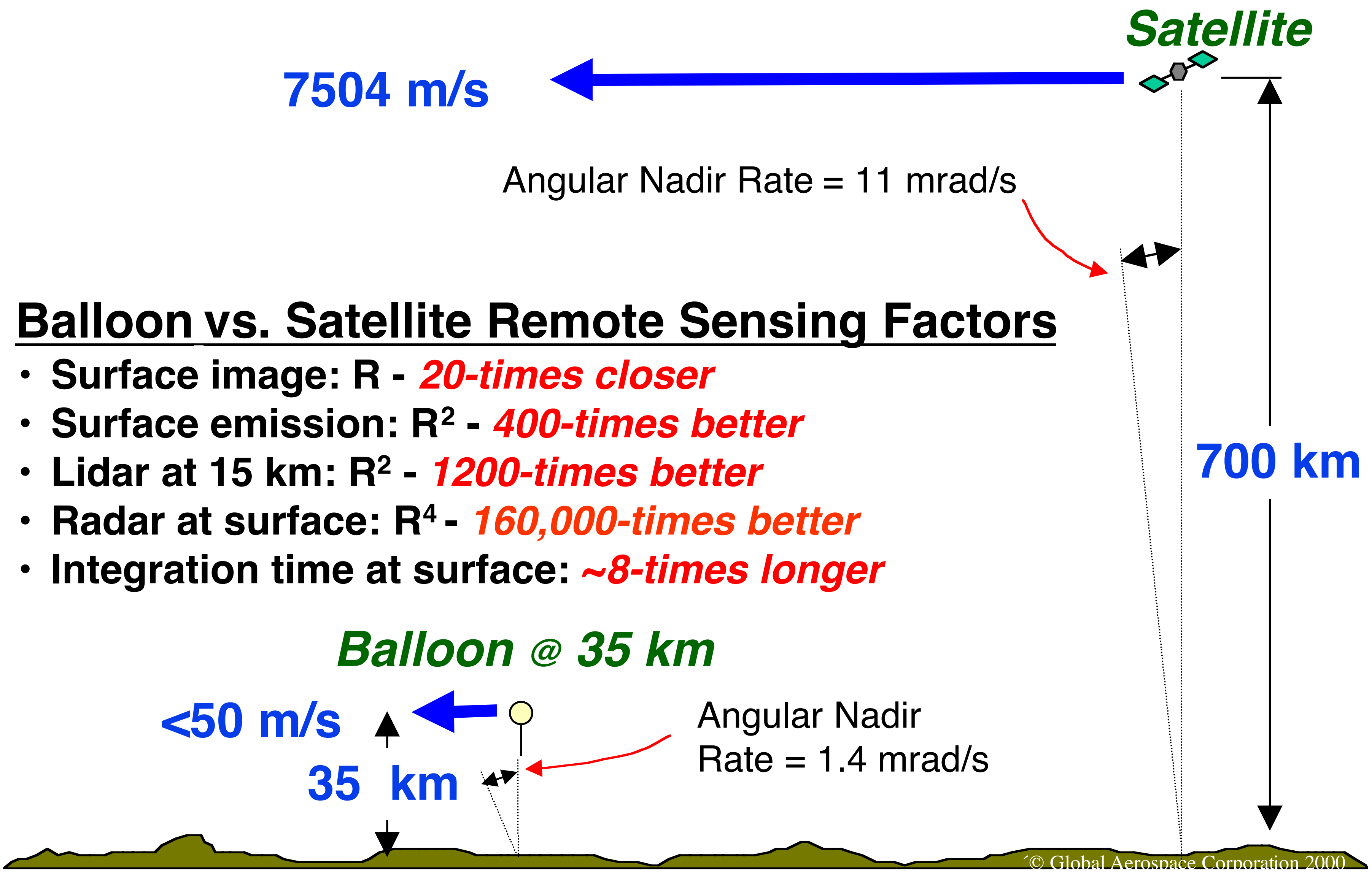
Max. ER-2 Alt.
~21 km

Small SP
~20 km

ALICE
3–13 km

Aeroclipper
Sea level

Satellite Comparison



Balloon vs. Satellite Remote Sensing Factors

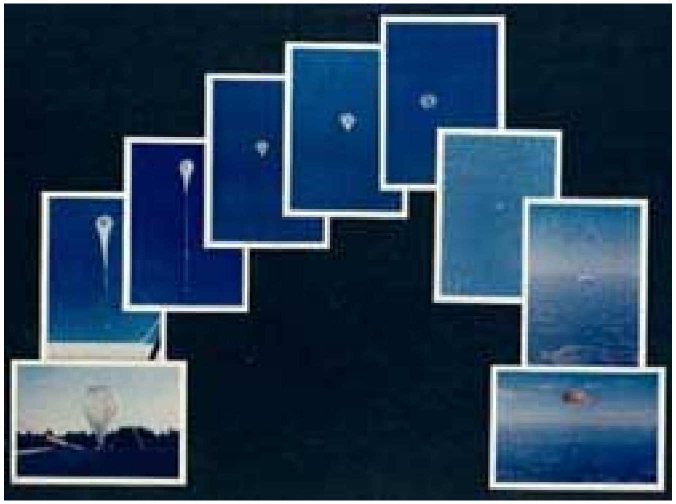
- **Surface image: R - *20-times closer***
- **Surface emission: R^2 - *400-times better***
- **Lidar at 15 km: R^2 - *1200-times better***
- **Radar at surface: R^4 - *160,000-times better***
- **Integration time at surface: *~8-times longer***

Launch and Recovery

- **Launches from many locations worldwide**
  - **NASA: Texas, New Mexico, Antarctica, Australia, Fairbanks, Canada, Sweden**
  - **CNES: France, South Africa, Antarctica, Sweden**
- **Payloads typically recovered on parachute**

ULDB Launch, March 2001

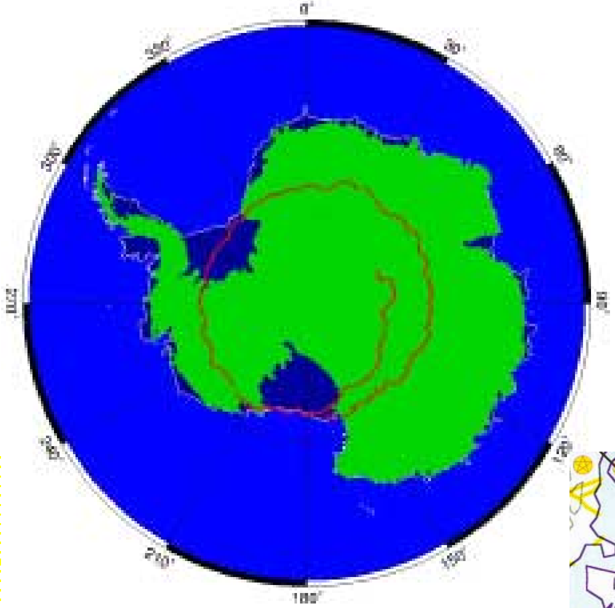
Flight Profile



Global Aerospace Corporation

Representative Trajectories

Conventional flight



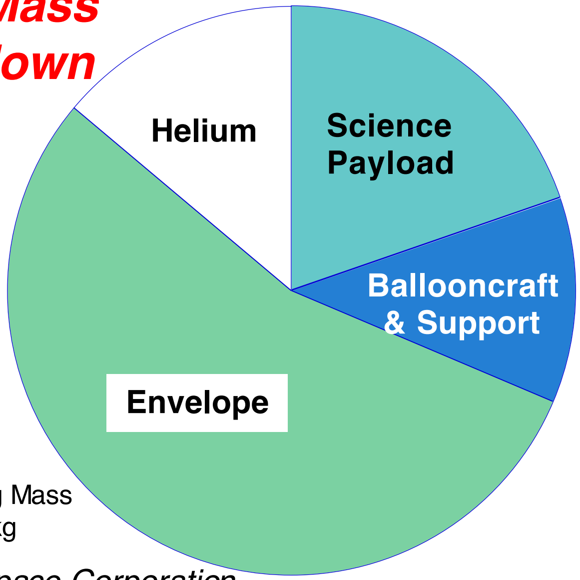
LDB Antarctica

LDB Arctic

LTA Platform Design Issues

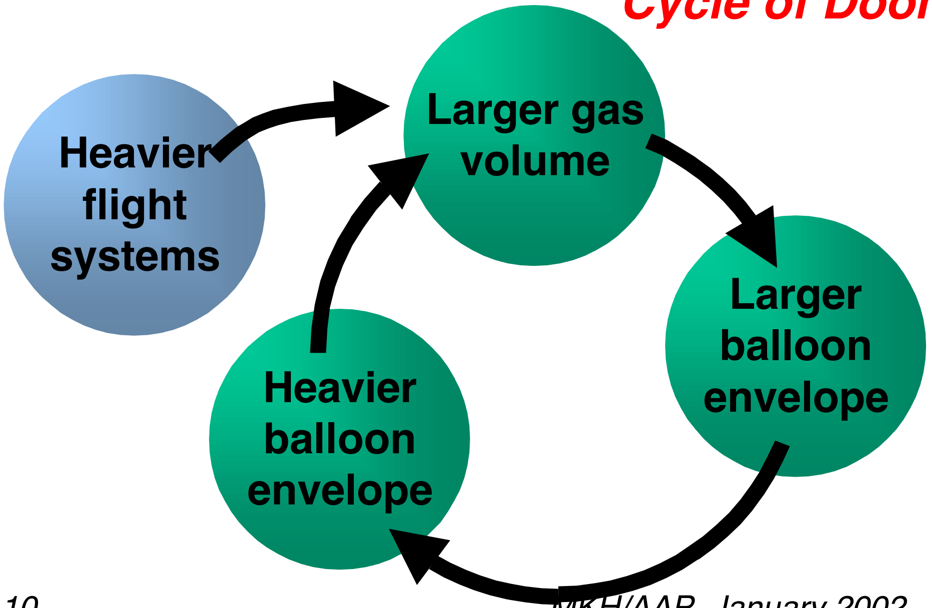
- LTA design sensitivity: “Cycle of doom”
- ULDB design: Δfloating mass/Δpayload mass = 1.7
- Small reductions in flight system mass
  - Reduced cost -- smaller & lighter balloon envelope and/or
  - More science payload

ULDB Mass Breakdown



Total Floating Mass
~ 5000 kg

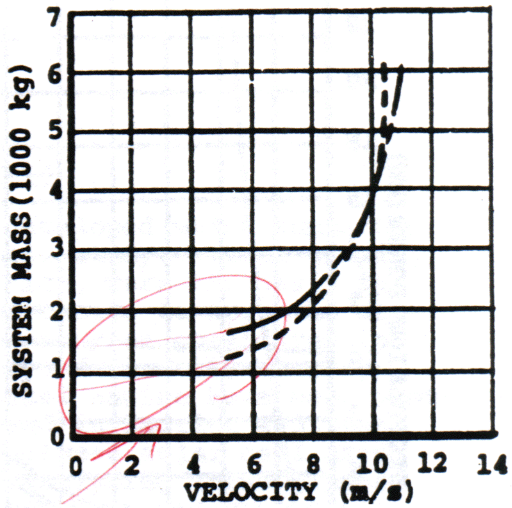
“Cycle of Doom”



Balloons and Airships

- **Several past & ongoing airship studies and activities**
  - POBAL (AFCRL, 1960s)
  - POBAL-S (Raven, 1970s)
  - HAPP (Batelle, 1975)
  - HASPA (Sheldahl, 1975)
  - Sounder (late 1990s)
  - DARPA/WFF (2000)
  - GSFC CETDP study (2000)
  - Onda (2001)
  - Proposed NORAD study
- **Airship speed is major driver**
  - Tight coupling with energy storage & structural mass
  - "Cigar" shape is inherently inefficient shape for containing gas volume

POBAL-S
Beemer, 1975



Onda, 2001

Altitude	22 km
Winds	40 m/s
Volume	1.5 Mm^3
Length	300 m
Power	830 kW
Payload Mass	2 mt
Total Mass	76 mt

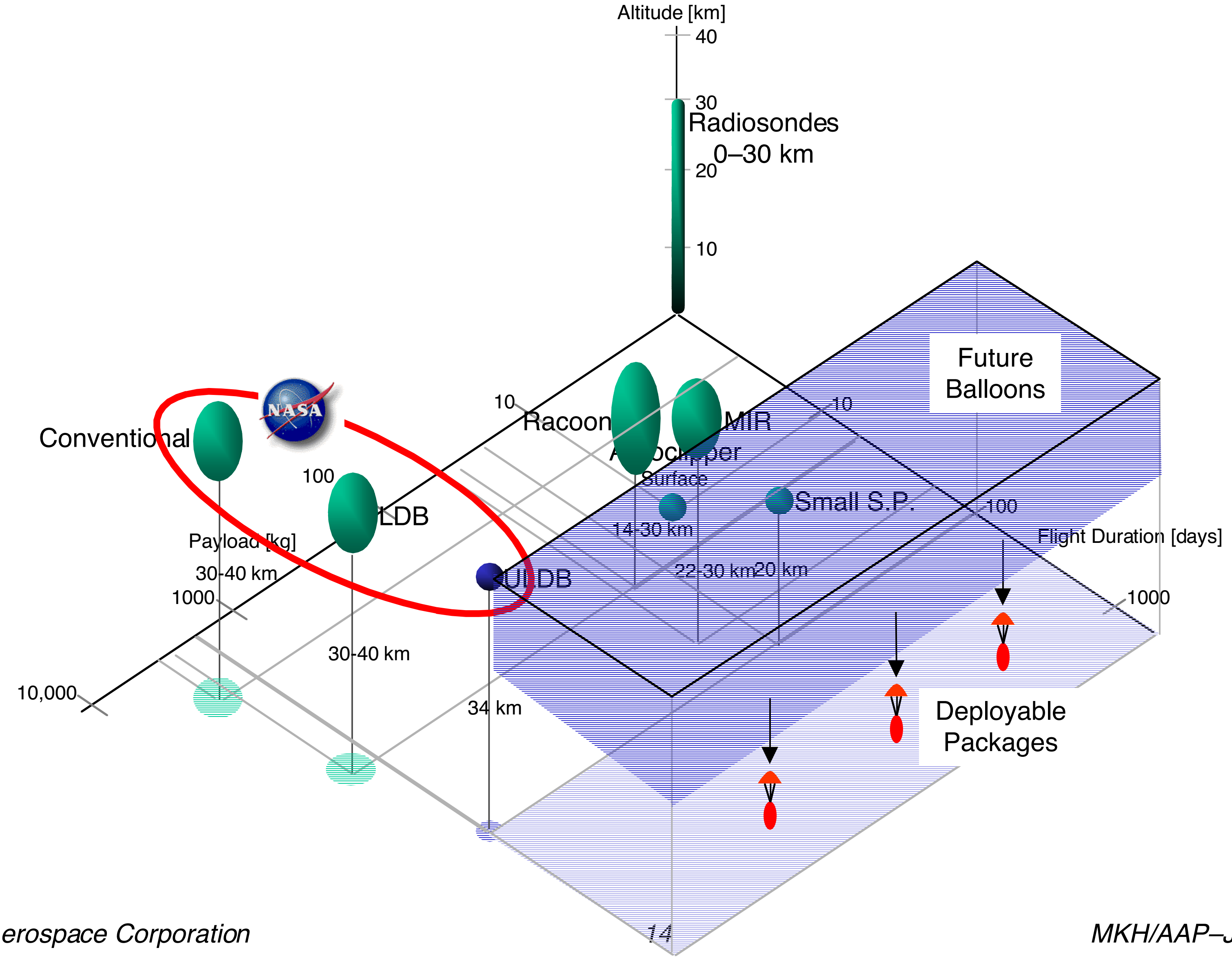
Present & Future Capabilities

Balloon Maneuverability

- **Present**
  - Balloon trajectories are at the mercy of the winds
  - Limited maneuverability with altitude control (consumables)

- **Future**
  - First generation trajectory control (1–2 m/s ΔV)
  - Extensive trajectory control (2–5 m/s ΔV)
  - No stationkeeping with single balloons
  - Virtual stationkeeping with multi-platform constellations using trajectory control

Altitude, Payload, & Duration



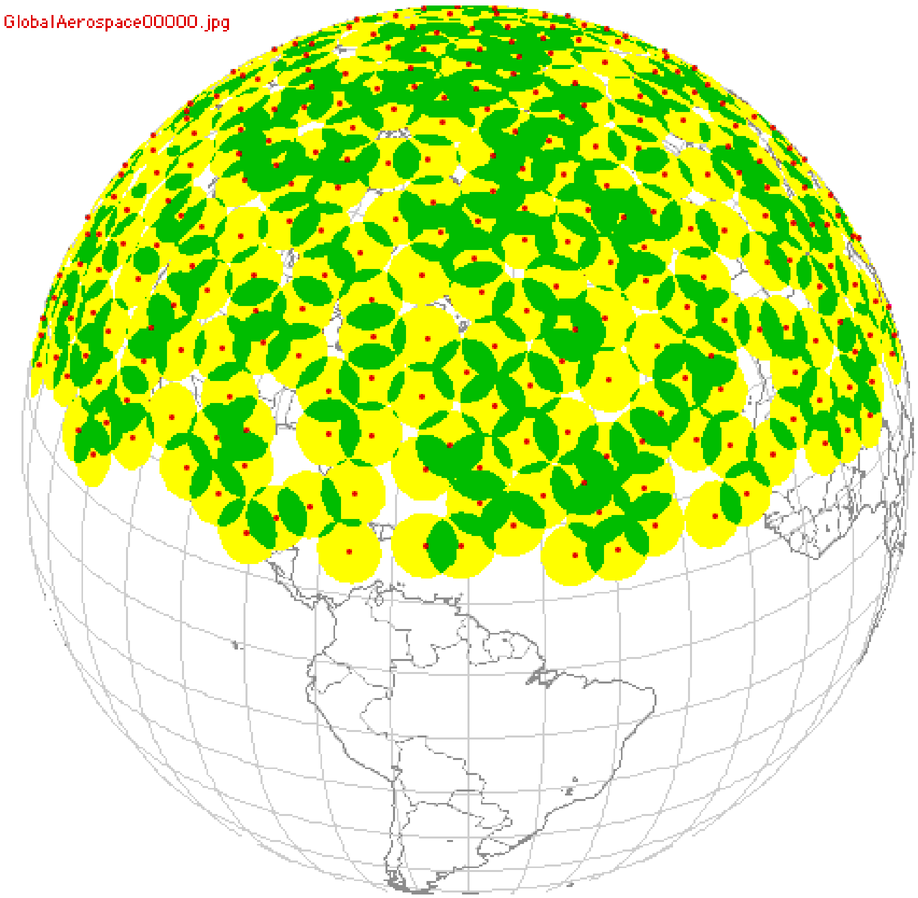
Notes on Flight Duration

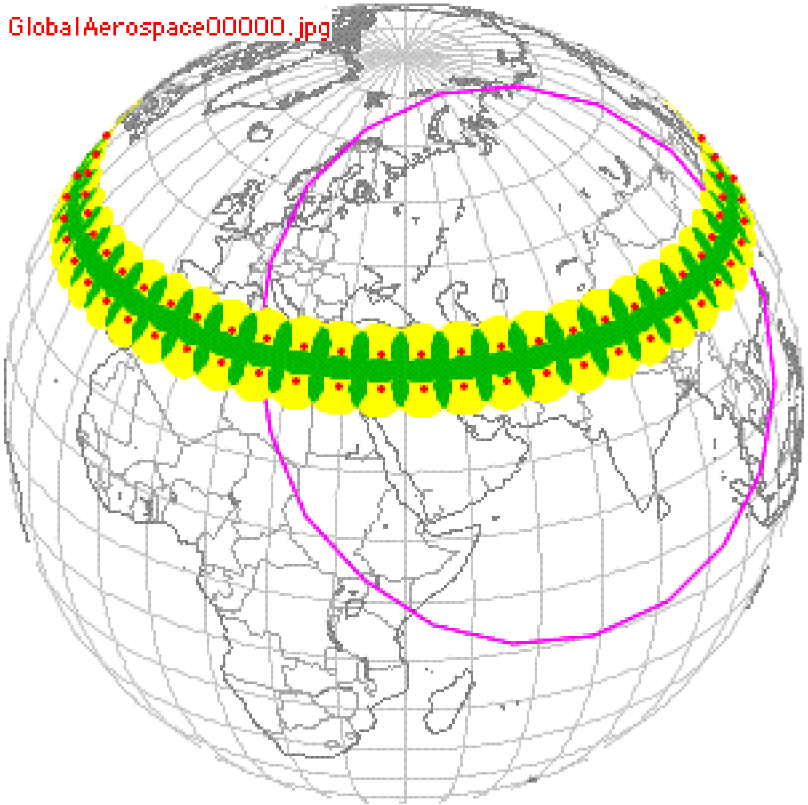
- Present
  - Limiting Factors
    - Zero-pressure
      - Ballast/vent diurnal cycle
      - Consumables: ballast buoyant gas
    - Superpressure: Leaks (manufacturing quality), UV damage to materials
    - Overflight permission
  - Max duration: ~ 21 days
- Future
  - Long duration with superpressure balloons (no consumables)
    - High-quality engineered seams
    - UV-resistant materials
  - International agreements and/or overflight avoidance
  - Max duration: years

Simultaneity (1)

- **Present**
  - **Single balloon flights with large payloads (> 1000 kg) for moderate duration (≤ 20 days)**
  - **Multiple balloon flights with small payloads (< 100 kg) for moderate duration (≤ 20 days)**
  - **"Campaign" mentality**
- **Future**
  - **Constellation(s) of very long duration balloons (> 3 years) provide permanent "edge-of-space" presence**
  - **International cooperation for overflight permission**
  - **"Infrastructure" mentality**

Simultaneity (2)





Flight Regions

- **Present**
  - **Limited flight trajectory opportunities**
    - **Conventional: Short CONUS flights**
    - **LDB: polar flights**
    - **ULDB: southern hemisphere**
  - **Per-flight international negotiations for overflight**

- **Future**
  - **Enhanced safety and reliability**
  - **International cooperation**
    - **COSPAR**
    - **WMO pathways**
    - **Worldwide science participation**

Onboard Power

- **Present**
  - Small balloons provide a few watts of power
  - Large balloons provide up to 1 kW continuous power
  - Additional power means significant added mass
- **Future**
  - Scaleable power generation systems that provide additional power with minimum added mass
  - Advanced energy storage technologies
  - Reduced $/W and kg/W

Data Storage & Transmission

- Present
  - Data stored onboard and relayed to ground with latency and bandwidth limitations
  - Majority of data recovered when payload is recovered
- Future
  - Increasing onboard storage capabilities
  - Constellations of balloons become nodes in the global information infrastructure
  - Significantly increased and increasingly inexpensive bandwidth between platforms and user community
  - Not dependent on payload recovery for complete data set

Conclusion

- Stratospheric balloons offer exciting opportunities for Earth science
- The future of stratospheric scientific ballooning will look much different from its past
- This meeting will help shape the future

Appendix C: Data Capture Questionnaire, Presentation to ESTO Ad Hoc Science Workshop, by Dr. Alexey Pankine

Data Capture Questionnaire

Presentation to
ESTO Ad Hoc Science Workshop

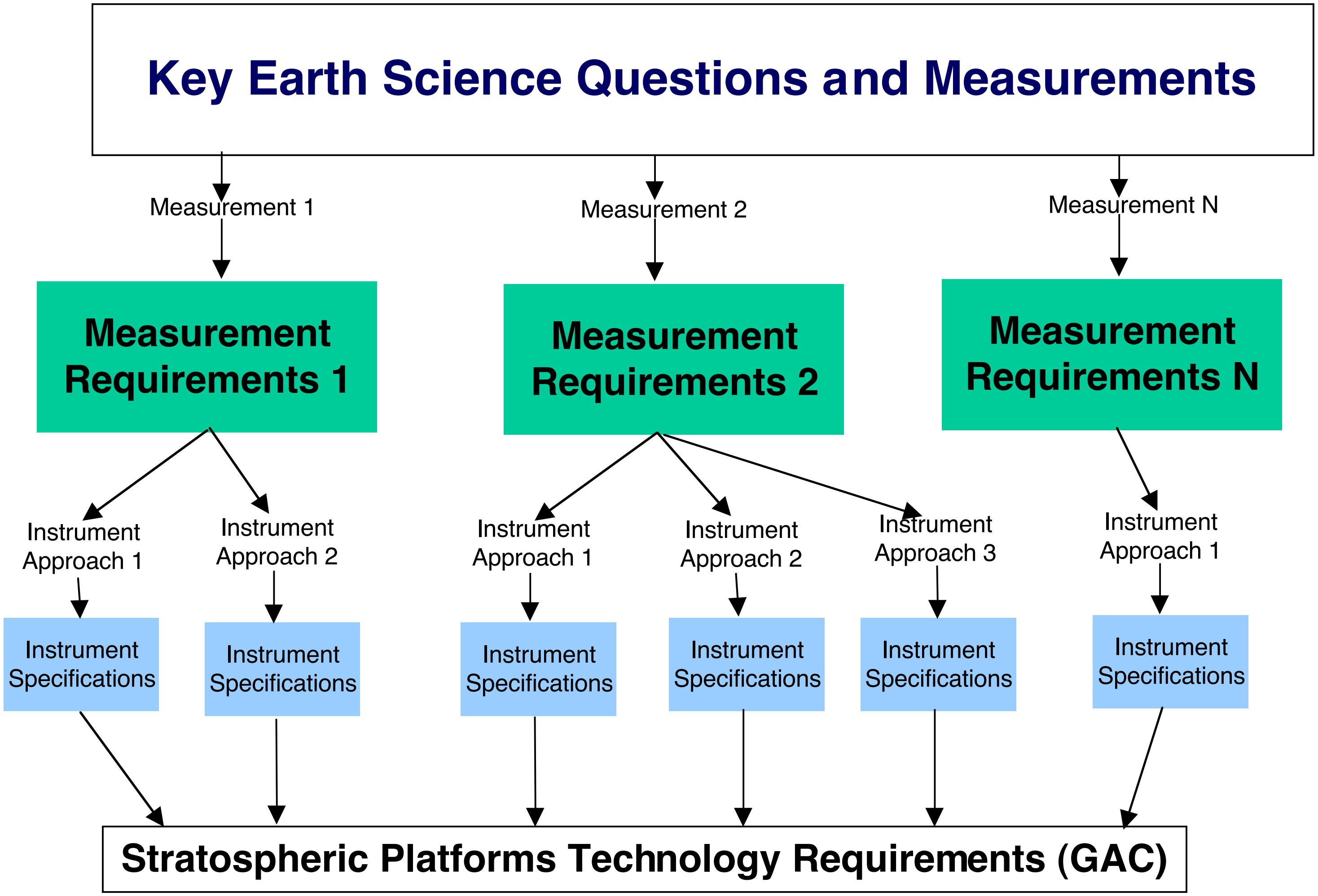
By Dr. Alexey A. Pankine
Global Aerospace Corporation
http://www.gaerospace.com/

7 January 2002

Introduction

- Future technology development needs to be driven by scientific requirements.
- For the rest of the day we will work in groups on science requirements that can affect stratospheric balloon design.
- Questionnaire helps guide your input.

Platform Requirements Flow



Key Earth Science Questions and Measurements

Measurement 1

Measurement 2

Measurement N

Measurement Requirements 1

Measurement Requirements 2

Measurement Requirements N

Instrument Approach 1

Instrument Approach 2

Instrument Approach 1

Instrument Approach 2

Instrument Approach 3

Instrument Approach 1

Instrument Specifications

Instrument Specifications

Instrument Specifications

Instrument Specifications

Instrument Specifications

Instrument Specifications

Stratospheric Platforms Technology Requirements (GAC)

Draft Breakout Groups

Atmosphere 1 (Turnkee Kitchen)

Bob Mahan (Virginia Tech)
Amie Smith Nestor (Virginia Tech)
Bob Stachnik (JPL)
Randy Friedl (JPL)
Geoff Toon (JPL)

Atmosphere 2 (GAC Office)

Li Li (JPL)
Warren Wiscombe (GSFC) (on the phone)
Paul Newman (GSFC) (on the phone)
Jim Margitan (JPL)
Ross Salawitch (JPL)

Surface (Turnkee Office)

Dave Pieri (JPL)
Ali Safaeinili (JPL)
Carol Raymond (JPL)
Frank Carsey (ice, JPL)

Agenda

- 9:00–9:05 Welcome (Kerry Nock, GAC)
- 9:05–9:15 Introduction (Loren Lemmerman, ESTO)
- 9:15–9:25 Plan for the study and meeting (GAC)
- 9:25–10:10 Present & future of scientific ballooning (GAC)
- 10:10–10:25 Instructions for breakout sessions (GAC)
- 10:25–10:35 Break
- 10:35–11:20 Breakout sessions (all)
- 11:20–12:00 Prepare breakout group reports (all)
- 12:00–12:45 Working lunch: review of reports (all)
- 12:45–13:00 Meeting wrap-up

DATA CAPTURE QUESTIONNAIRE

Group _ Atmosphere 1____

What are the key Earth Science questions to be answered in the next 10 - 15 years?
(List 2 or 3 major ones, for example "How is stratospheric ozone changing?").

How is stratospheric ozone changing?

What measurements are needed to answer these questions?
(For example "Profiles of stratospheric temperature, ozone, water vapor, and other trace constituents").
Profiles of stratospheric temperature, ozone, water vapor, and other trace constituents (HNO3, ClO, NO2, HCl, N20, CH4, HF)

For each measurement create separate Measurement Requirements (green) page.

Required Measurement:_ Profiles of stratospheric temperature and water vapor

Table 1. Measurement requirements:

Spatial characteristics of the measurements:	
Horizontal coverage	global maps
Horizontal resolution	horizontal resolution of 4 degrees
Vertical coverage	from tropopause to 55 Km
Vertical resolution	2-3 Km vertical resolution
Spatial accuracy	Average over 2 by 2 degrees box is acceptable
Temporal characteristics of the measurements:	
Length of observations	1 - 3 years
Frequency of observations	daily
Simultaneity	At local noon at every location
Temporal accuracy	Measurement to last not more than 15 minutes
Other:	

For each Measurement Requirements page create one (or several) Instrument Approach (blue) page(s).

Instrument Approach:_____ in situ (dropsonde)

Table 2. Instrument specifications driving platform design (consider both current and future – next 10 years – instrument specifications): (this example is for illustrational purposes only. The requirements given are not necessarily consistent with actual technology.)

Mass	300 g * 1000 days = 300 kg (reduces to 25-50 g in future)
Consumables	Sonde battery must be recharged after 100 days of flight
Power consumption (max, min, duty cycle)	5 W for 1 hour per day to warm up the sondes
Thermal regime (mean operational temperature, allowed temp. var.)	Min. operational temp. –20C.
Radiation regime other environmental regimes (UV exposure, SEUs, etc.)	UV exposure not to exceed 2 hours (thus requires cover).
Pointing accuracy, including: Platform attitude control; Platform attitude knowledge; Instrument pointing knowledge; Instrument pointing control.	Knowledge of platform position and attitude at release time with accuracy of 100 m. Control of platform attitude to within 5 degrees azimuth and with 1 degree of level.
Configuration (compact, distributed, side-looking)	Distributed – large number of identical sondes.
Mobility (rotating, tilting)	Instrument is stationary, does not have to be rotated or tilted to make measurements.
Calibration (frequent, infrequent)	Onboard calibration before release (+ details of calibration process)
Control (autonomous, remotely controlled)	Autonomous release at particular time of day
Data handling (storage, distribution, processing)	Store 1 Mb of data/day Upload 1 Mb/day
Coordination (multiple instruments, multiple measurements)	Multi-platform coordinated release at noon local time.
Other	

Appendix D: Key Questions Outlined in NASA's Earth Science Enterprise (ESE) Strategic Plan

The mission of NASA's Earth Science Enterprise (ESE) is to develop a scientific understanding of the Earth system and its response to natural or human-induced changes to enable improved prediction capability for climate, weather, and natural hazards. In short the ESE is devoted to answer the following question:

"How is the Earth changing and what are the consequences of life on Earth?"

The scientific strategy to answer this immensely complex question is laid out in five steps:

1) How is the global earth system changing?

    - How are global precipitation, evaporation, and the cycling of water changing
    - How is the global ocean circulation varying on interannual, decadal, and longer time scales?
    - How are global ecosystems changing?
    - How is stratospheric ozone changing, as the abundance of ozone-destroying chemicals decreases and new substitutes increases?
    - What changes are occurring in the mass of the earth's ice cover?
    - What are the motions of the earth and the earth's interior, and what information can be inferred about earth's internal processes

2) What are the primary causes of the earth system variability?

    - What trends in atmospheric constituents and solar radiation are driving global climate?
    - What changes are occurring in global land cover and land use, and what are their causes?
    - How is the earth's surface being transformed and how can such information be used to predict future changes?

3) How does the earth system respond to natural and human-induced changes?

    - What are the effects of clouds and surface hydrologic processes on earth's climate?
    - How do ecosystems respond to and affect global environmental change and the carbon cycle?
    - How can climate variations induce changes in the global ocean circulation?

- How do stratospheric trace constituents respond to change in climate and atmospheric composition?

- How is global sea level affected by climate change?

- What are the effects of regional pollution on the global atmosphere, and the effects of global chemical and climate changes on regional air quality?

4) What are the consequences of change in the earth system for human civilization?

    - How are variations in local weather, precipitation and water resources related to global climate variation?

    - What are the consequences of land cover and land use change for the sustainability of ecosystems and economic productivity?

    - What are the consequences of climate and sea level changes and increased human activities on coastal regions?

5) How well can we predict future changes in the earth system?

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

    - How well can transient climate variations be understood and predicted?

    - How well can long-term climate trends be assessed or predicted?

    - How well can future atmospheric chemical impacts on ozone and climate be predicted?

    - How well can cycling of carbon through the earth system be modeled, and how reliable are predictions of future atmospheric concentrations of carbon dioxide and methane by these models?

(http://www.earth.nasa.gov/science/index.html)

Appendix E: Data Capture Questionnaires as Filled Out by the Science Group