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Planetary Balloon-Based Science Platform Evaluation and Program Implementation

Final Report

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1.0 Executive Summary

This study evaluates the potential for a balloon-based optical telescope to augment the planetary science assets in achieving decadal class science. The study considered potential science achievable and science traceability relative to the most recent planetary science decadal survey, potential platform features, expected observation characteristics, and possible implementation approaches in the evaluation process. The evaluation indicates that high-value science can be accomplished with a balloon-borne observatory and unique measurements, or complimentary contributions, can be realized in a very cost effective manner.

The 2013 Planetary Science Decadal report (Ref. 1) did address high-altitude balloon platforms for planetary science. A quote from the executive summary is as follows:

> *"Balloon- and rocket-borne telescopes offer a cost-effective means of studying planetary bodies at wavelengths inaccessible from the ground. Because of their modest costs and development times, they also provide training opportunities for would-be developers of future spacecraft instruments. Although NASA's Science Mission Directorate regularly flies balloon missions into the stratosphere, there are few funding opportunities to take advantage of this resource for planetary science, because typical planetary grants are too small to support these missions.* ***A funding line to promote further use of these suborbital observing platforms for planetary observations would complement and reduce the load on the already over-subscribed planetary astronomy program."***

Science Potential and Benefits: This study confirms the cost-benefit value for planetary science purposes as posited by the National Research Council in their decadal survey. Forty-four important questions of the decadal survey are at least partially addressable through balloon based capabilities. Indeed, planetary science through balloon observations can provide significant science through observations in the 300 nm to 5 μm range and potentially at longer wavelengths as well. Each mission could make continued progress towards the science objectives identified in the planetary sciences decadal survey. Additionally, balloon missions have demonstrated the ability to progress from concept to observation to publication of data in a matter of a couple years verses over a decade which is typical for planetary spaceflight missions. This increases the speed of science return.

Planetary science from a balloon-borne platform is a relatively low-cost approach to new science measurements. This is particularly relevant within a cost-constrained planetary science budget. The cost of the development and first flight of a 100-day planetary science balloon mission is comparable to the cost of 100 nights on one of the Keck telescopes and potentially offers cost reduction for science data over both the Hubble Space Telescope (HST) and the Stratospheric Observatory for Infrared Astronomy (SOFIA). Repeated flights, where the gondola and/or instrument systems are re-used in subsequent launches, would further reduce the cost of the per unit science data. Such flights would offer observing time at a very competitive cost verses other solutions, and the cost per observing time is even better when including the daytime science capability.

Another advantage for planetary scientists is that the cost may be low enough to enable a dedicated asset for planetary science. This could provide significant new viewing opportunities not possible from the ground, and allow unprecedented access to observations that cannot be realized with the time allocation pressures faced by current observing assets. If such a balloon based observatory were available, it is envisioned that observing time, in other words the science implemented on a given flight, would be competed to ensure the best science return. The resulting data would be archived in the Planetary Data System (PDS) for broad community use in rapid time.

In addition, flight systems that have a relatively short life cycle and where hardware is generally recovered, are excellent opportunities to train early career scientists, engineers, and project managers. Early career professionals are eager to have hands on experience that prepare them for the more visible and expensive space based missions. The fact that balloon-borne payloads, unlike space missions, are generally recovered offers an excellent tool to test and mature instruments and other space craft systems. The near space environment provides a proving ground for future space applications.

Desired Gondola Features: Potential gondola characteristics or features are assessed in this study, and a concept is recommended for a baseline gondola system (Figure 1.1). The Gondola for High-Altitude Planetary Science (GHAPS) concept that is recommended would be a first generation platform designed around a 1 m or larger aperture, narrow-field telescope with pointing accuracies better than 1 arcsec. The narrow field of view (FOV) telescope was chosen because it can apply to all but the survey-type missions in the decadal survey. A classical Cassegrain, or variant like Ritchey-Chretien, telescope is recommended for the primary telescope.

The gondola should be designed for multiple flights so it must be robust and readily processed at recovery. It must be lightweighted to the extent possible to allow for long-duration flights on super-pressure balloons. For such configurations, science return up to 12 TB of data per flight can be expected.

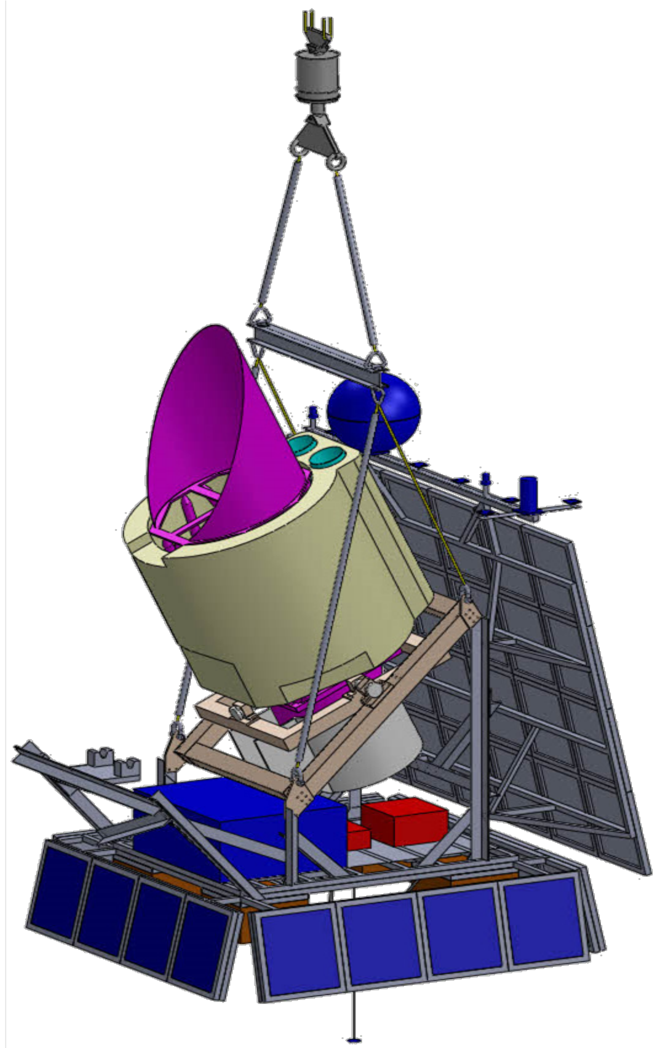


Figure 1.1.—Notional planetary science balloon gondola concept termed “Gondola for High-Altitude Planetary Science” (GHAPS).

Demonstration Flights: The recent flight of the Balloon Observation Platform for Planetary Science (BOPPS) and the previous Balloon Rapid Response for ISON (BRRISON) missions achieved several significant accomplishments that can feed forward to a GHAPS gondola project. Science results from BOPPS included the first ever Earth-based measurements for CO_2 in a comet, first measurements for CO_2 and H_2O in an Oort cloud comet, and the first measurement of 1 Ceres at 2.73 µm to refine the shape of the infrared water absorption feature. The performance of the Fine Steering Mirror (FSM) was demonstrated on the BOPPs mission along with other subsystems such as the coarse pointing of the telescope. BRRISON also demonstrated the feasibility of a balloon-borne payload to be a quick response asset, as shown with the mission being designed, built, and flown in less than a year, all-be-it leveraging the primary telescope and avionics from a prior mission. Additionally, BRRISON demonstrated the performance of the Fine Steering System (FSM) with ground tests showing significantly improved visible imaging quality by reducing image distortions due both to telescope movement and atmospheric disturbances.

The BOPPS platform can continue to be leveraged on future flights even as GHAPS is being developed. This would provide the community opportunity for some earlier science return with BOPPS, and realize the full science capability of balloon platforms by developing and flying GHAPS. GHAPS would be optimized for science return enabling ultra-long duration missions which would provide detection and observation of smaller and fainter objects than possible with BOPPS.

The study affirms the planetary decadal recommendations, and shows that a number of "Top Priority" science questions can be achieved. A combination GHAPS and BOPPS would provide the best value for PSD for realizing that science.

2.0 Study Overview

2.1 Purpose

The recent advances in pointing capabilities, long-duration super-pressure balloons, and the potential to open mid-latitude launch sites may be enabling for high-value planetary science from balloon-borne assets. The cost and access to space-based assets for planetary science limit the opportunities to meet the science objectives as provided by the Planetary Sciences Decadal Survey. There are insufficient resources to address the primary science goals at the wide range of targets within the next decade through space missions alone. Ground-based assets, though highly valued, have limitations due to atmospheric attenuation and turbulence. While new and more capable ground systems continue to be developed, there will still be atmospheric considerations that limit viewing in bands of interest to planetary scientists. The NASA Balloon Program Office (BPO) has successfully demonstrated the use of a balloon-based platform for heliophysics, astrophysics, earth science, and technology demonstration. The purpose of this study is to evaluate the potential for a balloon-based asset for planetary science. Can a balloon borne observatory augment the planetary science assets of today in a cost effective manner? Does a niche exist for planetary science from stratospheric balloon-borne platforms where the community has frequent access to an observatory that can contribute unique new science at relatively low cost? This study proposes to answer these and related questions.

2.2 Goals and Objectives

The objective of the planetary balloon study is to:

1. Develop traceability of balloon based asset science potential with NASA's science goals and objectives as outlined in the Planetary Sciences Decadal Survey, "Vision and Voyages for Planetary Science in the Decade 2013–2022," the Solar System Exploration Roadmap (Ref. 1), and NASA's SMD Science Plan.
2. Document the advantages and disadvantages of a balloon-based platform relative to alternative options (e.g., ground-based telescopes, aircraft-based telescopes, orbital telescopes, etc.)
3. Develop initial proposed requirements for balloon-based assets/instruments to meet NASA's planetary science goals and objectives, and assess existing instruments to meet the identified requirements.
4. Develop initial requirements for the instrument support system (i.e., the gondola and subsystems) and operations (e.g., durations, altitudes, locations, etc.).
5. Assess gondola systems/subsystems to meet the requirements identified above. Identify gaps in capability between requirements and existing systems.
6. Assess near-term and mid-term instruments and gondola subsystems for a near term mission that meets the requirements identified above. Develop schedule and cost estimates to the associated field near-term and mid-term technologies.
7. Identify the feasibility of a near-term mission with sufficient science justification.
    a. Science traceability
    b. Risk assessment and mitigation plan
    c. Detailed analysis and point design of a baseline instrument
    d. Detailed point design of gondola
    e. System-level integration assessment
    f. Concept of operations
    g. Cost assessment and development schedule
8. Assess near-term and mid-term instruments and gondola subsystems to meet the requirements for the long-duration flight requirements. Develop schedule and cost estimates to field near-term and mid-term technologies. Assess value of technology investments relative to science objectives and capability gap analysis.
9. Develop an executable project plan for the development and deployment of a balloon- based planetary science platform and instruments.

2.3 Internal Participants

The balloon study is funded by the Planetary Science Division (PSD) of NASA's Science Mission Directorate (SMD). Project Management is performed by the NASA Glenn Research Center (GRC). The project leverages technical expertise of Southwest Research Institute (SwRI), Johns Hopkins Applied Physics Laboratory (APL), and NASA's Wallops Flight Facility (WFF) for study objectives 1 to 8.

APL: APL serves as the lead for the science traceability/justification; Goals 1 and 2. APL supports goals 3 to 8.

SWRI: SWRI serves as the lead for gondola requirements; Goals 3 and 4. SWRI supports goals 1, 2 and 5 to 8.

WFF: WFF serves as the lead for existing gondola and stratospheric balloon capabilities; Goal 5. WFF supports goals 3, 4, and 6 to 8.

GRC: GRC serves as the study lead, performs the system-level point design and cost estimates, and develops project plans; Goals 6 to 9.

2.4 External Participants

Participation is open to all U.S. industries, universities, Federally Funded Research and Development Centers, national laboratories, and other government agencies. The internal participants shall leverage expertise wherever appropriate. The study leveraged the initial planetary science gondola workshop, solicited input through the study website, and included feedback through related conferences and assessment group (e.g., Small Bodies Assessment Group (SBAG), Venus Exploration Assessment Group (VeXAG), etc.) presentations and exchanges.

3.0 Science Objectives and Traceability

3.1 Science Rationale for Balloon Based Planetary Science Observations

A Planetary Science Balloon Workshop was held on January 25 and 26, 2012, at the NASA Glenn Research Center to understand if there is a scientific case and community support for balloon-based planetary science, and if so, identify and capture mission concepts for achieving the science objectives. The workshop included scientists and engineers representing Venus, giant planets, icy satellites, and small body communities. The workshop emphasized a range of scientific disciplines including atmospheric composition, atmospheric dynamics, and surface composition. The workshop confirmed the science potential and initial community interest, and produced more than 40 unique mission concepts along with estimating preliminary balloon-based system requirements.

Through the various mission concepts formulated, it was evident that there are four key niches for stratospheric observations applicable to planetary science:

1. High spatial acuity at wavelengths from 300 nm to 1 μm.
2. Infrared (IR) spectroscopy in the 2.5 to 9 μm range.
3. Potential for long-term uninterrupted observations of a target.
4. Quick response capability

In the range of 300 nm to 1 μm, a 1 m aperture telescope in the stratosphere can provide spatial resolutions of 0.1 to 0.2 arcsec. However, ground-based spectroscopy is plagued by extinction and absorption within the atmosphere. Absorption features that originate in the Earth's atmosphere (telluric features) are prevalent in the infrared and visible regions of the spectrum. Zero-pressure balloons nominally fly above 99.56 percent of the atmosphere, and super-pressure balloons fly above 99 percent. There is essentially no atmospheric turbulence at either super-pressure or zero-pressure float altitudes, which means that either platform is capable of providing diffraction-limited seeing. Additionally, the infrared transmission of the atmosphere at float attitude is enabling at CO_2 and H_2O wavelengths, and superior to ground and airborne platforms at all wavelengths from 2.5 to 5 μm and longer (not shown in Figure 3.1). Figure 3.1 highlights the advantages of balloon-based observations over ground and aircraft assets, including the Stratospheric Observatory for Infrared Astronomy (SOFIA). An example of scientifically valuable observations enabled by balloon missions, is the characterization of the CO_2:water ratio in comets as they become active within the inner solar system, which is an observation only possibly from balloon or space-based platforms. Currently, there is no space-based platform capable of conducting this measurement.

In addition to technologically enabling attributes, there is the practical advantage of balloon-borne telescopes' access to more observing time, especially continuous observation. Except for the Hubble Space Telescope (HST), only balloons can provide astronomers with high-resolution images in visible and UV wavelengths. However, the entire HST annual allocation is 2800 orbits across all scientific categories, or about 3000 hr for observations. In Cycle 19, about 34 percent of the 154 observing awards were imaging programs in visible wavelengths, representing about 1000 hr on target. Coincidentally, this is about the same amount of dark time that would be available from a single 100-day stratospheric balloon flight with the conservative assumption of about a 67 percent observational duty cycle. In other words from a time allocation perspective, a single balloon-borne telescope with a CCD and filter wheel could duplicate the annual HST allocation for all visible imaging programs. Just one example of science, enabled by a planetary science dedicated system, includes the decadal survey goal to understand circulation. The balloon-based telescope could obtain 0.1 arcsec resolution visible imaging of clouds on the gas giants with a duty cycle of minutes, over a time baseline that extends 100 days. Only HST currently has that capability, and HST allocation cannot support an observing program of that magnitude.

The recent BRRISON and BOPPS missions demonstrated another key niche balloons can fill for planetary science; a fast response capability. There have been several examples in the past 2 years where high priority targets (i.e., Oort cloud comets)

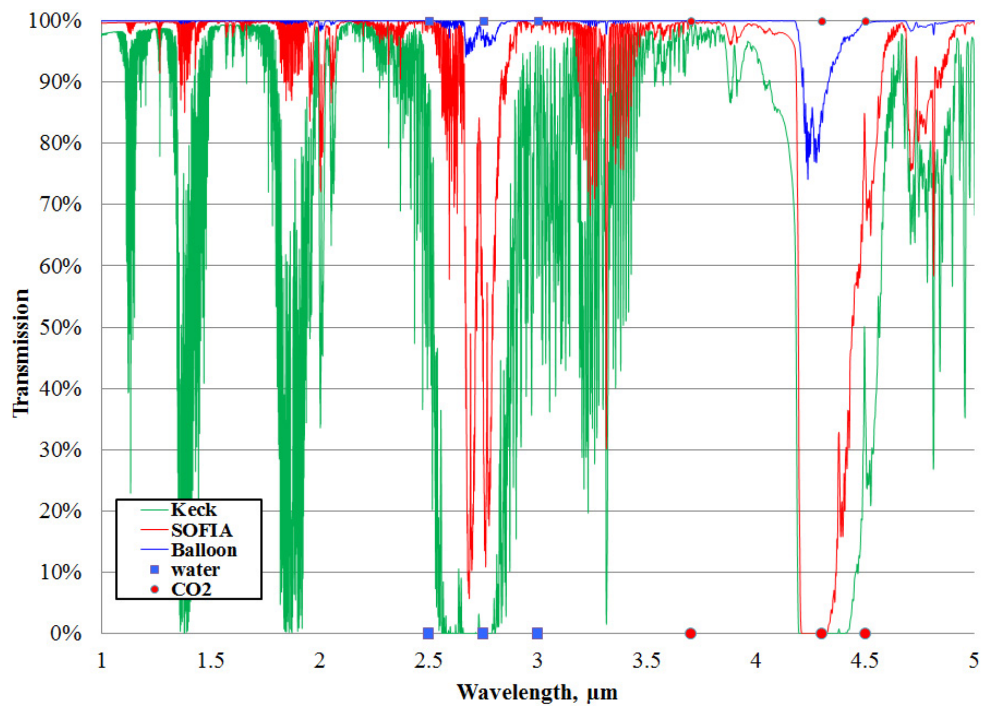


Figure 3.1.—Atmospheric transmission for NASA assets.

were discovered, and observing opportunities were less than 1 year. This is far too short a time to develop, fabricate, and launch a space mission. While ground assets and existing space assets can be tapped for some science, the existing instruments may be limited in the type of observations that can be made. With balloon platforms, as BRRISON and BOPPS showed, instruments can be tailored for the science to be achieved. Unique observations of CO_2 from an Oort cloud comet was accomplished on BOPPS, something that was not possible with the existing ground or space assets.

3.2 Relevance of Balloons to Planetary Decadal Survey Cross-Cutting Themes and Priority Questions

Table S.1 in Vision and Voyages (Ref. 1) lists three cross-cutting themes (building new worlds, planetary habitats and workings of solar systems), split into ten priority questions. Alongside each question are one or more conceptual spacecraft missions that will help to address that question. Many of these questions can also be addressed by the unique capabilities of balloon-borne telescopes, as outlined below.

For this exercise, we assume balloon platform capabilities that have been demonstrated or are close to flying: 1 m apertures, 1 arcsec pointing stability at the gondola level, 100 mas pointing stability at the instrument, and 100-day mid-latitude flights. We assume flight altitudes of 35 to 38 km, above 99.6 percent of the Earth's atmosphere. At these altitudes, atmospheric turbulence is negligible and properly engineered telescopes can provide diffraction-limited images. By flying above nearly all of the Earth's atmosphere, NASA's balloon-borne telescopes have three important advantages over ground-based and airborne facilities: access to the entire visible and IR spectrum, diffraction-limited imaging in the near UV and visible wavelengths, and very good sensitivity to faint point sources. This last capability derives from the narrow PSFs that balloon-bone telescopes provide—a narrow PSF dramatically lowers the background counts taken with the source counts. Given a sky background of 22 magnitudes per square arcsecond, we calculate that a 1-m aperture telescope at 125,000 ft should make a 5σ detection of a V=25 object in 340 s.

3.2.1 Top Priority Questions

This section highlights the science-based justifications for balloon borne observations for respective decadal questions. Not only do balloons offer some science results, but they offer cost effective and timely progress to the Top planetary science questions of today. Each subsection begins with a top priority question as found in the current decadal survey report, and the balloon based science applicability to that question is briefly described.

3.2.1.1 What Were the Initial Stages and Conditions and Processes of Solar System Formation and the Nature of the Interstellar Matter That Was Incorporated?

CO_2 and H_2O emission from comets: The ratio of CO_2 and H_2O in comets is thought to be a proxy for the heliocentric distances at which their constituent components condensed. Balloons and SOFIA have relatively clear access to water bands in the IR spectrum (e.g., near 1.9 and 2.9 µm), but SOFIA cannot observe CO_2 emission at 4.3 µm—the telluric opacity is too great from 40,000 ft. Balloons have about 40 times less atmosphere overhead: the recent BOPPS mission observed comet Jacques at 4.3 µm (Ref. 2)

Isotopic ratios in planetary atmospheres: Measurements of gases in planetary atmospheres requires careful modeling and subtraction of telluric absorptions. The search for CH_4 on Mars shows that, even with Mars' Doppler-shifted spectra, the putative CH_4 features in the Martian spectrum were dominated by various constituents in the Earth's atmosphere. From altitudes of 125,000 ft, the telluric transmission spectrum is much cleaner than at 14,000 or 40,000 ft, and therefore, a balloon borne telescope can make CH_4 observations of the Martian disk.

Determining D/H ratios in Oort cloud and Jupiter-family comets: The D/H ratio in comets is one of the few observational tests of the Nice model and other models of the evolution of the solar system. The variation in D/H ratios in different comet populations is a potential constraint on the origin of Oort cloud comets: is the D/H ratio interstellar or solar-like? Is it the same for all Oort cloud comets or does it vary? To date, the Herschel space telescope and some ground-based submillimeter telescopes have obtained D/H ratios for about a dozen comets. This is a difficult measurement to make because the diagnostic signal is so faint. A balloon mission would require a large telescope (Herschel's aperture was 3.5 m) and a cold OTA and instruments. Instruments in pressure vessels can be cooled to 1.4 K, for example, with liquid helium. Passive sunshades and earthshades can cool the OTA (optical tube assemblies) to temperatures around 180 K. A SNR calculation needs to be performed to determine whether the thermal emission from optics at 180 K precludes measurement of D/H ratios. The BLAST payloads (Balloon-borne Large Aperture Submillimeter Telescope) provide real-world measurements of sub-millimeter signals from the stratosphere.

3.2.1.2 What Governed the Accretion, Supply of Water, Chemistry, and Internal Differentiation of the Inner Planets and the Evolution of Their Atmospheres, and What Roles Did Bombardment By Large Projectiles Play?

Isotopic ratios in planetary atmospheres: Balloon-borne missions, using current capabilities, can investigate how isotopic abundances of H_2O, CO_2, CO and CH_4 are compatible with coupled atmosphere/surface models and models of atmospheric escape, with minor interference due to telluric opacity.

3.2.1.3 What Were the Primordial Sources of Organic Matter, and Where Does Organic Synthesis Continue Today?

Detection of organic molecules and amino acid precursors: Balloon-borne telescopes have an advantage in obtaining IR spectroscopy in the 3 to 5 µm region, where many organic molecules have strong fundamental absorption bands. NH_3, methanol and HCN, for example, combine to make glycine, the simplest amino acid, via the Strecker synthesis. All three precursor molecules have diagnostic features in the 3 to 5 µm region, a wavelength range that is very difficult to obtain from ground-based telescopes.

Balloon-borne telescopes have two key advantages over ground-based sites in the 2.5 to 5 µm range. First, they easily see the entire IR spectrum over this wavelength range. Second, balloon-borne OTAs can operate at temperatures near 180 K, compared to 253 K for most ground-based mountain-top sites. The decrease in thermal self-emission due to the ~70 K drop in telescope temperature means that balloon-borne telescopes are limited by background flux—not thermal self-emission—out to wavelengths as long as 4.8 µm. A 1 m telescope at 235 K in the stratosphere has better SNR at 4 to 5 µm than a 3 m telescope on the summit of Mauna Kea. Balloons also have an advantage over SOFIA (which sees roughly 40 times more atmosphere overhead than a balloon), particularly at 4.3 and 4.6 µm, where telluric CO_2 and CO are strong opacity sources.

3.2.1.4 Did Mars or Venus Host Ancient Aqueous Environments Conducive to Early Life, and Is There Evidence That Life Emerged?

Balloon missions can offer unique time of day observations of Mars: While balloon-borne missions cannot perform in situ investigations of terrain on Mars and Venus, they can complement Mars orbiters by providing compositional maps of the

Martian atmosphere at 2° resolution. In contrast to most orbiter observations, which usually image the same terrain on Mars at the same local time of day, balloon-borne observations would image Martian regions at all times of day.

Observing Venus through CO_2 windows: While stratospheric balloons cannot perform in situ investigations of the Venusian surface for evidence of past surface processes, balloons are well-suited to study Venus' atmosphere. A balloon-borne mission could address many of the questions that were the focus of the Akatsuki spacecraft mission: track the circulation of clouds from 40 to 70 km altitude with 1 m/s resolution to understand the origins of Venus' super-rotating atmosphere; track atmospheric tracers (like CO, H_2O, OCS and SO_2) to understand coupled atmospheric dynamics and chemistry; look for lightning flashes and investigate surface regions with anomalous surface emissivities (e.g., possible recent basalt flows).

3.2.1.5 Beyond Earth, Are There Modern Habitats Elsewhere in the Solar System With Necessary Conditions, Organic Matter, Water, Energy, and Nutrients to Sustain Life, and Do Organisms Live There Now?

Detection of organic molecules and amino acid precursors: The ability to detect organic molecules via 3 to 5 µm spectroscopy is one way that balloons could help address this question. The details of the advantage of balloons in this band is described in other subsections and not repeated here for brevity.

3.2.1.6 How Did the Giant Planets and Their Satellite Systems Accrete, and Is There Evidence That They Migrated to New Orbital Positions?

Determining size distributions for various small-bodies populations: A balloon-borne survey telescope could extend the limits of known size distributions to smaller, fainter objects in various solar system populations (e.g., main belt asteroids, NEOs, hot and cold Kuiper belt objects and Sedna-region objects). The smallest known Kuiper belt objects have sizes down to about 15 km. Competing theories of planetesimal formation predict radically different size distributions in the Kuiper belt for objects in the 1 to 15 km size range (Refs. 3 and 4) (e.g., Johansen et al., 2012 and Schlichting et al. 2013). A sensitive faint-object survey from a balloon-borne telescope could differentiate between models that predict 100 km versus 1 km size planetesimals.

To accomplish these measurements the balloon mission would require a relatively large aperture and an advanced focal plane. First, to detect objects in the 25 to 28 magnitude range in a reasonable exposure time, a 2 m aperture or larger is probably necessary. Second, gigapixel focal planes would be required to sample large areas of the sky at fine resolutions.

Large Synoptic Survey Telescope (LSST) is being built to cover about 10,000 square degrees of sky (about half of a hemisphere) "*...using pairs of 15-sec exposures twice per night every three nights on average, with typical 5σ depth for point sources of r ~24.5 (AB)*" (Ref. 5) <http://www.lsst.org/lsst/overview/>. LSST will discover tens of thousands of KBOs and determine their orbits. LSST will not extend the size distribution of KBOs to objects smaller than ~50 km; however, a balloon-borne survey complements LSST in its ability to detect fainter objects and address the key question: at what size did the accretion of planetesimals stop?

3.2.1.7 How do the Giant Planets Serve as Laboratories to Understand the Earth, the Solar System, and Extrasolar Planetary Systems?

Synoptic observations of weather on giant planets: HST and large ground-based telescopes with adaptive optics (e.g., Keck, VLT, Subaru, Gemini) are periodically used to observe cloud systems of giant planets. HST and ground-based telescopes have spatial resolutions of about 50 mas in visible wavelengths and J-H-K-bands, respectively. Neptune's disk (with a diameter of about 2.3 arcsec, or 46 resolution elements) contains over 1600 resolution elements. All of these observatories are constrained, and in practice, only a few observations per year are made of each of the giant planets with this spatial resolution.

A balloon mission could enable synoptic studies of the weather and circulation on the giant planets. The spatial resolution of a 2 m balloon-borne telescope would equal that of HST, and a 100-day balloon mission would provide a contiguous data set that could advance models of circulation on the giant planets.

Transit spectroscopy of exoplanet atmospheres: During events when an exoplanet transits in front of its star or when it is occulted as it moves behind its star, photometry of the resulting light curve in several filters can reveal the presence of specific molecules in the exoplanet's atmosphere. A balloon-borne platform has three advantages over ground-based telescopes for this experiment: there is virtually no scintillation at balloon altitudes for targets that have elevations above a few degrees, infrared observations (particularly longward of 2.5 µm) benefit from cooler telescope optics and lower thermal photon counts, and the narrow PSF afforded by balloon-borne telescopes reduces the sky background noise relative to ground-based telescopes.

At present, there are only a handful of known exoplanet systems that could provide useful spectrophotometry during a transit. Similarly, only a few "hot Jupiters" generate a useful multi-filter light curve as they move behind their respective stars. Nevertheless, a balloon-borne telescope, designed to provide carefully calibrated photometry, would be well-suited for performing spectrophotometry of exoplanet transits and occultations, and investigating the compositions of exoplanet atmospheres.

3.2.1.8 What Solar System Bodies Endanger and What Mechanisms Shield the Earth's Biosphere?

Detection of faint moving objects at small solar elongations: There are two prevailing strategies for detecting NEOs: look for them in visible wavelengths (the strategy currently used by ground-based sky surveys) or conduct a survey at wavelengths near 14 μm, corresponding to the blackbody peaks of NEOs (the strategy of the Sentinel mission). As described in 3.2.1.6 and 3.2.1.7, balloon-borne telescopes have good sensitivity to faint point sources. In addition, daytime sky backgrounds are lower in the stratosphere than on the Earth in visible wavelengths: the modeled downwelling radiation decreases by about a factor of two (at a given wavelength) for every 5 km gain in altitude. While daytime stratospheric sky backgrounds are not zero, they are about 100x lower than ground-based backgrounds, which allows balloon-borne telescopes to perform daytime searches for moving objects that are about 10 magnitudes fainter than the detection limit from a similar-sized ground-based telescope (assuming a factor of 100 times less sky background and an additional factor of 100 times reduction in background counts from 10 times narrower PSFs on the balloon telescope). Balloon-borne telescopes would have a strong advantage in searching the daytime skies for objects like the Chelyabinsk bolide, which arrived from the sunward direction.

3.3 Decadal Survey Traceability

The planetary science balloon workshop produced mission concepts and highlighted the science potential of balloon-based observations. However, it was unclear if the concepts generated were all inclusive, and what the traceability was to the Planetary Decadal survey. To identify potential science gaps unaddressed by the various concepts, the study team systematically evaluated every science objective and "important question" identified in the "Vision and Voyages for Planetary Science in the Decade 2013–2022" decadal survey (Ref. 1). A science traceability matrix was developed for each topic area with the major goals, specific science objectives, and important questions identified. For each question, the measurements required to make scientific progress were identified. From the required measurements, the specific instrument requirement and platform requirements were derived including the spectral range of interest, aperture size, altitude, pointing stability, day vs. night observational constraints, and mission duration. Note that the actual science observations may not need 100 percent duty cycle. The matrix also recognizes that balloon observations are not the only asset to address decadal survey questions, but notes any unique advantages to the stratospheric platform. The results of the individual topic areas are provided in the following sections. Also, science questions with an 'a' superscript denote a potential science question addressable with short or recommended first flights, and 'b' denotes a potential to address the science question for the recommended long-duration flight system.

3.3.1 Primitive Bodies Focus

A balloon-based platform has potential to address 10 of the 33 decadal survey questions, more than 30 percent. Table 3.1 provides the linkage between the scientific goals and desired measurements including stratospheric-unique observational advantages. For example, two important questions regarding the objective "Study condensation, accretion, and other formative processes in the solar nebula" are: (1) How variable are comet compositions, and how heterogeneous are individual comets? (2) How do the compositions of Oort cloud comets differ from those derived from the Kuiper belt?

The question of comet compositions can benefit from spectroscopy in wavelengths that are normally obscured from ground-based sites. Spectroscopy around 305 to 310 nm is a UV window containing emission from OH radicals, the region near 2.7 to 3.0 μm contains water emission, and the 4.3 μm region is where CO_2 emits. Detection of these species can determine the H_2O/CO_2 ratio on a comet, which in turn constrains the heliocentric region in which the comet condensed in the early solar nebula. The 4.3 μm region is particularly opaque: even SOFIA will not see targets in this wavelength, but a telescope at 125,000 ft altitude has about 75 percent transmission through the 4.3 μm CO_2 band.

Measurements such as these can be made from balloons as seen with the recent BOPPS mission, flown on September 25, 2014, where Comet Jacque (C/2014 E2) was observed in filters at 2.7 and 4.3 μm by the infrared camera.

Examples of questions concerning the objective "Composition, Origin, and Primordial Distribution of Volatiles and Organic Matter in the Solar System" are: (1) How stable are organic molecules in different space environments? (2) What kinds of surface evolution, radiation chemistry, and surface-atmosphere interactions occur on distant icy primitive bodies?

The 3 to 5 μm window is a good spectral region for detecting organic molecules. There is a well-known C-H stretch near 3.3 μm, and several amino acid precursors (e.g., NH_3, HCN, methanol) have strong fundamental absorptions between 4 to 5 μm. These molecules also have absorption features between 1 to 2.5 μm, but those are generally overtone features that are 10 to 100 times weaker than the fundamental bands. That is unfortunate, because observations at 3 to 5 μm are an order of magnitude more difficult than ones at 1 to 2.5 μm: there is less reflected solar light at the longer wavelengths and the backgrounds are much higher. A balloon-borne infrared spectrograph will be much more sensitive than ground-based instrument for two reasons: both the sky background and the thermal flux from the cold optics are much lower from a stratospheric platform. For example, a 1-m telescope in the stratosphere will achieve better SNR than a 3 m ground-based telescope, assuming an infrared target at 4.8 µm and that the stratospheric optics are 235 K or lower, compared to 273 K for optics on the summit of Mauna Kea. If the balloon optics can be lowered to 180 K (not unreasonable with sunshields, earthshields and a thermal enclosure for the telescope), then the thermal flux from the telescope becomes a minor background source compared to the sky background at 4.8 µm.

Table 3.2 continues with the linkages from the desired measurements to the instruments and platform requirements. Key drivers within the primitive body mission concepts include the fact that all of them can be at least partially addressed with only a 1 m class telescope, and few require very fine pointing or long- duration missions. Also, the primitive bodies question #2 regarding distribution of asteroids, is the only decadal survey question requiring a wide field of view (WFOV). All of the non-survey missions require narrow FOV systems. For purposes of this chapter, pointing stability refers to the ability of the overall system to precisely locate and remain focused on a desired target. The detailed trades for telescope options relative to requirements are discussed further in Section 4.1.5.

TABLE 3.1.—LINKAGE OF SCIENCE GOALS TO DESIRED MEASUREMENTS FOR PRIMITIVE BODIES

No.	Goals	Objectives	Questions	Measurements	Stratospheric advantage
1[a]	Decipher the record of epochs and processes.	Study condensation, accretion, and other formative processes.	Did evaporation and condensation of solids from hot gas only occur locally?	Volatiles, D/H ratios, CO, methane, water, CO_2, OH.	CO_2 in coma and surface. 2.6 to 2.8 µm region unavailable from ground, still some extinction on SOFIA.
2[b]			What are the abundances and distributions of different classes of asteroids, comets, and KBOs?	Survey mission.	Large VNIR detector, good seeing, use two wavelengths, stable photometry.
3[a]			How do the compositions of Oort cloud comets and KBOs differ?	Comet volatiles, D/H ratios, CO, methane, water, CO_2, OH band.	Fundamental IR absorption bands of volatiles, ices, organics, amino acid precursors. However, SOFIA should be able to do this except CO_2 and access for enough SOFIA time.
4[a]		Determine effects and timing of evolution secondary processes.	How does spin-up, binary object interaction, and space weathering impact evolution?	NUV-Vis slope effects.	NUV-Vis multispectral, low-resolution spectroscopy. NUV atmospheric transmission. Main belt binaries resolved with 1m aperture.
5[a]	Understand the role of primitive bodies as building blocks for planets and life.	Determine the composition, origin, and primordial distribution of volatiles and organics.	What are the chemical routes leading to organic molecule complexity?	Spectroscopy of KBOs, asteroids, Trojans, irregular satellites.	Reduced atmospheric absorption from H_2O, CO_2, and CH_4 relative to ground and SOFIA.
6[b]			What is the proportion of surviving presolar organic material?	Presolar is IDP composition.	Platform for dust collection.
7[a]			What caused the depletion in volatile elements observed in asteroids and planets?	Measure/constrain OH on differentiated asteroids.	Reduced atmospheric absorption from H_2O, CO_2, and CH_4 relative to ground and SOFIA.
8[a]		Understand how and when planetesimals were assembled to form planets.	Are there chemical or isotopic gradients in the solar system?	Compositional information.	Reduced atmospheric absorption from H_2O, CO_2, and CH_4 relative to ground and SOFIA.
9[a]			How did the Earth get its water and other volatiles?	Modeling and remote sensing, organics and volatiles in small bodies.	High- and low-resolution spectroscopy. Reduced atmospheric absorption from H_2O, CO_2, and CH_4 relative to ground and SOFIA.
10[a]		Constrain the dynamics of SS evolution.	What are the sources of the unexplored asteroid groups?	Observations in spectral regions with diagnostic absorptions.	Reduced atmospheric absorption from H_2O, CO_2, and CH_4 relative to ground and SOFIA.

TABLE 3.2.—LINKAGE OF INSTRUMENT AND PLATFORM REQUIREMENTS TO PRIMITIVE BODY IMPORTANT QUESTIONS

No.	Questions	Wavelength, µm	Primary aperture size, m	Pointing stability, arcsec	Altitude, ft	Night required	Minimum duration, days
1[a]	Did evaporation and condensation of solids from hot gas only occur locally?	2.5 to 5	1	1	120,000	No	< 1
2[b]	What are the abundances and distributions of different classes of asteroids, comets, and KBOs?	0.4 to 1.0	1	1	120,000	Yes	< 7
3[a]	How do the compositions of Oort cloud comets and KBOs differ?	2.5 to 5	1	1	120,000	Yes	< 1
4[a]	How does spin-up, binary object interaction, and space weathering impact evolution?	0.3 to 0.75	1	0.05	120,000	Yes	< 1
5[a]	What are the chemical routes leading to organic molecule complexity?	2.5 to 5	1	1	120,000	No	< 1
6[b]	What is the proportion of surviving presolar organic material?	NA	NA	NA	120,000	NA	< 7
7[a]	What caused the depletion in volatile elements observed in asteroids and planets?	2.5 to 5	1	1	120,000	No	< 1
8[a]	Are there chemical or isotopic gradients in the solar system?	2.5 to 5	1	1	120,000	No	< 1
9[a]	How did the Earth get its water and other volatiles?	2.5 to 5	1	1	120,000	No	< 1
10[a]	What are the sources of the unexplored asteroid groups?	2.5 to 5	1	1	120,000	No	< 1

3.3.2 Inner Planets

A balloon-based science platform also has potential to at least partially address 10 out of 34 important questions for inner planet science. Inner planet objectives can be met with some of the smallest balloon systems with several questions addressable with primary apertures in the 0.5 m class, and lower allowable float altitudes. However, many of the questions do require sub-arcsecond pointing and mission durations of several days. The majority of inner planet missions can also collect daytime science. Unsurprising, the observations for inner planet missions may require the system to tolerate smaller solar elongation angles than typical observatory platforms. Table 3.3 and Table 3.4 provide the linkages between the science questions and desired measurements and then to the platform and instrument requirements, respectively.

3.3.3 Mars

Mars has been a focus of a large set of missions including orbiters, landers, and rovers. Due to the past missions, there are a limited number of science objectives that can be addressed by additional terrestrial observations. However, the ability to detect CO_2 and methane are still balloon-based advantages. Not only can balloon-based systems detect methane, otherwise blocked by telluric limitations, but the balloon-based system can make observations at all local Martian times of the day. If methane is present on Mars or a transient phenomenon, balloons are ideal for potential source identification and episodic exploration. Balloons can also observe the whole disk for long periods of time. Table 3.5 and Table 3.6 provide the linkages between the science questions and desired measurements and then to the platform and instrument requirements, respectively.

3.3.4 The Giant Planets

Balloon observations are able to make progress on seven of the 39 important questions among the giant planets. The giant planets category is the major driver for both large apertures and for very fine pointing; on the order of 0.01 arcsec. The giant planet missions drive the desire for very long duration (> 60 day) missions. Many of the other remaining science questions would require both impractical and prohibitively large aperture class systems. Due to the mass and complexity, apertures sized beyond 2.5 m were deemed beyond the scope of this study. Table 3.7 and Table 3.8 provide the linkages between the science questions and desired measurements and then to the platform and instrument requirements, respectively.

3.3.5 Satellites

The balloon borne platform is capable of making progress on 13 of the 75 important questions relative to the major satellites of the giant planets. Despite the distance and faintness of these objects, many of the questions can be addressed with moderate aperture systems and proven pointing stability. However, many of the missions require flights of several days, and nearly all of the satellite missions require nighttime observations. Table 3.9 and Table 3.10 provide the linkages between the science questions and desired measurements and then to the platform and instrument requirements, respectively.

TABLE 3.3.—LINKAGE OF SCIENCE GOALS TO DESIRED MEASUREMENTS FOR INNER PLANETS

No.	Goals	Objectives	Questions	Measurements	Stratospheric advantage
1[a]	Understand the origin and diversity of terrestrial planets.	Constrain the bulk composition of the terrestrial planets to understand formation and evolution.	What are the proportions and compositions of the major components of the inner planets?	Mercury surface composition. Silicate composition.	TIR Spectroscopy. Low background and good transmission. SOFIA could also do this with FORCAST if pointing allowed.
2[b]			What are the volatile budgets of the inner planets?	NUV–NIR atomic emission.	Temporal and spatial resolution variations of Mercury.
3[b]		Characterize planetary interiors.	What are the major heat-loss mechanisms and associated dynamics?	Venus thermal emission.	Thermal emissions in CO_2 windows in NIR.
4[b]		Characterize planetary surfaces.	What are the major surface features and modification processes?	Identify major surface features on Venus.	Thermal emissions in CO_2 windows in NIR.
5[b]			What are the distribution and timescale of volcanism?	Observe volcanism on Venus.	Thermal emissions in CO_2 windows in NIR.
6[a]	Understand how evolution of terrestrial planets enables and limits origin and evolution of life.	Understand composition and distribution of volatile chemicals.	How are volatiles distributed, transported, and sequestered in near-surfaces?	Evolution of H_2O and OH^-	Above telluric absorption, long temporal baseline. (SOFIA is marginal.)
7[a]			What are the chemical and isotopic compositions near the Moon's surface?	Surface composition/silicate composition	TIR spectroscopy. Better spectral resolution than SOFIA.
8[a]		Understand effects of internal processes on life and habitability.	What are the timescales of volcanism and tectonism?	Measure Venus thermal emission.	Thermal emissions in CO_2 windows in NIR.
9a[b]	Understand processes that control climate.	Determine how solar energy drives mechanisms of climate balance.	How do the global circulation patterns of Venus differ?	Observe cloud circulation. (day)	Excellent seeing and time available.
9[b]				Observe cloud circulation. (night)	Excellent seeing and time available.
10[a]			What processes control the chemistry of the Venus atmosphere?	Lightning observations.	Excellent seeing and time available.

TABLE 3.4.—LINKAGE OF INSTRUMENT AND PLATFORM REQUIREMENTS TO INNER PLANETS IMPORTANT QUESTIONS

No.	Questions	Wavelength, µm	Primary aperture size, m	Pointing stability, arcsec	Altitude, ft	Night required	Minimum duration, days
1[a]	What are the proportions and compositions of the major components of the inner planets?	>5	0.5	1	100,000	No	< 1
2[b]	What are the volatile budgets of the inner planets?	0.3 to 1	1	1	120,000	Yes	< 15
3[b]	What are the major heat-loss mechanisms and associated dynamics?	0.75 to 2.5	1	0.1	110,000	No	< 7
4[b]	What are the major surface features and modification processes?	0.75 to 2.5	1	0.1	110,000	No	< 7
5[b]	What are the distribution and timescale of volcanism?	0.75 to 2.5	1	0.1	110,000	No	< 7
6[a]	How are volatiles distributed, transported, and sequestered in near-surfaces?	2.5 to 5.0	0.5	1	100,000	No	< 1
7[a]	What are the chemical and isotopic compositions near the Moons' surface?	>5	0.5	1	100,000	No	< 1
8[a]	What are the timescales of volcanism and tectonism?	0.75 to 2.5	1	0.1	110,000	No	< 1
9[a]	How do the global circulation patterns of Venus differ?	0.3 to 2.5	1	0.05	110,000	No	< 30
9[b]		1.0 to 5.0	2	0.1	110,000	Yes	< 30
10[a]	What processes control the chemistry of the Venus atmosphere?	0.3 to 1.0	0.5	1	110,000	Yes	< 1

TABLE 3.5.—LINKAGE OF SCIENCE GOALS TO DESIRED MEASUREMENTS FOR MARS

No.	Goals	Objectives	Questions	Measurements	Stratospheric advantage
1[b]	Determine if life ever arose on Mars.	Assess whether life is or was present on Mars in its geochemical context.	Do habitable environments or life exist today as evidenced by biosignatures, atmospheric gases, or other indicators of extent metabolism?	Methane detection.	Episodic release exploration, 10-hr intervals can cover all local Martian times of day.
2[b]	Understand the processes and history of climate.	Characterize Mars' atmosphere, present climate, and climate processes.	What are the processes coupling the CO_2, dust, and water cycles?	SWIR imaging. Repeat every few days.	Balloons observing over 10-hr intervals can cover all local Martian times of day.
3[b]			Do unexpected short-lived trace gases indicate a subsurface activity or even the presence of life?	Methane detection.	Episodic release exploration. Reduced atmospheric absorption from H_2O, CO_2, and CH_4 relative to ground or aircraft: track methane line.
4[b]			How do the climate and especially the water cycle vary with orbital and obliquity variations?	SWIR imaging. Global imaging every superior conjunction.	Episodic release exploration. Balloons can cover all local Martian times of day. Reduced atmospheric absorption from H_2O, CO_2, and CH_4 relative to ground and SOFIA.

TABLE 3.6.—LINKAGE OF INSTRUMENT AND PLATFORM REQUIREMENTS TO MARS IMPORTANT QUESTIONS

No.	Questions	Wavelength, µm	Primary aperture size, m	Pointing stability, arcsec	Altitude, ft	Night required	Minimum duration, days
1[b]	Do habitable environments or life exist today as evidenced by biosignatures, atmospheric gases, or other indicators of extent metabolism?	1.0–5.0	1	1	120,000	Yes	< 7
2[b]	What are the processes coupling the CO_2, dust, and water cycles?	1.0–2.5	2	0.1	120,000	Yes	< 7
3[b]	Do unexpected short-lived trace gases indicate a subsurface activity or even the present of life?	1.0–5.0	1	1	120,000	Yes	< 7
4[b]	How do the climate and especially the water cycle vary with orbital and obliquity variations?	1.0–5.0	1	1	120,000	Yes	< 7

TABLE 3.7.—LINKAGE OF SCIENCE GOALS TO DESIRED MEASUREMENTS FOR THE GIANT PLANETS

No.	Goals	Objectives	Questions	Measurements	Stratospheric advantage
1[b]	Explore processes and properties of giant planets as ground truth for exoplanets.	Investigate the chemistry of giant planet atmospheres.	What is the atmospheric composition of the ice giants?	Thermal imaging (but don't get the poles) and SWIR-MIR imaging.	Low background. Repeated observations. Good seeing.
2[b]			What are the current pressure/temperature profiles for these planets?	Vis- IR imaging spectroscopy. Measurement over full rotation of the planet.	Atm. transmission, low background. Continuous viewing.
3[b]		Analyze the properties and processes in planetary magnetospheres.	What is the detailed plasma composition in any of these systems?	Multispectral NUV- Vis imaging.	Seeing and atmospheric transmission.
4[b]		Use ring systems as laboratories for planetary formation processes.	What can differences among the ring systems teach us?	Vis imaging, diffraction limited.	Diffraction limited seeing.
5[b]			Can the structures forms of the ring systems be maintained for billions of years? Are dark surfaces space weathering?	NUV-Vis observations of rings over wide range of phase angles to obtain BDRF.	Diffraction limited seeing.
6[b]			What drives orbital evolution of embedded moonlets and how do they interact?	Hi-res imaging over a season to see ring dynamics.	Diffraction limited seeing.
7[b]	Establish the relevance of the giant planets as laboratories for properties and processes on Earth.	Investigate atmospheric dynamical processes in the giant planet laboratory.	What processes drive the visible atmospheric flow and how do they couple to the interior structure and deep circulation?	Imaging over time, mapping waves and dynamics.	Diffraction limited seeing, low background, good transmission.

TABLE 3.8.—LINKAGE OF INSTRUMENT AND PLATFORM REQUIREMENTS TO GIANT PLANETS IMPORTANT QUESTIONS

No.	Questions	Wavelength, μm	Primary aperture size, m	Pointing stability, arcsec	Altitude, ft	Night required	Minimum duration, days
1[b]	What is the atmospheric composition of the ice giants?	0.4 to 2.5	> 2.5	0.1	120,000	Yes	< 1
2[b]	What are the current pressure/temperature profiles for these planets?	1.0 to 100	2	0.1	100,000	No	< 1
3[b]	What is the detailed plasma composition in any of these systems?	0.3 to 0.75	> 2.5	0.01	120,000	No	< 15
4[b]	What can differences among the ring systems teach us?	0.4 to 0.75	1.5	0.01	100,000	No	> 60
5[b]	Can the structure forms of the ring systems be maintained for billions of years? Are dark surfaces space weathering?	0.3 to 0.75	1	0.01	100,000	No	> 60
6[b]	What drives orbital evolution of embedded moonlets and how do they interact?	0.4 to 0.75	1.5	0.01	100,000	No	> 60
7[b]	What processes drive the visible atmospheric flow and how do they couple to the interior structure and deep circulation?	0.75 to 5.0	>2.5	0.01	100,000	No	< 15

TABLE 3.9.—LINKAGE OF SCIENCE GOALS TO DESIRED MEASUREMENTS FOR SATELLITES

No.	Goals	Objectives	Questions	Measurements	Stratospheric advantage
1[b]	How did the satellites form and evolve?	What were the conditions during satellite formation?	What features of Triton are indicative of origin?	Composition.	Telluric bands. Background limited.
2[b]		What determines the abundance and composition of volatiles?	In what ways to the volatile constituents differ between Callisto and Ganymede?	Composition.	Telluric bands. Background limited.
3[a]			What does the Enceladus plume tell us about its volatile inventory?	Periodic measurements of the OH emission. Spatial distribution of emission around Saturn.	Good atmospheric transmission. Long observing time for single observation.
4[b]			How, and to what extent, have volatiles been lost from Io?	Global inventory of volatile molecules and Io exosphere.	Atmospheric transmission and seeing.
5[a]			What does the volatile inventory of Titan tell us about its history? How is methane resupplied?	Isotopic methane.	Reduced atmospheric absorption from H_2O, CO_2, and CH_4 relative to ground and SOFIA.
6[b]		How are the thermal and orbital evolution and internal structure related?	What is the magnitude and spatial distribution of Io's total heat flow?	Global thermal mapping and secular variations.	Reduced atmospheric absorption from H_2O, CO_2, and CH_4 relative to ground and SOFIA.
7[a]			What do Uranian moons tell us about evolution of icy satellites? What drove Miranda and Ariel endogenic activity?	Composition and surface texture, including grain size.	Reduced atmospheric absorption from H_2O, CO_2, and CH_4 relative to ground and SOFIA.
8[b]	What processes control the present-day behavior of these bodies?	What processes control the chemistry and dynamics of satellite atmospheres?	What is the variability of Io's atmosphere, how is it controlled, and how is it affected by volcanism?	NUV-Vis atomic emission spectroscopy.	Atmospheric transmission.
9[a]			Do the large organic molecules detected by Cassini in Titan's haze contain amino acids, nucleotides, and other pre-biotic molecules?	NIR-MIR spectroscopy.	Atmospheric transmission.
10[b]			What processes control the exchange of methane between Titan's surface and atmosphere?	VNIR multispectral imaging.	Diffraction limited seeing.
11[b]			How do Titan's clouds originate and evolve?	Broadband visible imaging.	Diffraction limited seeing.
12[b]		How do satellites influence their own magnetospheres and parent bodies?	What fraction of materials in Jupiter's magnetosphere originates from Europa or others?	H3+ aurora and ions.	Diffraction limited seeing and atmospheric transmission.
13[a]	What are the processes that result in habitable environments?	What are the sources, sinks, and evolution of organic material?	Are organics on the surface of Europa and what is their provenance?	Trailing hemisphere of Europa (little ice).	Reduced atmospheric absorption from H_2O, CO_2, and CH_4 relative to ground and SOFIA.

TABLE 3.10.—LINKAGE OF INSTRUMENT AND PLATFORM REQUIREMENTS TO SATELLITE IMPORTANT QUESTIONS

No.	Questions	Wavelength, µm	Primary aperture size, m	Pointing stability, arcsec	Altitude, ft	Night required	Minimum duration, days
1[b]	What features of Triton are indicative of origin?	2.5 to 5.0	1	1	120,000	Yes	< 7
2[b]	In what ways to the volatile constituents differ between Callisto and Ganymede?	2.5 to 5.0	1	1	120,000	Yes	< 15
3[a]	What does the Enceladus plume tell us about its volatile inventory?	0.3 to 0.4	1	0.1	120,000	Yes	< 1
4[b]	How, and to what extent, have volatiles been lost from Io?	0.3 to 5.0	1	1	120,000	Yes	< 7
5[a]	What does the volatile inventory of Titan tell us about its history? How is methane resupplied?	1.0 to 2.5	1	1	120,000	Yes	< 1
6[b]	What is the magnitude and spatial distribution of Ios total heat flow?	1.0 to 100	1	1	120,000	Yes	< 7
7[a]	What do Uranian moons tell us about evolution of icy satellites? What drove Miranda and Ariel endogenic activity?	1.0 to 5.0	1	1	120,000	Yes	< 1
8[b]	What is the variability of Ios atmosphere, how is it controlled, and how is it affected by volcanism?	0.3 to 1.0	2	1	120,000	Yes	< 7
9[a]	Do the large organic molecules detected by Cassini in Titans haze contain amino acids, nucleotides, and other pre-biotic molecules?	1.0 to 100	1	1	100,000	No	< 1
10[b]	What processes control the exchange of methane between Titan's surface and atmosphere?	0.4 to 1.0	2	0.01	120,000	Yes	< 15
11[b]	How do Titan's clouds originate and evolve?	0.4 to 0.75	2	0.01	100,000	Yes	< 30
12[b]	What fraction of materials in Jupiter's magnetosphere originates from Europa or others?	0.3 to 1.0	2	1	120,000	Yes	< 1
13[a]	Are organics on the surface of Europa and what is their provenance?	2.5 to 5.0	1	1	120,000	No	< 1

3.4 Science Drivers and Architectures

The overall science traceability results show that a balloon-based observatory can make progress at addressing 44 unique "important questions." All except the "survey" primitive body question optimize for a narrow field-of-view telescope. For system capabilities, there are dependencies on primary aperture size, pointing capability, mission durations, available wavelengths, etc.

As stated earlier, major advantages of balloon-based platforms are imaging observations in the ultraviolet and visible bands between 300 nm and 1 µm and IR spectroscopy between 2.5 to 5 µm. Though a capability of ground-based systems, IR spectroscopy between 1.0 to 2.5 µm is also easily accommodated and could be included in a baseline science instrument package. Thermal IR is also of interest, but adds to the overall system complexity for only a six percent increase in decadal science capture. The science capture for various spectral ranges is shown in Figure 3.2. The trades for the baseline science instruments are discussed in greater detail in Section 4.1. However, the recommendation is to pursue science objectives in the near-ultraviolet (NUV) through MIR for the baseline planetary science platform.

The aperture class and pointing stability are key drivers for potential science capture within the 44 addressable questions identified in Section 3.3. The aperture class is the single largest cost and mass driver of the system. As will be shown in the cost analysis section, the larger primary mirror options can exceed 10 percent of the total mission cost. For pointing options, multiple paths exist that have demonstrated arcsecond-class pointing. The Wallops Arcsecond Pointer (WASP) has demonstrated sub-arcsecond pointing as has the BOPPS and BRRISON missions during ground hang tests and flight, and the use of a fine-steering mirror has shown pointing capability well below 0.1 arcsec with anticipated performance below 0.01 arcsec. The science capture dependence on aperture class and pointing capability is illustrated in Figure 3.3 and Figure 3.4.

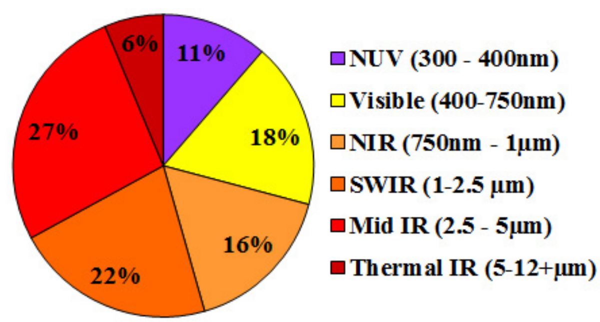


Figure 3.2.—Science capture by wavelength.

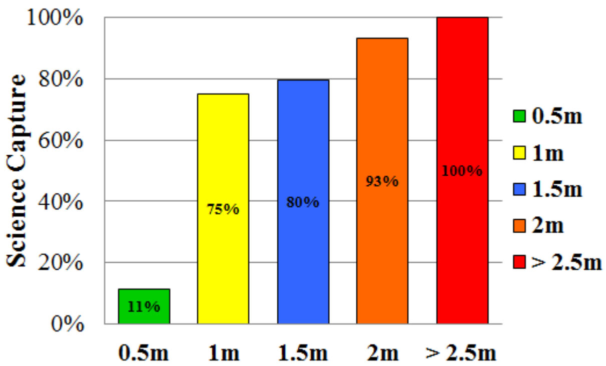


Figure 3.3.—Science capture by aperture class

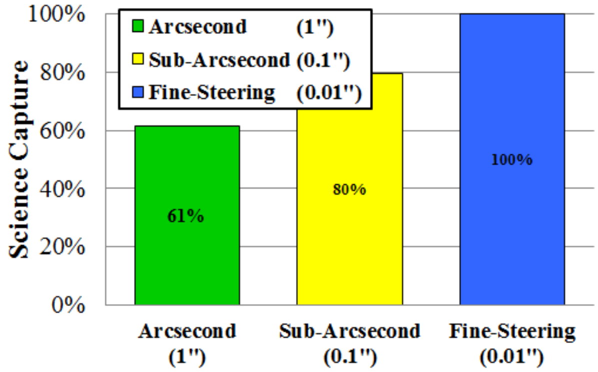


Figure 3.4.—Science capture by pointing capability.

Based on the decadal survey traceability to mission requirements, there are a finite set of gondola capability architectures. Three of the "important questions" required aperture sizes greater than 2.5 m, and were considered impractical for a first generation of planetary gondolas due to high complexity, and for ultra-long duration balloons, too massive. Because a 1 m class and 1.5 m class telescopes offer similar science capture and the 1.5 m will be heavier and cost more, it will not be considered further in this study. Six architectures were evaluated to assess science return for various implementation options of the pointing options at 0.5, 1, and 2 m class telescopes. Figure 3.5 to Figure 3.10 identify the percentage science questions that can be addressed by the asset with respect to the 44 "important questions" previously identified.

3.4.1 Architecture (DRM) 1 (0.5 m Class, ~1 arcsec Pointing)

A few planetary balloon missions can be accomplished with a small 0.5 m diameter primary and a rather coarse pointing stability of better than 1 arcsec. Both NUV-NIR multispectral imaging and MIR hyperspectral imaging are valuable. While the relatively coarse pointing mitigates the value of high spatial resolution imaging, compositional measurements can still be

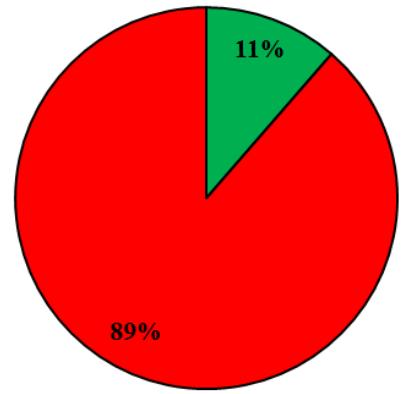


Figure 3.5.—Science capture for architecture 1.

achieved, and the longer duration enables the measurement of more objects and the study of secular processes.

Measurements, to observe and characterize the lightening on Venus, can be made with NUV-NIR multispectral imaging (which requires nighttime observations). With MIR hyperspectral imaging (which can be done day or night), water cycle on the Moon and Mercury surface composition measurements can be made. The NUV-VNIR instrument would likely employ ~24 filters, each from 10 to 100 nm wide. The hyperspectral MIR imager would ideally need to provide ~10 nm spectral resolution from 2.5 to 5 µm.

The measurement of Venus lightening in the visible will improve knowledge of its provenance and global atmospheric processes. Understanding the lunar water cycle, including the roles of H_2O versus OH, will enable one to understand if solar wind can form water and the fate of this or pre-existing water on the Moon. The IR mapping will provide approximately 2-arcsec images in the 3-µm region, regions where measurements have not yet been taken. For Figure 3.5 to Figure 3.10 in Sections 3.4.1 through 3.4.6, the green color indicates the amount of science, in percent, that the respective DRM can achieve compared to the 44 science questions that a balloon based observatory is expected to address in total.

3.4.2 DRM 2 (1 m Class, ~1 arcsec Pointing)

With a 1 m diameter primary and a rather coarse pointing stability of better than 1 arcsec that can be achieved through the control of the gondola and telescope without the use of a fine guidance mirror or camera, the number of planetary balloon missions that can be accomplished jumps to over 50 percent. With ultra-long duration missions, multiple science questions can be worked on a single flight. Both NUV-NIR multispectral imaging and MIR hyperspectral imaging are enabled with this larger aperture. While the relatively coarse pointing inhibits the acquisition of high spatial resolution imaging, compositional measurements can be achieved. Longer duration flights

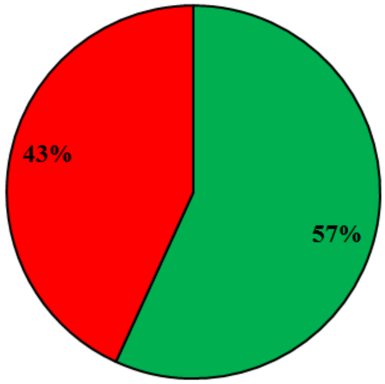


Figure 3.6.—Science capture for architecture 2.

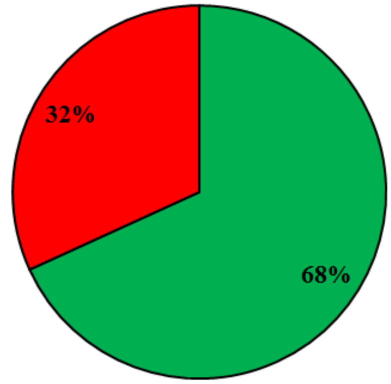


Figure 3.7.—Science capture for architecture 3.

enable the measurement of more objects and the study of secular processes, and the ~1 arcsec pointing is well matched to the ~1 arcsec spatial resolution (in the IR) of a 1 m diameter mirror. This combination provides the greatest signal to noise possible without progressing to the use of a fine-steering mirror (both in the visible and in the IR). A fine-steering system would be needed to take full advantage of a larger-diameter telescope in the visible. As a result, objects several magnitudes dimmer can be observed compared to a 0.5 m telescope.

With NUV-NIR multispectral imaging (which requires nighttime observations) the following additional measurements can be made with respect to DRM 1: Mercury exosphere composition (NUV-NIR), which would be enabled by the greater sensitivity provided by the larger aperture. Compositional measurements are enabled in the IR to include: volatile and organic compositional measurements of small bodies from asteroids to Kuiper Belt Objects (KBOs), methane on Mars, organics on icy satellites (such as Europa, Triton, and Ganymede), and Io volcanism detection. The NUV-VNIR instrument would likely employ ~24 filters, each from 10 nm to 100 nm wide. The hyperspectral MIR imager would ideally need to provide ~10 nm spectral resolution from 2.5 to 5 µm. It is the compositional measurements in the IR that are enabled by the larger aperture even with coarse pointing. Io volcanism would be a new capability to obtain a global heat flow estimate for understanding tidal heating processes much better. The organic and volatile compositional measurements of small bodies would be new measurements to help our understanding of small body processes to include differentiation and hydration, test the Nice model for planetary (and small-body) migration through the solar system, better understand the relationships between taxonomic classes, and understand the extent of prebiotic material delivery to the proto-Earth. Organic compositional measurements of icy satellites will inform on the processes responsible for their occurrence.

3.4.3 DRM 3 (1 m Class, ~0.1 arcsec Pointing)

With a moderate 1 m diameter primary and improved pointing of 0.1 arcsec that can be achieved with a fine-steering mirror, the performance of the IR observations are improved for unresolved targets by decreasing the background signal, and the number of NUV-Vis measurements are increased. Both NUV-NIR multispectral imaging and MIR hyperspectral imaging are valuable. A pointing capability of 0.1 arcsec enables imaging at a similar level, which is consistent with the diffraction limit of a 1 m telescope in the near UV and Vis, assuming the optical design is sufficiently optimized to achieve a high Strehl ratio. Thus, many NUV-NIR imaging missions are enabled with this architecture.

With NIR multispectral imaging, imaging through the "spectral windows" to the surface of Venus to measure the thermal emission is possible. Also enabled are NUV measurements of OH emission from distant or small icy objects such as from the plumes of Enceladus. However, if 0.1 arcsec stability is achieved in the IR, the signal to noise of measurements of subpixel objects would be improved at shorter wavelengths where the diffraction limit of the telescope can take advantage of tighter pointing. The instrument characteristics would not change and the same instruments can be used for DRM 2 or DRM 3. The NUV-VNIR instrument would likely employ ~24 filters, each from 10 to 100 nm wide. The hyperspectral MIR imager would ideally need to provide ~10 nm spectral resolution from 2.5 to 5 µm.

The improved pointing stability would thus enable many imaging and compositional measurements for the NUV-NIR and would improve several IR measurements over DRM 2.

3.4.4 DRM 4 (1 m Class, ~0.01 arcsec Pointing)

With a modest 1 m diameter primary and a precision pointing stability of 0.01 arcsec, a larger number of NUV-NIR missions can be improved. A total of ~20 percent of the planetary balloon

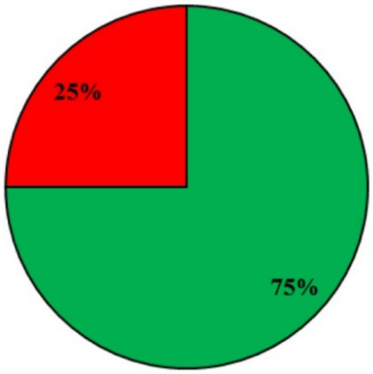


Figure 3.8.—Science capture for architecture 4.

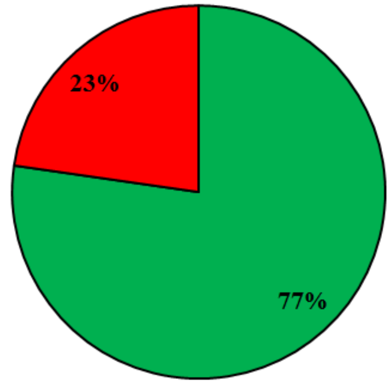


Figure 3.9.—Science capture for architecture 5

missions can be addressed with short-duration missions; with ultra-long duration missions, the number is closer to 75 percent of the planetary balloon missions, assuming both NUV-NIR multispectral imaging and MIR hyperspectral imaging are capable of being conducted (i.e., mid-latitude launches). The pointing stability is advantageous to the NUV-NIR as it enables crisp diffraction-limited imaging at these wavelengths for a 1 m aperture. However, the greater precision pointing stability does not significantly increase the capability of the IR instrument compared to 0.1 arcsec pointing stability. As always, a longer duration flight enables the measurement of more objects and the study of secular processes.

With NUV-NIR multispectral imaging (which requires nighttime observations), the following measurements can be made: ice giant rings, binary asteroid observations (investigating spin-up effects on the VNIR color), and global atmospheric circulation on Venus. In the MIR, the SNR would be improved allowing observations of dimmer targets. The NUV-VNIR instrument would likely employ ~24 filters each from 10 to 100 nm wide. The hyperspectral MIR imager would ideally need to provide ~10 nm spectral resolution from 2.5 to 5 µm.

The measurement of Venus clouds will improve understanding of its global circulation and global atmospheric processes. The ring studies would include investigating possible secular variations as well as characterizing the spectral nature of the rings (by separating signal from scattered light from the planet). Compositional measurements benefit from large aperture for obtaining signal and fine pointing for small unresolved bodies to reduce the background signal by using as small a FOV as possible.

3.4.5 DRM 5 (2 m Class, ~0.1 arcsec Pointing)

With a 2 m diameter primary, a balloon mission would approach the same collecting area and resolving power of the airborne platform SOFIA. Adding precision pointing stability of 0.1 arcsec, the ability to obtain high-resolution images exceeds that of SOFIA, but not significantly better than Architecture #4 with a 1 m aperture and 0.01 arcsec pointing. The science drivers benefit more from the order of magnitude improvement in pointing relative to the larger aperture. Still, the larger aperture is quite enhancing for science achievable with 0.1 arcsec pointing. The larger primary, yet degraded pointing performance, mostly helps missions that observe dim objects that do not require imaging (therefore compositional measurements) of small objects. It also helps imaging at longer wavelengths that remain diffraction limited and are not pointing limited. As always, a longer duration mission enables the measurement of more objects and the study of secular processes.

Seven more mission concepts become possible with this capability, including those concepts that require only 1 arcsec pointing, but still need the larger 2 m diameter aperture to obtain sufficient SNR. With NUV-NIR multispectral imaging (which requires nighttime observations), Io's exosphere measurement is enabled. The NUV-VNIR instrument would likely employ ~24 filters, each from 10 nm to 100 nm wide. The hyperspectral MIR imager would ideally need to provide ~10 nm spectral resolution from 2.5 to 5 µm. Measurements enabled over this range are: MIR thermal imaging of gas giants' atmospheres and aurorae, of Venus's atmosphere, and Mars' CO_2 and dust cycle.

The measurement of Io's exosphere enables us to better understand the bulk composition of that moon. This includes the process of tidal heating and the composition of the escaping ions that will affect the compositions of the icy Galilean satellites. The MIR thermal imaging of the atmospheres of Venus and the gas giants allows us to better understand the global circulation on those bodies and better constrain the energy balance. Mars' volatile and methane measurements can improve the upper limits on atmospheric abundances. As always, compositional measurements benefit from large aperture for obtaining signal and fine pointing for small unresolved bodies to reduce the background signal by using as small FOV as possible.

3.4.6 DRM 6 (2 m Class, ~0.01 arcsec Pointing)

This is the most aggressive of the gondola architectures considered, but represents only an incremental advance over existing flight technology. The combination of a 2 m diameter primary and precision pointing stability of 0.01 arcsec enables both high SNR measurements of dim and distant objects as well as hyperfine imaging of resolved bodies throughout the solar system. The high-resolution images exceed that of SOFIA by a factor of 60x, and is twice that of 1 m aperture with 0.01 arcsec pointing. It also helps imaging at longer wavelengths that remain diffraction limited and not pointing limited. A longer duration mission enables the measurement of more objects and the study of secular processes.

All previous measurements are improved because of the larger aperture enabling the collection of additional signal, and because of the finer pointing that ensures that the signal remains within a single pixel and is not distributed over a larger box (2x2, for instance). The diffraction limit of < 0.1 arcsec in the visible is fully realized with this pointing capability as well. More mission concepts become possible with this capability, including those concepts that require only 1 arcsec pointing, but still need the larger 2 m diameter aperture to obtain sufficient SNR. With NUV-NIR multispectral imaging (which requires nighttime observations), the following measurement is enabled: Io's exosphere. Measurements in the MIR enabled over this range are: MIR thermal imaging of gas giants' atmospheres and aurorae, of Venus's atmosphere, and Mars' CO_2 and dust cycle.

The combination of large aperture and fine pointing enables scientifically valuable high resolution VNIR imaging of the gas giants and Venus's atmosphere. The cloud and dust imaging campaigns require both fine pointing stability and long mission durations to map, with as high a spatial resolution as possible, the origin, evolution, and dissipation of these features. As always, compositional measurements benefit from large aperture for obtaining signal and fine pointing for small unresolved bodies to reduce the background signal by using as small FOV as possible that matches both the spatial resolution of the telescope and the pointing stability of the system.

In order to capture the remaining science objectives possible through a balloon asset, there are two additional augmentations. First, the instrument must see further in the IR. The longer wavelengths provide critical science, but create significant system level challenges for dichroic materials or optical path design in addition to challenging thermal design requirements. Last, a larger aperture is required especially for several of the outer planet science objectives. The cost and complexity to capture the remaining science is high relative to the baseline system.

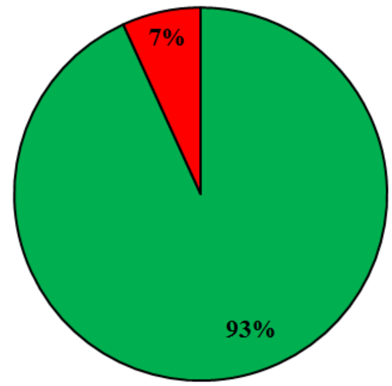


Figure 3.10.—Science Capture for architecture 6.

3.5 Comparison with other Assets

The benefit of balloon-based science must be compared to alternative and existing asset capabilities. NASA already has access to world class facilities for planetary science observations. Existing assets range from very large aperture ground-based options with adaptive optics, atmospheric observations with SOFIA, and space-based science through the HST. Alternatives have significant science capabilities but 0can be complemented by a balloon-based asset, as illustrated in Table 3.11 and described below. Table 3.11 is a qualitative and relative comparison of some figures of merit among existing observatories and the balloon borne platforms assessed in this study. A green color field indicates strongest relative performance of that observatory system for that figure of merit. Red indicates the weakest relative performance of the respective observatory for planetary science related purposes. The rankings are based on a planetary science perspective, and are subjective in nature. Despite the subjective nature of Table 3.11, it does offer some insight into expected relative performance of the observatory options.

Of current NASA capabilities, only balloons and SOFIA can truly conduct observations in the "water bands." Only balloons and HST have the capability of imaging visible targets at the 0.05 arcsec level. Only balloons can conduct daytime MIR observations. Only balloons can measure CO_2, and have 10x lower downwelling radiance than SOFIA and near 100 percent transmission at other MIR wavelengths. Balloons also have no measureable wavefront errors at 120,000 ft, and could perform diffraction-limited visible imaging with an aperture less than 2 m. The cost and duty cycle is also a critical factor. Balloon observations (assembly and flight) should have comparable costs to Keck, and offer much lower cost observations than that from SOFIA and the HST. Table 3.11 in Section 3.5.4 offer rough cost comparisons among the comparable assets.

TABLE 3.11.—COMPARISON OF BALLOON BASED OBSERVATIONS TO ALTERNATIVE ASSETS.

	SOFIA	HST	Ground	Balloon
Time allocation	Red	Red	Green	Green
Above telluric absorption and background	Yellow	Green	Red	Green
Spatial resolution/pointing	Yellow	Green	Yellow	Green
Observing efficiency	Yellow	Yellow	Yellow	Green
Cost per observation campaign	Yellow	Red	Green	Green
Aperture	Yellow	Yellow	Green	Yellow

3.5.1 Keck

Keck is representative of ground-based observation capabilities with two 10 m class telescopes. Instruments currently available with Keck I or II include the High Resolution Echelle Spectrometer (HIRES) capable of operating between 300 nm and 1 μm; the Low Resolution Imaging Spectrometer (LRIS) operating between 300 nm and 1 μm; the OSIRIS lenslet array instrument to approach the diffraction limit of the 10 m telescope; MOSFIRE for faint object imaging and near IR spectroscopic capabilities over the atmospheric bands Y (0.97 to 1.12 μm), J (1.15 to 1.35 μm), H (1.46 to 1.81 μm), or K (1.93 to 2.45 μm); the Deep Imaging Multi-Object Spectrograph (DEIMOS) visible-wavelength, faint-object, multi-slit imaging spectrograph. The annual cost for Keck is approximately $30M and a nightly cost of approximately $55K ($5.4K cost for 1 hr) for one of the telescopes (Ref. 8). A balloon based observatory and the Keck observatories (Figure 3.11) can effectively complement each other in several ways. For example, they can make simultaneous measurements of the same target, and/or by taking measurements with complementing instruments to broaden the science return. The varying viewing locations and times may also contribute to synergistic observations. The recent concurrent observations of Oort cloud comets by BOPPS and ground based assets are an example of the coordinated observations possible.

3.5.2 Stratospheric Observatory for Infrared Astronomy (SOFIA)

SOFIA (Figure 3.12) is a Boeing 747 outfitted with a 2.5 m telescope that flies above nearly all of the telluric water vapor. SOFIA has improved transmission over ground-based alternatives, has relatively easy access, and allows for rapid instrument upgrades. However, the SOFIA has a limited observing efficiency per night with a duty cycle goal to fly 3 to 4 nights per week. SOFIA is projected to have a lifetime cost of $3.75B over 2014–2034 for 16,000 hr of observations. The estimated cost of SOFIA is $106K per hour (Ref. 6). SOFIA suffers from more than 20 times more atmosphere overhead than a balloon at 120,000 ft, and the image-seeing blur size from SOFIA is 3 arcsec or larger.

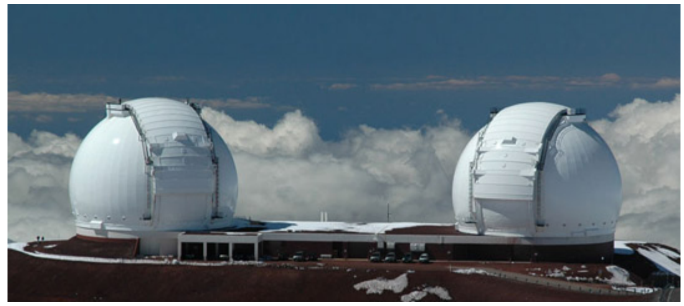


Figure 3.11.—Keck observatories.

Figure 3.12.—SOFIA.

3.5.3 Hubble Space Telescope (HST)

HST is one of the most capable observatories available to date, and has contributed tremendously to several science disciplines. Actual observations by HST's 2.4 m telescope are void of atmospheric limitations, and offer a very stable platform. While it required a large upfront investment, the science return has been immense. HST offers limited opportunities for technology improvements, and therefore, balloons may offer a supporting function where gaps in observing windows can be filled with complementing instruments. Balloon-based observations may offer independent measurements to support HST observations. HST has an estimated cost of $11.2 K per hour of observation time.[2] It has very limited access for planetary science observations, another area where balloon based observations can complement HST capability. A single 100-day balloon mission could provide 1,000 hr of dark time, more than ten times the typical annual solar system allotment on HST. In addition to more access for the planetary community, another area where balloons offer an advantage is the ability to make extended or frequent and repeated observations of planetary targets to do temporal or dynamics oriented science.

3.5.4 Cost Comparison

An attempt is made to offer a cost comparison between a dedicated balloon platform such as DRM 3 and other assets that may have similar science objectives. The data is presented in Table 3.12. An apples–to–apples cost comparison is very difficult because objectives, expectations, and stakeholders vary.

TABLE 3.12.—COST OF MISSION

Cost benefit summary per asset						
Mission/Asset	Lifetime cost (US$ billion) (assuming 5 more years)	Sustaining Budget per year—2013 ($M)	Hours of observation per year (average)	Observation costs per hour ($K) calculated based on lifecycle costs (assessed)	Observations cost per hour ($K) based on annual operating cost	Cost references
Hubble Space Telescope	14.1	98.3	8760 (total but much smaller fraction allocated for planetary observations)	1,610	11.2	6 and 7
Keck	13	30.8	574 nights 10 h/night = 5740 h	2,265 (assessed cost is 53.7/night 5.4/h)	5.4	8
SOFIA	3.75[2]	85.5	800 (total but smaller fraction allocated for planetary observations)	4,688	106	2 and 9
IRTF	N/A	5	Assume 3000 for typical year	N/A	20/night 2/h	Operating budget is from 2014 presentation to MOWG
Dedicated Balloon Platform Estimate	~0.045	[a]3 to 5	[b]800	[a]56/h	5	

[a] Depends on launch location. Launch cost from Fort Sumner is ~$0.5M while Antarctica would be ~$2M

[b] Annual observation time assumes 100 day biannual flights or average of 1200 hr/yr. With 2/3 duty cycle = 800 hr/yr

Life cycle costs est. at $25M development + ($4M*5 flights) = $45M

Other comparison issues are: timing (such as lifecycle and age), and what modifications or upgrades it may have received. Published costs aren't always easily interpreted, and in some cases it is unclear if all costs are available. In addition, there is the aspect of what costs to actually compare, life cycle costs verses annual operating costs. Operating costs tend to vary based on several factors some of which are not easily predicted. All these points are caveats that the data presented should not be assessed with a rigid quantitative eye. The sources for cost data are presented, and readers are encouraged to look up references to understand context and assumptions. The main purpose is to show relative costs, in two general approaches, a life cycle based approach and an ongoing operating cost based approach, whichever is most appropriate to the respective readers' interest.

4.0 System Requirements and Implementation Trades

The following sections describe requirements, trades, and implementation methods of balloon-based planetary science campaigns with a focus on a low risk and near-term implementation. An option was evaluated for a near-term, low-risk, and high-science-value mission to demonstrate balloon science potential while reducing risk for future, more aggressive science campaigns. The detailed mission description for a short-duration mission is provided in Section 6.0. A detailed mission description for a long-duration flight option is provided in Section 7.0. Higher science implementation through subsystem upgrades is discussed in Section 8.0, System Evolution.

4.1 Performance Requirements

The requirements are relatively soft for the payload system design, as the achievable science may be gracefully degraded, but still remain valuable if the requirements cannot be fully met. A 1 m aperture is sufficient for most of the science questions derived from the Planetary Science Decadal Survey. In visible wavelengths, the diffraction limit of a 1 m aperture is ~0.12 arcsec, better than the typical performance of any other telescope except the Hubble Space Telescope (HST). Two types of instruments that are recommended play to the viewing vantage strengths of a stratospheric telescope, visible wavelength imager and a 2.5 to 5 µm spectrograph. These instruments could be realized on a single telescope that is equipped with a dual-channel optical bench. The visible channel requires a 40 m focal length to achieve a plate scale of 0.075 arcsec per pixel (for 15 µm pixels). This plate scale oversamples the 0.12 arcsec diffraction limit point spread function (PSF). The IR channel focal length only needs to be around 10 m because of the broader PSF of 2.5 to 5 µm.

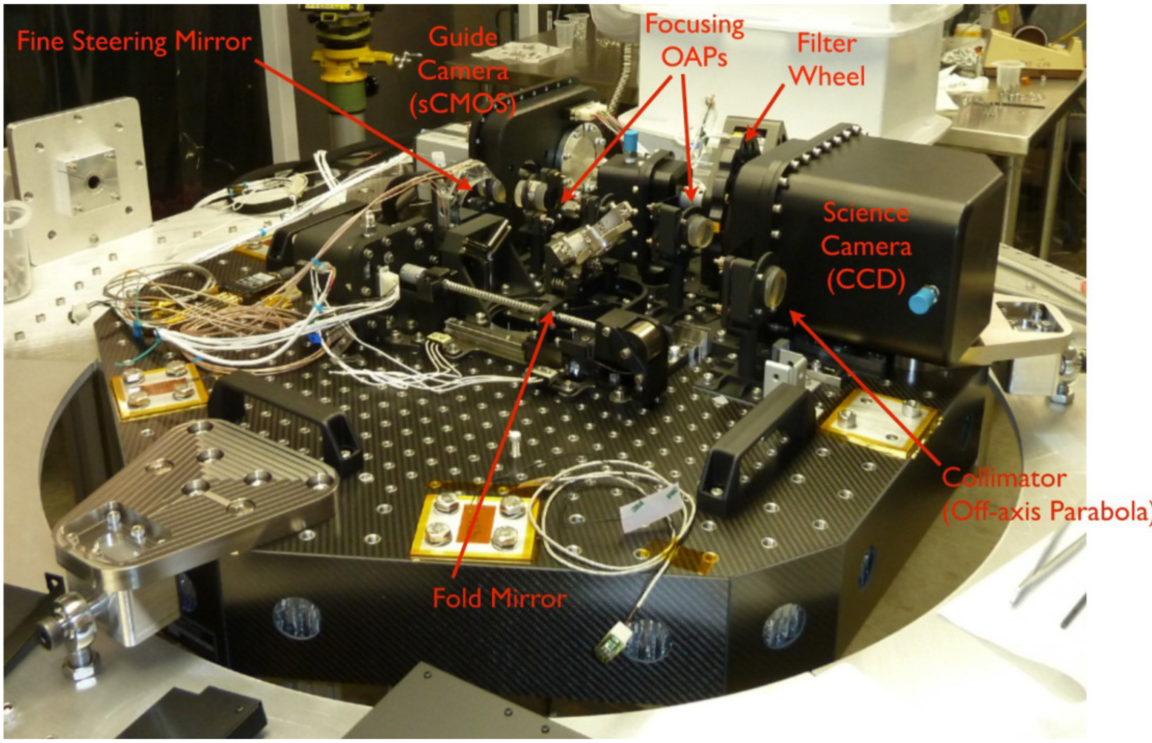


Figure 4.1.—The UVVIS Optical Bench for BRRISON and BOPPS

4.1.1 Imaging at 0.3 to 1.0 µm

A balloon-borne telescope can take advantage of the excellent seeing in the stratosphere to improve its sensitivity to faint sources. Background counts can be minimized if the pixel scale is matched to the Point Spread Function (PSF) width. Preliminary modeling indicates that 25th magnitude objects can be detected with a signal-to-noise ratio (SNR) of 5 in a 5 min exposure, assuming a sky background of 22 magnitudes per square arcsecond due to zodiacal light.

The focal length is unambiguously determined by the desired plate scale (in arcseconds per pixel, for example) and the physical size of the pixel. In visible wavelengths (0.5 µm), the diffraction limit of a 1 m telescope is 0.12 arcsec. A reasonable plate scale would be 0.05 arcsec per pixel, which allows two pixels across the FWHM (full-width at half-maximum) of the diffraction-limited PSF. If the pixel size were to be 10 µm, then a focal length of 41.25 m produces the desired plate scale of 0.05 arcsec per 10 µm.

Not all of the magnification needs to be produced by the telescope itself. Indeed, if the telescope beam is to be shared between visible and infrared instruments, it is likely that that plate scale for the IR instrument will be much coarser than for the visible one. In the dual-beam case, the focal length should be a compromise between the desired plate scales for the visible and IR beams, with additional optics in each beam to expand or condense the plate scales as needed.

The desired visible acuity of 0.1 arcsec or better (for a 1 m aperture) translates to specific pointing requirements, such as stabilizing the focal plane at the 0.05 arcsec level or better. The stabilization requirement consists of two parts: the need for an accurate pointing error signal and the ability to correct pointing errors. The 2013 BRRISON and 2014 BOPPS balloon payload demonstrated solutions to both parts of this problem.

The BRRISON and BOPPS payloads included a guide camera, a sCMOS camera (shown in Figure 4.1) with 6.5 µm pixels. The next couple of paragraphs describe the imaging approach on the BRRISON and BOPPS missions.

The FSM was exercised by performing tip-tilt corrections of the apparent image motion of a bright star during the hang tests of the BRRISON payload at Fort Sumner, New Mexico. The seeing during the hang tests was poor, an estimated 3 arcsec width of the best-focus PSF. Nevertheless, a bright star was centroided, the estimated errors were turned into FSM commands, and a sequence of short exposures were obtained at 50 Hz. A co-added stack of 50 of these star images, with no additional co-registration, produces an image with a FWHM of 1.5 arcsec (Figure 4.2).

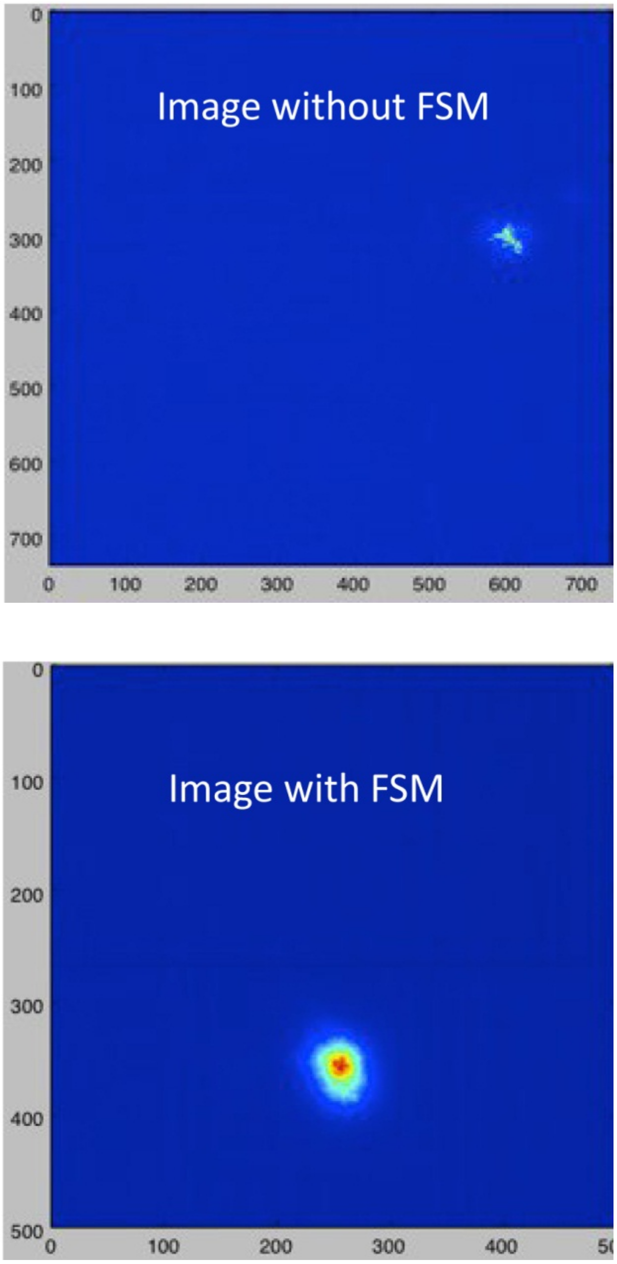


Figure 4.2.—Individual exposures and the stack of 50 co-added images

The reduction of the PSF width by a factor of two (from 3 to 1.5 arcsec) is approximately the improvement expected in the presence of atmospheric turbulence by a tip-tilt correction system in visible wavelengths.

Thermal gradients across the mirrors or the Optical Telescope Assembly (OTA) have the potential to deform the mirror or misalign the telescope and must be considered during the system design. However, for these measurements, the system is insensitive to thermal photons, and is not an emissivity driver on the optics.

In the September 2014 BOPPS flight, the UVVis bench was able to take a few image sequences of Polaris during the daytime segment of the flight. The image sequences spanned windows in which the cryocooler was turned off for 10 or 20 s. Figure 4.3 shows the correction in elevation (EL) and azimuth (AZ) as the cryocooler was turned off. The rms pointing errors were 280 mas and 165 mas in AZ and EL, respectively, when the cryocooler was ON. The rms pointing errors improved to 33.3 and 58.1 mas in AZ and EL when the cryocooler was OFF. The overall stability was 66 mas with the cryocooler off, surpassing the BOPPS Level-I goal of demonstrating sub-0.1 arcsec pointing stability for the mission. Based on this analysis, the recommended requirements for UV/Vis observations are listed in Table 4.1.

TABLE 4.1.—RECOMMENDED REQUIREMENTS FOR UV AND VISIBLE SCIENCE OBJECTIVES.

	Requirement	Comment
Aperture	1 m	Sufficient SNR
Focal length	20 to 40 m	PSF is 0.1 to 0.2 arcsec
FOV	60 arcsec	Venus imaging
Emissivity	N/A	
Pointing	0.02 arcsec	
Resolution ($\lambda/\Delta\lambda$)	N/A	
T_{optics}	N/A	
Stray light	10^{-6}	Baffling required
PSF FWHM	0.12 arcsec	Diffraction limited

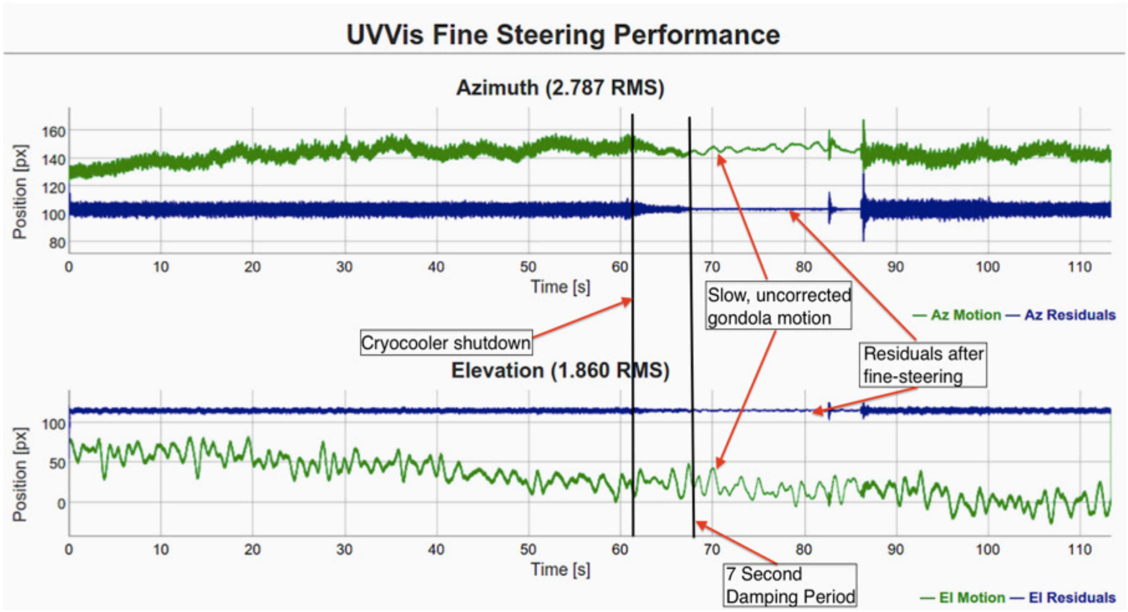


Figure 4.3.—UVVis Fine Steering Performance

4.1.2 Spectroscopy at 2.5 to 5 µm

For science in the 2.5 to 5 µm range, the diffraction limit is 0.6 to 1.2 arcsec. The requirements are listed in Table 4.2. The *focal length* does not need to be long, so this requirement is driven by the shorter wavelength imaging science. Assuming the diffraction limit is 18 µm pixels, a focal length of 10 m provides a plate scale of 0.37 arcsec per pixel, oversampling the diffraction limit at 2.5 µm from a 1 m aperture. Pointing stability can be driven by the long wavelength measurement requirements. For instance, atmospheric modeling conducted in support of the BRRISON mission suggested that downwelling radiance outside the 4.3-µm CO_2 band is essentially absent, thus integration times for individual observations can potentially be seconds to even minutes with pointing stability needing to be maintained continuously for that length of time. In comparison, downwelling radiance in the CO_2 band is considerable, limiting integration times to a fraction of a second and reducing the requirement on pointing stability.

Emissivity must be minimized for the IR science due to emitted flux from the optics adding to the background. The telescope's primary and secondary mirrors can be passively cooled, and can be maintained around 60 K below the ambient daytime temperature while any additional focusing optics on an instrument bench would likely need to be actively cooled to achieve temperatures significantly below the ambient temperature of the instrument optical bench. The blackbody peak of the optics is around 14 µm; the 5 µm observations fall well onto the Wein side of the blackbody emission curve, but nonetheless, can contribute greater signal than from dim targets at wavelengths beyond 3 µm.

TABLE 4.2.—RECOMMENDED REQUIREMENTS FOR 2.5 TO 5 µm SCIENCE OBJECTIVES

Aperture	1 m	Sufficient SNR
Focal length	10 to 20 m	PSF is 0.6 to 1.2 arcsec
FOV	60 arcsec	Allows nods along slit
Emissivity	~6 percent	SNR requirement
Pointing	0.2 arcsec	Keep PSF on slit
Resolution (λ/Δλ)	200	Ice spectroscopy
T_{optics}	–70 °C	~Ambient temperature
Stray light	10^{-6}	Baffling required
PSF FWHM	1.2 arcsec	PSF at 5 µm

The *FOV* is an optimization between the size of the largest objects to be imaged and the optical system. For the science identified, Venus is largest, 60 arcsec at inferior conjunction. However, that geometry only exists for a few days every 19 months. For point sources, a FOV of 20 arcsec is sufficient to allow A–B nod patterns on the slit without overlapping spectral traces between the nod positions.

The *spectral resolution* is a function of the instrument, not the telescope. However, it is noted here that the system is purposed for observations of solid state vibrational features on airless bodies including on small satellites, trans-Neptunian objects (TNOs), clouds of atmospheres of Jupiter, clouds of Venus, etc. Based on the lower limit for frost spectroscopy, a resolution of R=200 or better is specified.

4.1.3 Optical Bench

Given the similarities in the system requirements, even over the four-octave range from 0.3 to 5 µm, an optical bench can be designed for a common telescope. The primary difference in the two wavelength ranges is the plate scale and need for cooling the optics in the MIR. A dual-channel optical bench, splitting the beam into visible and IR channels with a dichroic, would allow separate focal lengths to be implemented for the two channels. The more stringent pointing requirements for the shorter wavelength imaging are not detrimental to the IR spectroscopy. Similarly, the low temperature requirements for the IR science should not degrade the shorter wavelength science. In practice, multiple design considerations must be addressed to accommodate the wide range of science drivers. For example, the optimal coatings for the 2.5 to 5 µm region may not be the same in the 0.3 to 1.0 µm range, a concept design of an optic bench for fine guidance, IR, and UV/Visible channels is shown in Figure 4.4.

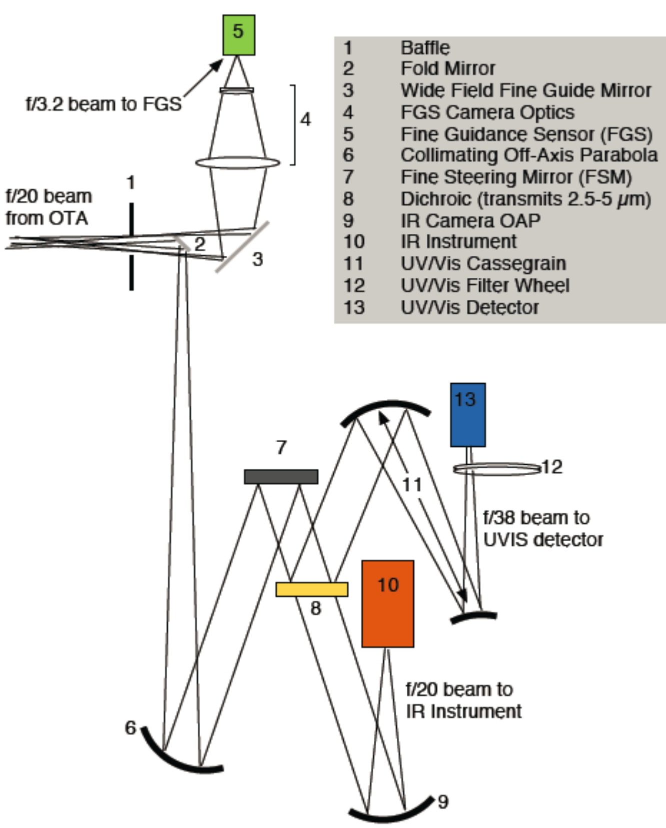


Figure 4.4.—Concept diagram of an optical bench for fine guidance, UV/Visible, and IR channels.

4.1.3.1 Separating Channels

There are several options available to separate the shorter and longer wavelength channels. The study considered three options: sharing in space with separate fields in the focal plane, sharing in time with a flip mirror, and sharing in wavelength with a dichroic.

Field sharing: The HST instruments share the focal plane. A field-sharing layout has the advantage of all reflective elements in all the beams. Any field can be rapidly pointed to the same real estate on the sky by the fine-steering mirror. Also, all the beams can share the fine-steering mirror. The primary disadvantages of the field-sharing layout are the lack of simultaneous observations with all detectors and the fact that it may be difficult to put a cold stop and the fine-steering mirror near the same exit pupil.

Flip mirror: A beam-switching layout can provide the cleanest signal to all channels. The IR channel can arrive directly from the OTA and an insertion mirror can move into the beam to redirect rays to alternate channels. The early separation of channels lets each channel be optimized. The short wavelength channel can use mirrors with high UV reflectance or lenses that can conveniently change the plate scale. The IR channel can be separately cooled, and the IR optics can be coated to minimize emissivity. There are two key disadvantages to the beam-switching layout. First, the channels cannot observe the same target at the same time. Second, a beam-switch layout that separates the beam as early as possible cannot share a common fine-steering mirror.

Dichroic separation: A dichroic-based layout is the only strategy that allows both channels to view the same field simultaneously. If the dichroic follows the fine-steering mirror, then both beams are uniformly corrected. Unlike the flip mirror, the dichroic layout has no moving parts except the FSM. The key disadvantages include the need to cool the dichroic to minimize thermal photons in the IR beam and the need to crowd the FSM, the dichroic, and a cold stop at the exit pupil, or form a second pupil for the cold stop. Note that the cold stop and dichroic could be put onto a single substrate. Furthermore, an implementation could be to use the dichroic as a window to an enclosed region of the optical bench that is cryogenically cooled. The transmission and reflectance curves of a selected dichroic are shown in Figure 4.5 (Ref. 10). The selected material achieves good transmission from 2.5 to 5 µm and fairly good reflection from 0.3 to 1 µm. While the performance is relatively noisy in the 1 to 2.5 µm range, those wavelengths are accessible from the ground.

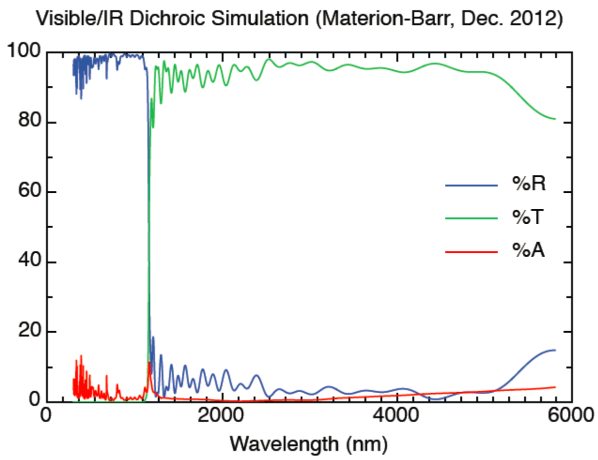


Figure 4.5.—Calculated dichroic performance for reflection, transmission, and atmospheric transmission.

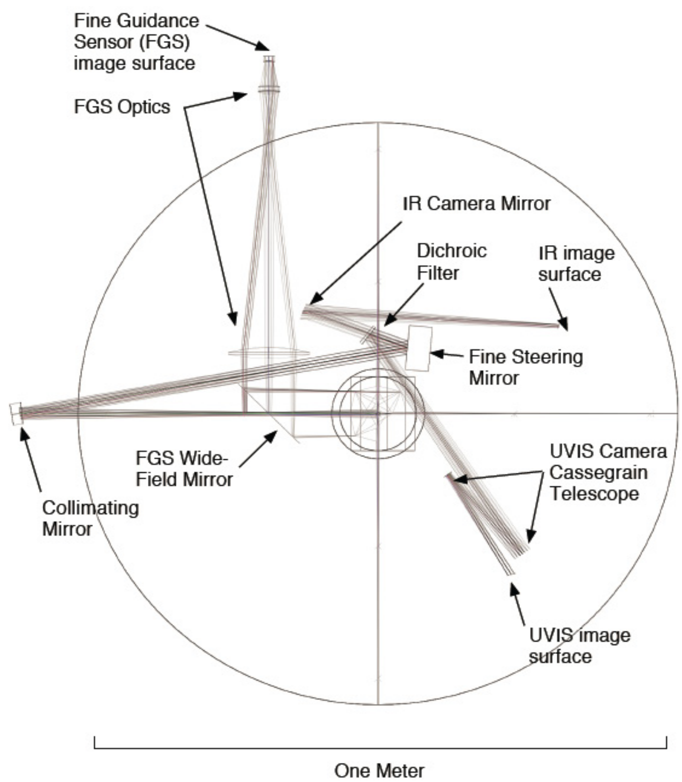


Figure 4.6.—Top-down view of the baseline optical bench.

A dichroic-based optical bench is the recommended layout and is illustrated in Figure 4.6, rendered in Zemax. The bench receives an F/20 beam from the telescope. A wide-field pick-off mirror sends a 14 arcmin field to the fine-guidance sensor. A hold in that mirror passes the 60 arcsec science beam to a collimating mirror. A fine-steering mirror and a dichroic are located near the exit pupil of the telescope. The dichroic reflects light to the UV/Visible camera and transmits to the IR camera.

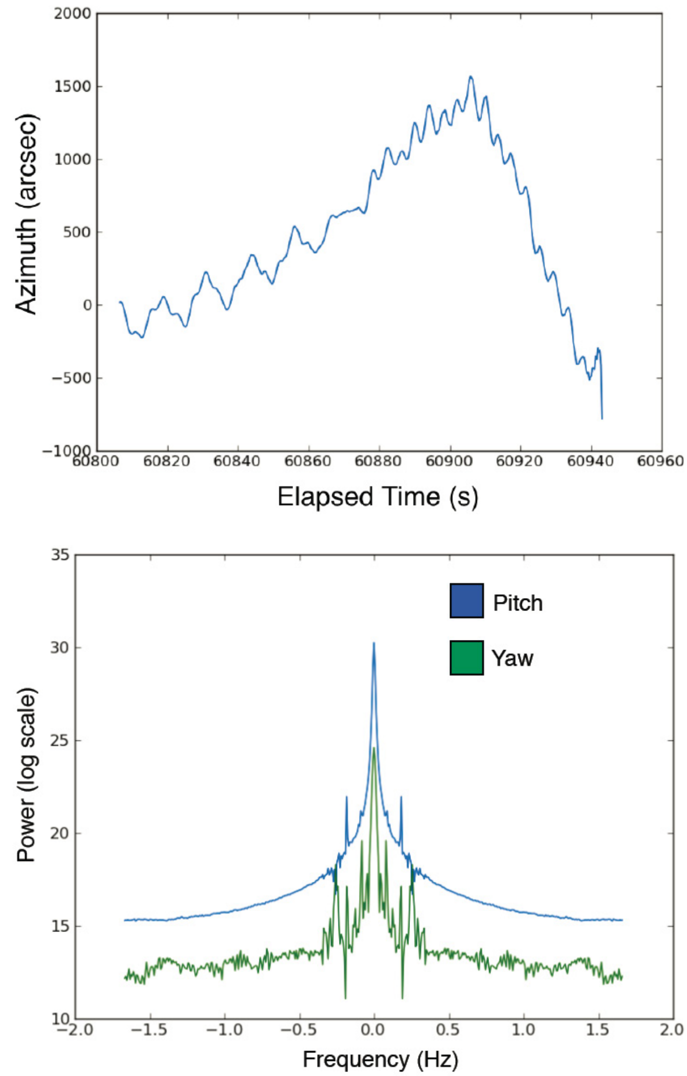


Figure 4.7.—Two-minute sequence from ST5000 elevation sensor (left) and power spectrum of pitch and yaw pointing positions (right).

4.1.4 Pointing Reference Signal

A pointing reference signal is necessary to actuate the fine-steering mirror. The requirements for the guide camera depend on the frequency of motion that is corrected. The optical reference signal should be 10x faster than the frequency of the FSM corrections. In the absence of self-induced motion, the balloon gondola will experience relatively slow perturbations. Based on flight experience with an ST5000 star tracker, perturbations at frequencies higher than 0.5 Hz are not expected for passively cooled optics and instruments; see Figure 4.7 (Ref. 11). The FSM will be controlled at 5 Hz from an optical reference signal taken at 50 Hz. This requirement drives the star magnitude capability to provide sufficient SNR in a 0.02 s exposure.

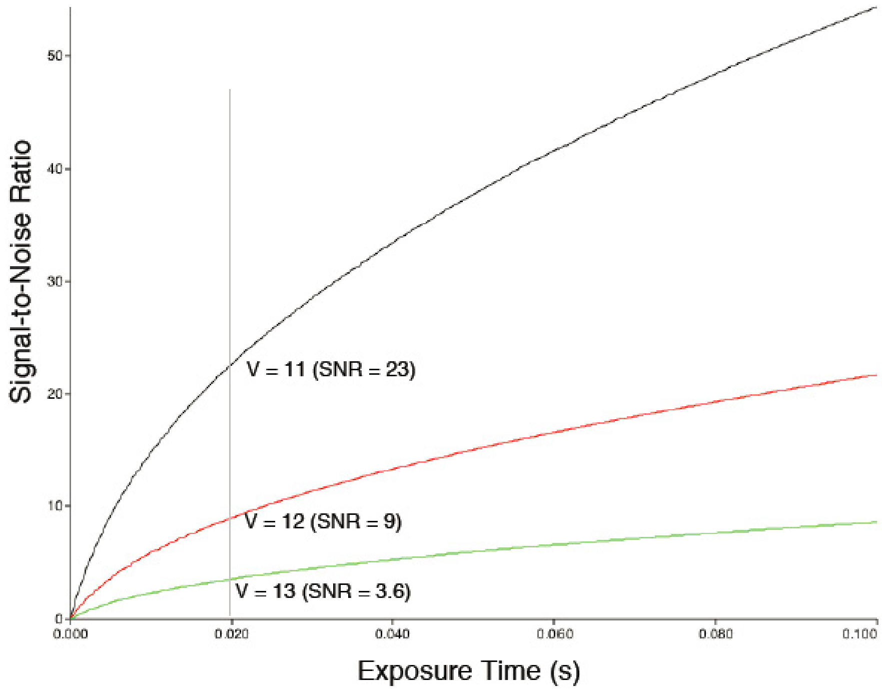


Figure 4.8.—Estimated SNR for 11, 12, and 13 magnitude stars.

Figure 4.8 illustrates the signal-to-noise ratio for 11th, 12th, and 13th magnitude stars, assuming a 1 m aperture with 12 percent obstruction due to the secondary mirror, an sCMOS camera with 1.3 electron read noise quantum efficiency of 60 percent, a PSF with a FWHM of 0.25 arcsec, and a pixel size of 6.5 µm. The simulation results indicate that an 11th magnitude star provides a sufficient optical reference with an accurately measured centroid at 50 Hz. From Table 4.3, there is an average density of 21.9 11th magnitude stars per square degree. Conversely, there is an expectation that one star will be available in a 12.8- by 12.8-arcmin field.

Stars can be considered as Poisson-distributed objects across the sky. The probability of finding one or more stars in a given FOV is given by Equation (1), where *n* is the number of stars found and *a* is the average number of stars in the field.

$$P(n) = \frac{a^n e^{-a}}{n!} \tag{1}$$

For *a* = 1, *P*(0) is 37 percent; so the probability of finding one or more stars in a field is 63 percent. For slightly larger (14- by 14-arcmin) fields, 70 percent are expected to have one or more 11th magnitude stars detectable with a SNR of 23. Also, 95 percent of the fields will contain a 12th magnitude star with an SNR of 9, adequate for centroiding. Finally, fields that lack even 12th magnitude stars can lower the frame rate from 50 Hz until sufficient SNR can be achieved for fainter stars, and should provide a graceful degradation of performance.

TABLE 4.3.—AVERAGE NUMBER DENSITY OF STARS PER SQUARE DEGREE AS A FUNCTION OF MAGNITUDE

Magnitude	Number/Degree^2
8.0	1.00
9.0	2.82
10.0	8.13
11.0	21.88
12.0	57.54

Because fine-guidance sensors need to see a relatively large area on the sky, the mirrors on the optical bench need to be significantly larger than necessary for the nominal science FOV unless the FGS field is extracted before the beam is collimated and passed to the FSM. In an open-loop configuration, an annular mirror is placed at the prime focus, just behind the primary mirror. The FGS sees a star field that has been corrected by the coarse pointing system (e.g., Wallops Arcsecond Pointer), but not the FSM. In a close-loop configuration, the annular mirror is placed just in front of the UV/Vis camera.

4.1.4.1 Open Loop

There is an option to obtain the fine-guidance signal before the fine-steering mirror, which means that the commands to the FSM are not reflected in the FGS frames. This type of system is called open loop. The FSM requires good absolute pointing, as it receives open-loop commands derived from FGS images. Open loop is the baseline recommended implementation for a simplified option with reduced component dimensions and overall bench area. The baseline FSM has an angular range of 5 mRad and absolute angular positioning precision of 50 nRad. The precision translates to an angular precision on the sky of 0.00025 arcsec. In the absence of systematic errors, such as flexure between the FGS and the science cameras on the optical bench, the capabilities of the FSM are orders of magnitude more accurate than necessary for open-loop pointing corrections. The advantage of the open-loop design is that the entire layout and all of the optics in the bench (Figure 4.9), specifically the OAPs and the FSM, can be much smaller (1 arcsec FOV instead of 14 arcsec).

4.1.4.2 Closed Loop

Closed-loop control is also possible (Figure 4.10). Closed-loop designs have an advantage that the FGS see adjustments made by the FSM, whereas the open-loop design relies on the FSM accurately responding to pointing commands from the FGS without feedback. If the FGS were placed downstream of the FSM, the OAPs and the FSM would have to be much larger (each around 10 in. across) to propagate the WFOV of the FGS; the free-path distances between the elements on the optical bench would increase as well.

4.1.5 Telescope Options

As discussed in the science traceability sections, all but survey missions are targeted narrow-field observations. The main telescope design assumes a 60 arcsec FOV, equivalent to the diameter of Venus at inferior conjunction. The study traded options for a three-mirror anastigmat (TMA), Gregorian, Dall-Kirkham, and Cassegrain designs. The team also initially assessed recent pointed telescope missions.

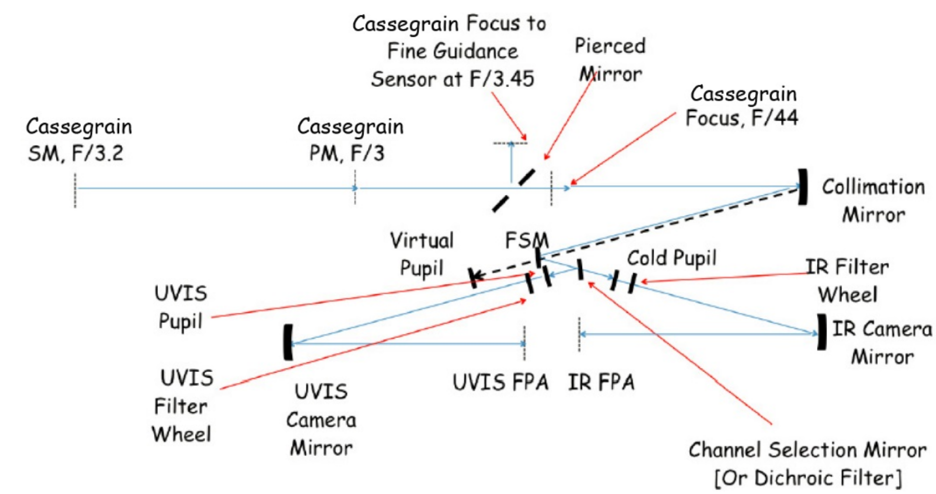


Figure 4.9.—Open-loop optics bench layout.

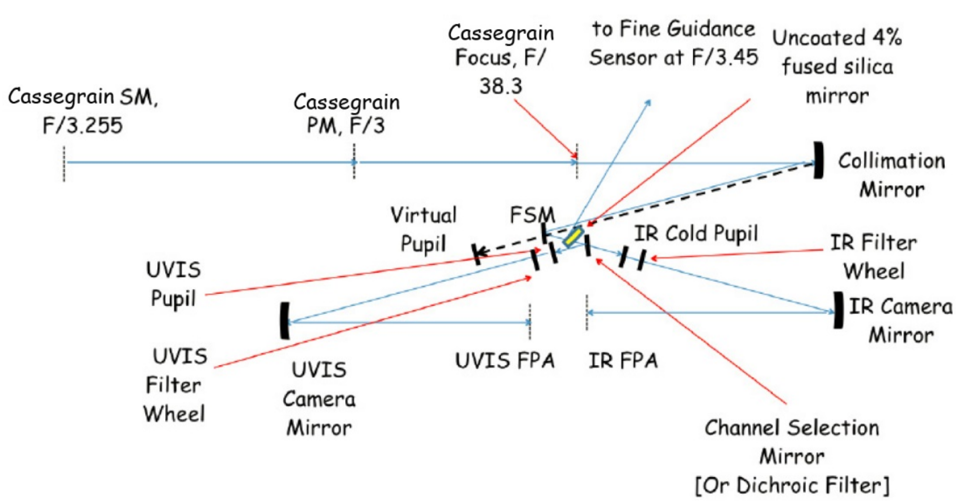


Figure 4.10.—Closed-loop optical bench layout.

4.1.5.1 Recent Missions and Pointing System Overviews

4.1.5.1.1 Faint Intergalactic-medium Red-shifted Emission Balloon (FIREBALL)

FIREBALL flew a 1 m classical Cassegrain telescope with a fiber-fed spectrograph (Ref. 12). The spatial resolution was only 3 to 4 arcsec because the fibers did not require higher resolution. The FIREBALL telescope was a fixed, downward-pointing OTA fed by a 1.2 m sidereostat that reflected light up into the telescope. The gondola was azimuthally stabilized with a suspension bearing. To dampen the azimuthal modes, the rotary bearing provided viscous friction. Pendulum modes were also dampened by oil-immersed pendulums on the gondola. Optical elements were made of thin, low-expansion Corning Titania Silicate Low Expansion Glass substrate. The gondola trusses were made from carbon fiber tubes.

4.1.5.1.2 Balloon-borne Large-Aperture Sub-millimeter Telescope (BLAST)

BLAST flew in 2010 to map the sky at sub-millimeter wavelengths (250 to 500 μm) (Ref. 13). Like FIREBALL and all recent flights noted, there is a pivot connecting the gondola to the flight train. However, BLAST used a large reaction wheel to maintain its precise (30 arcsec) azimuthal heading in addition to the rotary bearing to exert against the flight train. The BLAST mirror was 1.8 m in diameter, but only polished to the 1 μm level.

4.1.5.1.3 Stratospheric Terahertz Observatory (STO)

STO was another sub-millimeter wavelength (158 to 205 μm) system. STO uses a reaction wheel to maintain its azimuthal heading. The STO gondola is narrow and tall by design, and the elevation drive of the telescope OTA torques against the rest of the gondola, which has a high moment of inertia due to the height. The system uses an 80 cm on-axis Cassegrain optical telescope, and STO successfully mapped the sky with a resolution of 1 arcmin.

4.1.5.1.4 Sunrise

The Sunrise mission, like some of the previous missions identified, relied on a rotator to connect the gondola to the flight train. However, Sunrise then used a frictionless bearing to let the gondola rotate without any connection to the flight train. The mission achieved the most accurate pointing to date by a balloon-born telescope, with 20 arcsec of target (Ref. 14). Sunrise used an optical reference signal from an off-axis instrument in the focal plane to control a tip-tilt fine-steering mirror. When the control loop was closed, the pointing was stable at the few milliarcsecond level. Sunrise used a Gregorian telescope, exploiting the focus between the primary and the secondary mirrors to intercept light from the Sun and disperse it via heat pipes and radiation panels. Figure 4.11 shows FIREBALL, BLAST, STO, and Sunrise.

4.1.5.2 Three-Mirror Anastigmat (TMA)

TMA telescopes were considered as an option for low aberrations over a relatively large FOV. Also, an annular field TMA design provides very effective stray-light baffling. The native Cassegrain focus (before the tertiary mirror) is a possible location for a guider array which often benefits from coarser plate scale than the science focal plane. The advantages of the TMA include the performance for wide fields, a cold stop, stray-light baffling, and a practical implementation for a wide-field guider array. However, the science drivers do not necessitate a WFOV and TMA telescopes are generally more costly than two-mirror alternatives.

4.1.5.3 Gregorian

Several balloon-borne telescopes have been Gregorian designs, ranging from the Stratoscope telescope from the 1960s to Sunrise flown in 2009. Gregorian telescopes consist of two concave mirrors. The primary mirror is a concave paraboloid that collects the light and brings it to focus before the secondary mirror, a concave ellipsoid, and then reflects the light back through a hole in the center of the primary. In a Gregorian design, the primary mirror creates an actual image before the secondary mirror. This allows a field stop before the secondary mirror, and stray light can be baffled and will not reach the secondary mirror. The concave secondary mirror is also easier to build and test as a concave ellipsoid. The disadvantages of a Gregorian include a 50 to 80 percent longer OTA, and the secondary mirror is slightly larger than a regular Cassegrain. Figure 4.12 illustrates a Gregorian telescope design.

4.1.5.4 Classical Cassegrain

Classical Cassegrain telescope designs have a parabolic primary mirror and a hyperbolic secondary mirror that reflects light back through the primary. Folding the optics makes this a compact design. The concave parabolic reflector will reflect all incoming light rays parallel to its axis of symmetry to a single focus.

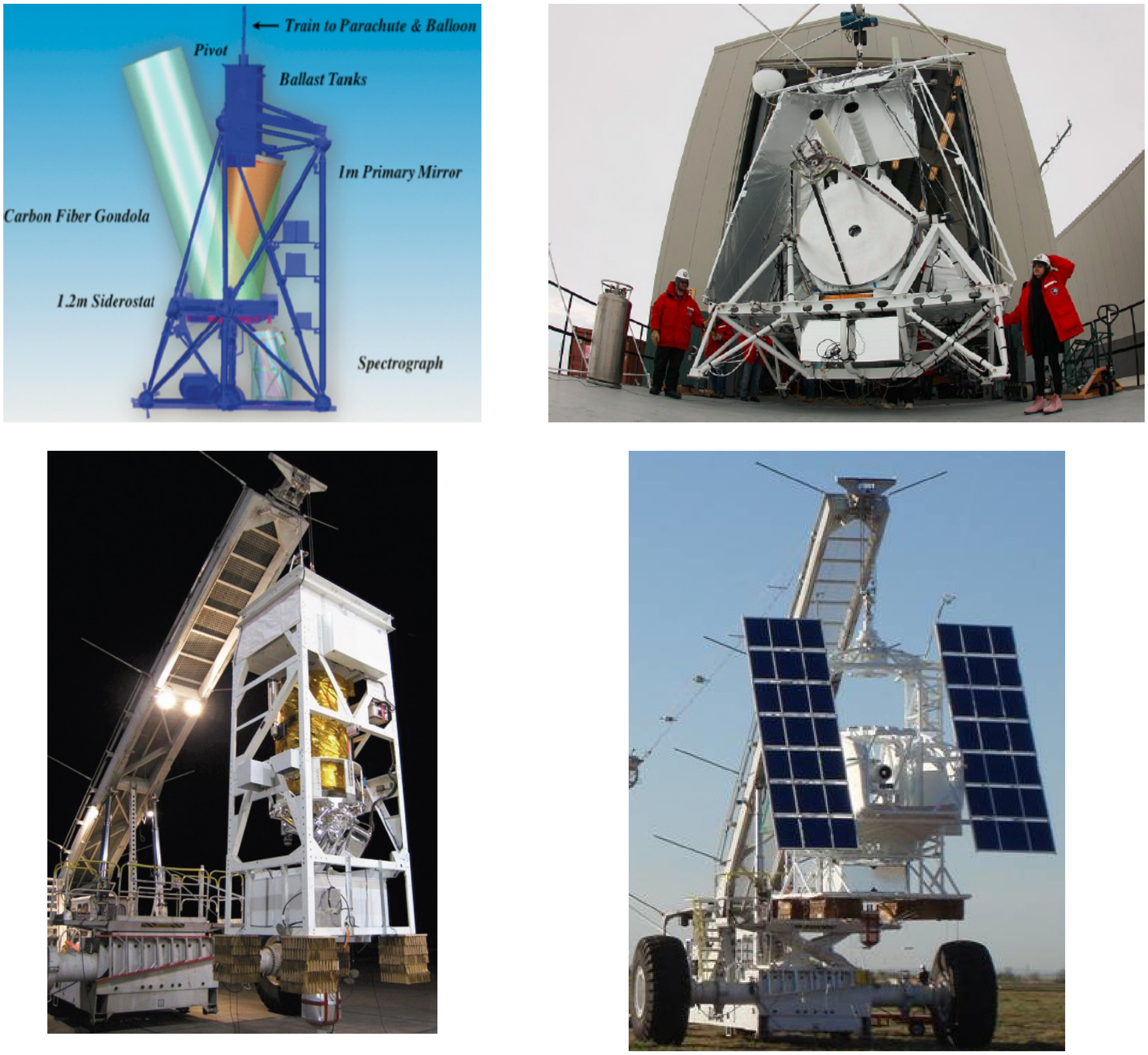


Figure 4.11.—Recently flown balloon borne telescope FIREBALL (top left), BLAST (top right), STO (bottom left), and Sunrise (bottom right).

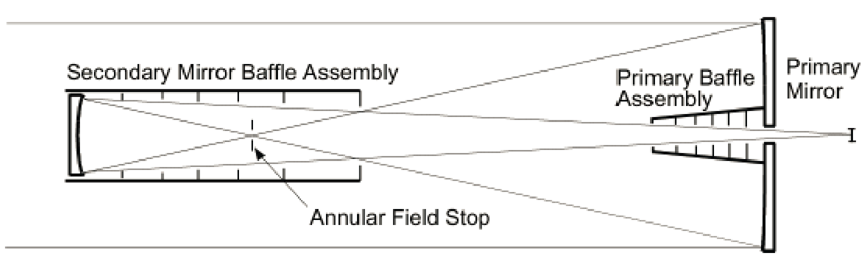


Figure 4.12.—Gregorian telescope layout.

A telescope's focal length is determined unambiguously by the choice of platescale on a detector's pixel. If, for example, a given detector has 10 µm pixels and the desired platescale is 0.06 arcsec per pixel (a reasonable choice, oversampling the PSF of a 1-m aperture by a factor of 2 at a wavelength of 500 nm), then the telescope focal length must be set to 34.4 m. The FOV of a 1K x 1K detector will be 60 arcsec (also a reasonable choice—the largest planetary object is Venus at inferior conjunction, with an angular diameter of 60 arcsec).

Spot sizes from three telescope designs were modeled over a 60 arcsec FOV at wavelengths of 500 nm. These designs were a Dall-Kirkham (DK), a classical Cassegrain and a Ritchey-Chrétien (RC) Cassegrain. The DK design (an elliptical primary and a spherical secondary), assuming an F/4 primary, produced off-axis spot sizes that were significantly larger than the diffraction-limited PSF and was judged to be unacceptable. Corrected Dall-Kirkham designs were not considered because of the difficult (but not impossible) requirement that the refractive corrector lenses transmit light over a wavelength span from 300 nm to 5 µm.

The classical Cassegrain telescope has a parabolic primary mirror and a hyperbolic secondary. It produces coma for off-axis objects, but for a 60 arcsec x 60 arcsec FOV, even objects in the corners of the have spot sizes that are smaller than the diffraction PSF. A Ritchey-Chrétien Cassegrain telescope modifies the primary mirror's figure from a parabola to a hyperbola and eliminates low-order coma.

The classical or Ritchey-Chrétien are leading candidates for first generation telescope designed to for planetary science observations from the stratosphere (Ref. 15).

4.1.5.5 Dall-Kirkham

A Dall-Kirkham (DK) telescope uses a concave elliptical primary mirror with a convex spherical secondary mirror. Dall-Kirkham telescopes are easier to manufacture than classical Cassegrain or Ritchey-Chrétien systems, but have larger off-axis aberrations. Because the field curvature is less than a classical Cassegrain, DKs are rarely faster than f/15. The advantage of a DK is the loose alignment tolerances of the spherical secondary. Figure 4.13 illustrates DK and Classical Cassegrain acuity from a Zemax simulation. The off-axis performance is poor, even for the longest OTA considered. The alignment advantage of the DK telescope is offset by the inexpensive availability of COTS hexapod mount for secondary mirrors. The off-axis aberrations increase with faster systems/shorter focal lengths. Even with a 4 m focal length, the DK telescope produced Strehl ratios of ~80 percent for sources only 60 arcsec off axis. While an F/3 Cassegrain shows more compact spot sizes over the field and with Strehl ratios very close to one.

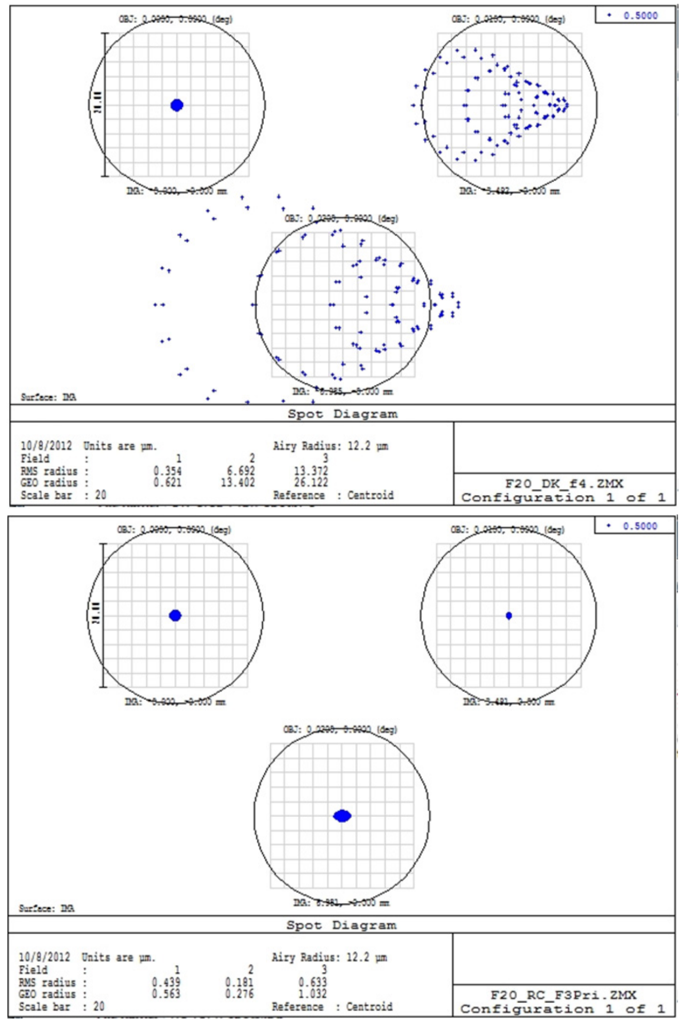


Figure 4.13.—Spot diagrams of a Dall-Kirkham (top) and classical Cassegrain (bottom).

4.1.5.6 Telescope Mirror Coatings

Protected aluminum or silver offer excellent performance in the visible through NUV, with a thin (~10s of nanometers) coating of a hard, weather -resistant, and optically neutral material that doesn't affect the reflectivity of the surface, such as magnesium fluoride. However, because a single telescope will need to support optical measurements from the NUV through the MIR, the thermal emissivity of the surface needs to be minimized. Because the emissivity of silver and aluminum are a few percent, whereas gold emissivity is less than one percent, a protected, gold primary and secondary will have less than half the thermal self-emission than would silver or aluminized surfaces. While gold is not preferred in the visible or NUV, a reflectance of about 38 percent for each of the two surfaces, while not ideal, would not prohibit observation in the NUV. In lieu of the development of a surface that has both very high reflectance in the

NUV-NIR, but nearly unity emissivity in mid-IR wavelengths, the recommendation is to use protected gold coated primary and secondary telescope optics.

4.1.5.7 Summary

A wide range of telescope designs have been considered for planetary science objectives. The TMA telescopes are technically compatible with the telescope requirements, but have higher costs and are unnecessary to meet system performance. The advantage of TMAs is for wide field science. A sidereostat implementation was determined to add mass and complexity relative to the proven ability of WASP to point large telescopes. The Dall-Kirkham designs had poor performance and Strehl ratios at off-axis positions. A Ritchey–Chrétien Cassegrain telescope variant has several advantages with excellent spot shape and Strehl ratios throughout the FOV. The recommendation is for a classical Cassegrain or Ritchey-Chrétien telescope to achieve the desired performance.

5.0 Existing Gondola Subsystems and Demonstrated Mission Capabilities

In addition to the compelling science rationale, it is the capabilities developed over the years by the NASA Balloon Program Office and previous mission teams that are enabling near-term high-value planetary science missions and far-term objectives to be met. NASA's BPO regularly flies large payloads to altitudes of 120,000 ft or higher for missions of days to weeks in duration. Progress on long-duration balloons and improved pointing capabilities, demonstrated by other missions, has increased the potential for planetary science missions. The BPO already fields campaigns for heliophysics, astrophysics, earth science, and technology maturation flights. There are significant assets already available to the ballooning community and plans for continued development. It is assumed in this study that NASA-supported planetary science flights will work closely with the Columbia Scientific Balloon Facility (CSBF) and its staff for subsystem support. The capabilities already demonstrated by CSBF and the BPO on previous campaigns and flights have demonstrated sufficient capabilities to meet all near-term and mid-term requirements for planetary science missions. The exception is long-duration flights from mid-latitude sites to allow long-duration nighttime observations, and those observation targets best viewed from equatorial or mid-latitudes. BPO is addressing those needs, and is implementing a test flight or a super pressure balloon launched from New Zealand in 2015.

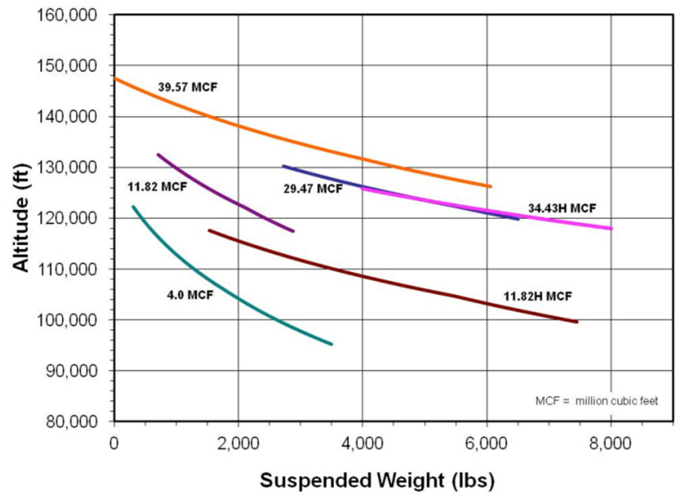


Figure 5.1.—Zero-pressure balloon suspended mass capability.

5.1 Balloons

5.1.1 Zero-Pressure Balloons

There are significant capabilities existing relative to zero-pressure balloons. Zero-pressure balloons are typically used over an altitude of 60,000 to 135,000 ft, but higher altitudes are possible. In 2002, a balloon named BU60-1 reached an attitude of 173,900 ft. The existing capabilities of zero pressure balloons are illustrated in Figure 5.1. The balloons have significant suspending mass capability, and can support all planetary science balloon options considered to date. Numerous flights, both short and long duration (>1 day), have flown on zero pressure balloons at the various launch sites. Thirty-seven Antarctic balloon flights have been conducted since the first successful launch in 1991, most with zero pressure balloons. As of the summer of 2014, there have been 29 long-duration balloons flown, 20 from Antarctica and nine from Sweden, with only one balloon failure in 2005 (a success rate of 96.5 percent). The longest flight to date has been 54 days; the flight was brought down for an Antarctic recovery, but otherwise could have continued.

5.1.2 Super Pressure Balloons and Ultra- Long-Duration Flights (ULDB)

ULDB flights can be enabled by super-pressure balloons through eliminating the diurnal helium loss.

Zero-pressure balloons are lighter for the same size, and therefore, take larger payloads to the same altitude (or take the same mass to higher altitudes). However, they must vent about 10 percent of their helium each day and drop about 10 percent of the payload weight each night to maintain altitude. This makes them impractical for ultra-long-duration missions except for latitudes that see continuous daylight.

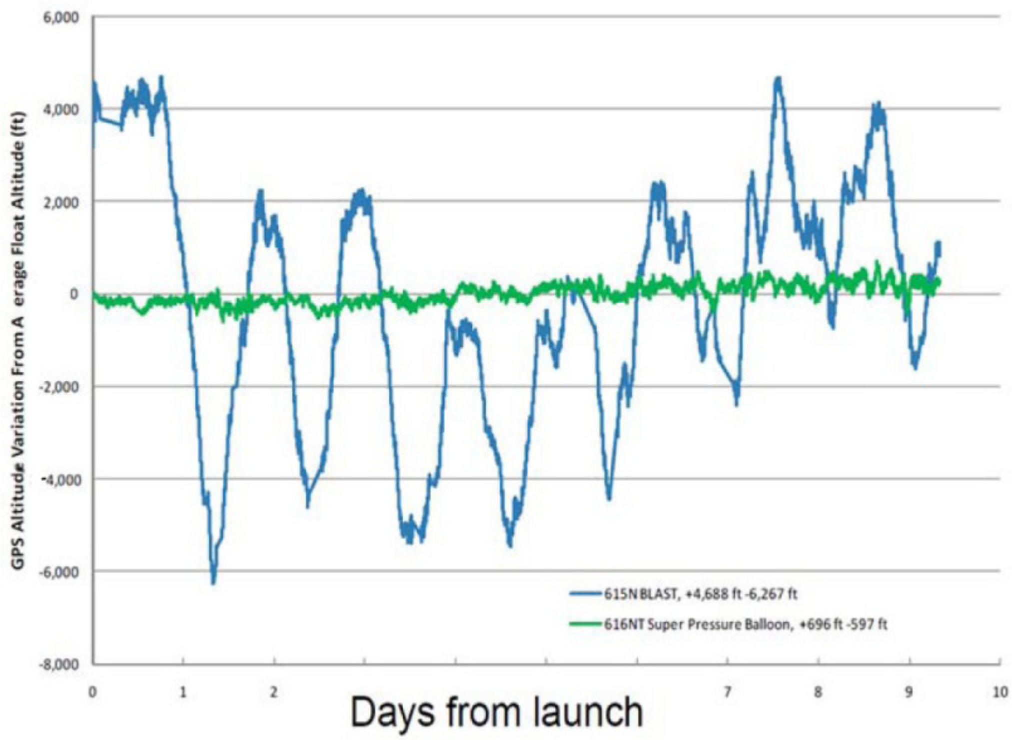


Figure 5.2.—Altitude variations over time.

Unlike the zero-pressure balloons, super-pressure balloons are sealed and can maintain a pressure gradient with respect to the stratospheric environment. The super-pressure balloon enables stable-altitude long-duration flights. A plot of altitude variation between a zero-pressure and super-pressure balloon is shown in Figure 5.2.

The difference of 10,000 ft in float altitude means that super-pressure balloons see more atmosphere overhead relative to zero-pressure balloons. Zero-pressure balloons flying at 120,000 ft would nominally fly above 99.56 percent of the atmosphere, while a similar size super-pressure balloon may fly above 99 percent with similar suspended mass. For many purposes, the difference in altitude is inconsequential. For example, there is essentially no atmospheric turbulence at either super-pressure or zero-pressure float altitudes, which means that either platform is capable of providing diffraction-limited seeing. In other regards, the difference in altitude is significant: super-pressure balloons will see higher daytime sky brightness (about 1.5 times higher) and more telluric opacity at certain wavelengths (notably ones in the ultraviolet and in the MIR at the 4.3-µm CO_2 absorption).

NASA recently tested an 18.75 million-cubic-feet (MCF) super-pressure balloon capable of lifting 5000 lb to 110,000 to 115,000 ft. NASA is investing in a larger super-pressure balloon for higher altitude, although the mass capability is lower at the higher altitude. As with all balloon systems, there is the standard mass - altitude trade.

5.1.2.1 Potential Planetary Balloon Launch Sites

There are a wide range of sites currently available for balloon flights. Short-duration missions can be conducted from all long-duration launch sites in addition to the Fort Sumner launch site. The longest missions to date have flown from Antarctica in the December to February window to take advantage of the polar vortex and circumnavigate the Antarctic continent. Unfortunately, there are severe limitations for planetary science flights out of Antarctica during its summer: limited access to the celestial sphere, limited mission duration potential, and most importantly, limited access to nighttime skies. The BPO continues to make progress to open additional launch sites for long-duration flights. Current and projected launch sites are shown in Figure 5.3.

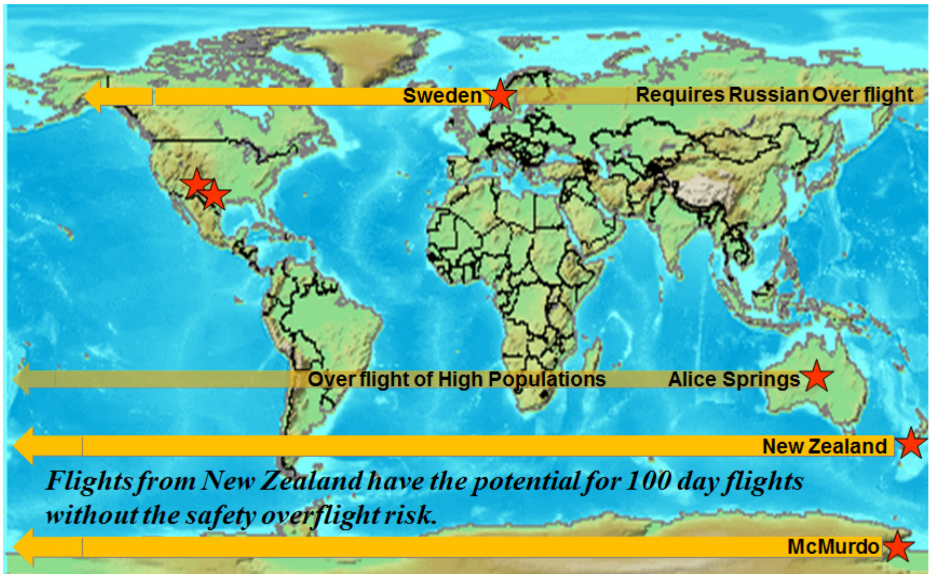


Figure 5.3.—Current and projected long duration launch sites.

5.1.2.1.1 Fort Sumner

Fort Sumner is NASA's primary launch site for stratospheric turnaround flights; chosen for increased safety and high probability of payload recovery. Fort Sumner is at 4,000 ft altitude in a desert environment with low level winds. Launch campaigns are held primarily in the fall, and test flights are often conducted at Fort Sumner prior to long duration flights. Five flights were launched in 2012, and nine flights were launched in 2011 from Fort Sumner. Fort Sumner launches are low cost flight opportunities with nominal mission duration of up to 1 day.

5.1.2.1.2 Sweden

Sweden is a proven launch site for scientific balloons; however, durations are limited due to the restriction of no Russian overflights. The Balloon Program Office has completed flights and is planning future flights from Sweden to Canada. Departing from Sweden allows for nighttime observations. Even without the Russian overflights, missions exceeding 1 week have been demonstrated. Launches from Sweden, or any other international location, cost several times more than domestic launches due to additional travel costs, limited availability of specialized products and capabilities required, and the increased logistical challenges.

5.1.2.1.3 Antarctica

The Antarctic launch site, located at McMurdo Station, provides the longest flight opportunities available to balloon payloads at this time. Flights from this location have lasted over 50 days (circumnavigating the continent several times), but even longer flights have been proposed by allowing the payload to drift off continent. Flights occur during the Antarctic summer (typically launching in December or January). This results in flights in which the Sun never goes below the horizon. There are many targets that can be observed during the daylight and take advantage of the longer duration flights. Antarctica does, however, provide the greatest logistical challenges of the launch sites, and the gondolas need to be ready to ship 3 to 4 months before the actual flight.

5.1.2.1.4 New Zealand

The BPO is targeting launch opportunities from New Zealand, with the first flight demonstration planned for 2015. The balloons would depart from New Zealand and target a landing in South America after multiple revolutions around the Earth assuming no overflights of major populated areas. This launch location would offer the only long duration night-time observations to date.

5.2 Pointing Systems

The main technical hurdles for planetary science balloon-borne telescopes have been their pointing and stability. Multiple institutions have demonstrated the ability to point within several arcseconds or even subarcsecond. For example, this was demonstrated on the BOPPS mission using APL's pointing system with STO heritage. However, to take advantage of diffraction limits of 0.1 to 0.05 arcsec, for 1 to 2 m apertures respectively, a suspended telescope must be stabilized at the 0.05 to 0.02 arcsec level.

NASA has made advancements in pointing capability over the past several years. The Balloon Program Office has been working a technology development effort to design, build, and flight test a control system capable of pointing balloon-borne telescopes at inertial targets with subarcsecond accuracy. The control system is called the Wallops ArcSecond Pointer (WASP) shown in Figure 5.4. The WASP system is a set of nested gimbals that can keep a large (1500 lb) telescope on target through the use of constantly rotating bearings to eliminate static friction. The results from the first two WASP flights indicate that the dummy telescope payloads were stabilized at the 0.25 arcsec level. Raw data from a WASP test flight is shown in Figure 5.5. Reducing pointing errors from 1 to 0.01 arcsec is within the range of many fine-steering mirrors, provided they can be driven by an accurate pointing signal.

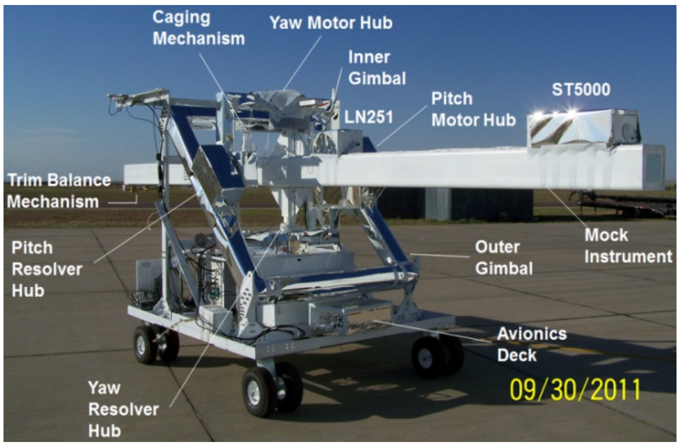


Figure 5.4.—WASP test flight article.

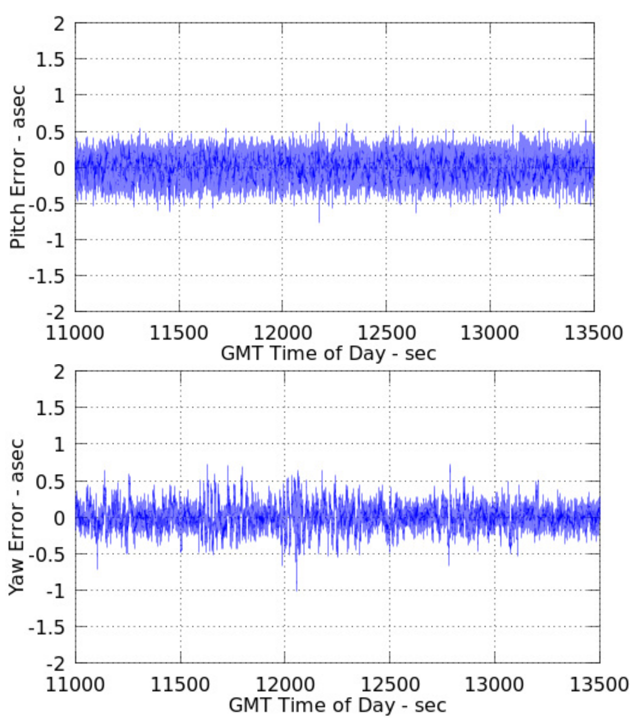


Figure 5.5.—WASP test flight article pointing accuracy data.

5.3 Power Systems

CSBF can provide the solar array and battery options required for the balloon system and for the science-specific elements. Lead acid battery options include the Odyssey PC625 (13.6 Ah) at 6 kg per module and PC1200 (32.1 Ah) at 17.4 kg per module. The batteries have been flown successfully by CSBF for the past 7 years. They are typically doubled up in series for a nominal bus voltage of 26.5 Vdc. They are inexpensive and robust, but are low energy and have poor power density. Lithium-ion batteries are also available including the Valence U1-12XP (40 Ah) at 9.5 kg per module and the Valence U-BMS-LV. CSBF is currently conducting charge/discharge testing in a high-vacuum environment. The lithium-ion batteries offer high energy and power density and can be used with most lead acid charging systems, but have thermal sensitivity to charging and are more costly than lead acid alternatives. CSBF offers multiple charging system options, but has the most experience with the Sun-Savor MPPT 15.

5.4 Instrument Packages

The NASA Balloon Program flies an instrumentation package on all balloon payloads to support the balloon operations and the user commands and data. Depending on the operational and user requirements, a Micro-Instrumentation Package (MIP), Consolidated Instrument Package (CIP), a Support Instrumentation Package (SIP), or a mini SIP may be flown. Shorter flights with limited data requirements use the simpler and lower cost options, while longer duration flights require more complex systems.

A short-duration flight from Fort Sumner could be performed with line-of-sight (LOS) communications and fly with the CIP. The CIP includes LOS command receivers, command decoders, and routers for balloon operations and user commands. Commands would include the balloon operations such as ballast drops, commands for payload operation, housekeeping data acquisition, and LOS transmitters of on-board systems.

Longer duration flights require over-the-horizon (OTH) communication. For this, the Tracking and Data Relay Satellite System (TDRSS)/Iridium SIP uses an Octagon Pentium computer for Comm1 and Comm2. A Trimble global positioning system (GPS) receiver is also used on the flight computer along with a TDRSS transceiver and the Iridium side uses two iridium satellite data modems. The Iridium modems can be used in both dial-up and short-burst data modes. The system has a LOS ultra-high frequency (UHF) command uplink and uses a UHF command re-transmitter to the universal termination package. The LOS data downlink is L-band and has backup ability for uplink and downlink of critical commands.

Telemetry returned via TDRSS has a low-rate science data capability of 255 bytes every 30 s and a real-time high-rate science data capability of 6 kbps with an omni-directional antenna and up to 93 kbps with a high-gain antenna. TDRSS data is received at the Mission Operations Control Center (MOCC) in Palestine. Telemetry returned via Iridium has a low science data rate of 255 bytes every 15 min and also real-time science data rates up to 2-kbps in dial-up mode all through the MOCC in Palestine. The typical SIP science configuration has two low-rate science ports, one per SIP flight computer, to provide uplink commanding. The SIP data includes GPS position, time and the pressure, and two high-rate science ports, one per flight computer, with a baud rate of 115,200 and data rates of 6 kbps and 93 kbps or 2 kbps with TDRSS and Iridium respectively. BPO has also recently demonstrated the Openport protocol used by Iridium. It is believed that data rates above 80 kbps may be realized. The SIP science stack includes 56 analog inputs and 40 digital inputs and is optically isolated and powered by the science power system. The CIP and SIP are shown in Figure 5.6 and Figure 5.7.

Figure 5.6.—Consolidated Instrumentation Package.

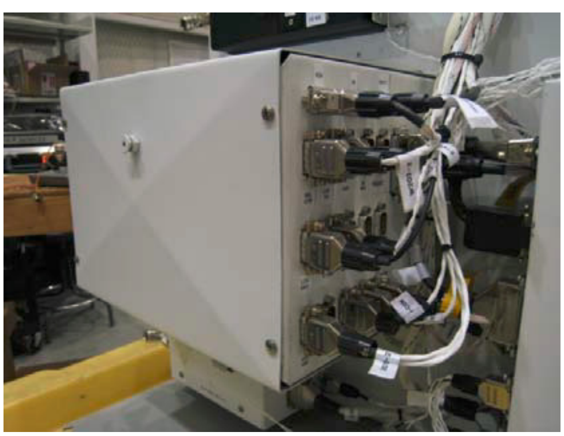


Figure 5.7.—Support Instrumentation Package.

5.5 Required Elements

The Balloon Program Office provides the components above the gondola including the solar pointing system, ballast release systems, helium valves, parachutes, and the universal termination package (UTP). These subsystems are external to the gondola and required for the mission. The solar pointing system (SPS), or “rotator,” provides course pointing for the gondola either for Sun tracking for the solar arrays or for science payload orientation. The SPS can provide azimuthal orientation accuracy on the order of ±1°. The WASP requires implementation of the SPS. Ballast and venting systems are required to achieve the desired rate of climb and altitude control and is standard equipment. The BPO provides a system to terminate the balloon at the end of the mission. The UTP provides fully redundant UHF command receivers, command decoders and command execution for flight termination. The UTP has flown successfully more than 100 times. Standard balloon flight components are shown in Figure 5.8.

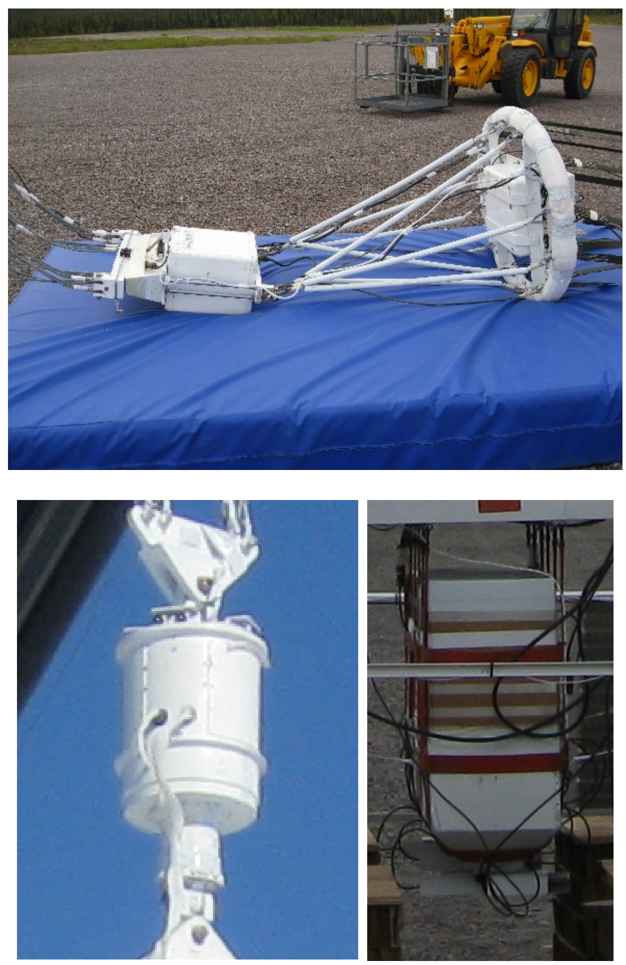


Figure 5.8.—UPT, SPS, and ballast hopper.

5.6 Ground Support

The BPO and CSBF provide all the required ground support equipment for operations. Ground support includes the site safety and ordinance and pressure system preparation, forklift operations, launch certification, balloon inflation, meteorology data support, etc. Ground station support is also provided. At Fort Sumner, there is a ~350 NM line-of-site range, a fully redundant telecommunications monitoring station, and the capability for transmitting data through the Internet or for digitally recording the data. The mission operations center (MOC) and the Remote Operations Control Center (ROCC) are provided for all launches as are down-range stations. Tracking and recovery of the payload is also provided. There are ROCCs located at the standard launch sites; however, a new ground station may be required in South America if long-duration launches are executed from New Zealand. The MOC at the Wallops Flight Facility (WFF) and a ROCC located at Fort Sumner are shown in Figure 5.9.

Figure 5.9.—WFF MOC (top) and ROCC (bottom).

6.0 Low-Risk and Near-Term Mission Implementation

6.1 Mission Overview

This section presents a concept design and mission to achieve decadal science with the notional platform discussed previously. This concept is for a near-term, low-risk, and high science value mission to demonstrate balloon science potential while reducing risk for future, more aggressive science campaigns.

For the point design, the assumption is that the mission is to be launched from Fort Sumner, New Mexico, and will carry a balloon-borne telescope for planetary object imaging over 10 to 24-hr flight duration. The gondola is designed to support a 1 m class telescope system with science based on Near UV to MIR observations of gas giants, ice giant systems, Pluto, Ceres, Vesta, the Moon, and other targets of opportunity.

The mission will gather roughly half a million 1 Mpixel visible and IR images during the mission. Images are stored on a 1 TB drive with one percent sent to the ground for sampling and the rest recovered on landing. Communications are provided by the Support Instrument Package (SIP), which is assumed to be off the shelf from CSBF. Accurate pointing is enabled by the WASP gimbal platform, which is aided by a daytime star tracker and azimuth pointing system. The WASP has a proven pointing capability of better than1 arcsec accuracy. The structural system is composed of aluminum frame and honeycomb aluminum (Al) shock absorption for safe recovery of telescope optics, assuming worst case of 10 g at balloon separation shock and 5 g at landing or ~25 ft/s. System Power is provided by lithium-ion batteries sized for 24-hr operations. The thermal system consists of 20 cm aerogel insulation around telescope to provide –70 °C temperatures for allowing IR imaging during daylight. The recommended balloon systems (provided by the NASA Balloon Office) is an approximately 25 MCF zero-pressure helium (He) balloon, with ~500 kg ballast deployed from hopper.

6.2 Mission Description and Concept of Operations (CONOPS)

A typical research balloon mission event timeline has been modified to include the science observations appropriate for the assumed launch date and available targets. The mission design and operations are based on four elements: 1) the planetary payload including the telescope, optical bench, instruments, and data storage; 2) The gondola system including all of the subsystems required to support the science payload and perform the mission (analogous to a spacecraft bus); 3) the balloon system including the balloon, termination system, parachute, etc. (analogous to a launch vehicle); and 4) the ground support systems. A top-level mission illustration is shown in Figure 6.1.

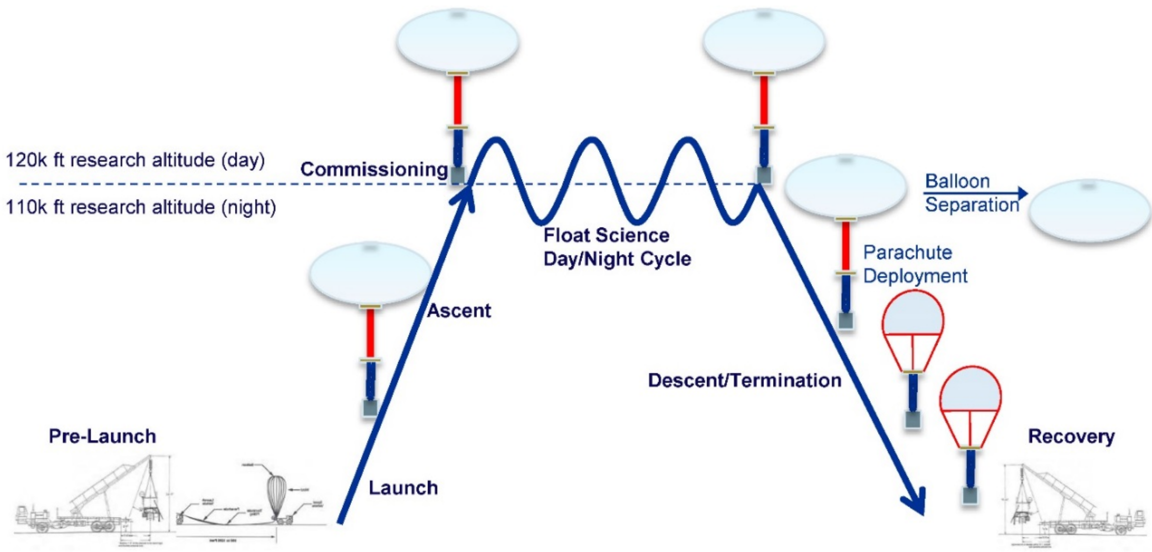


Figure 6.1.—Top-level CONOPS for the short-duration mission.

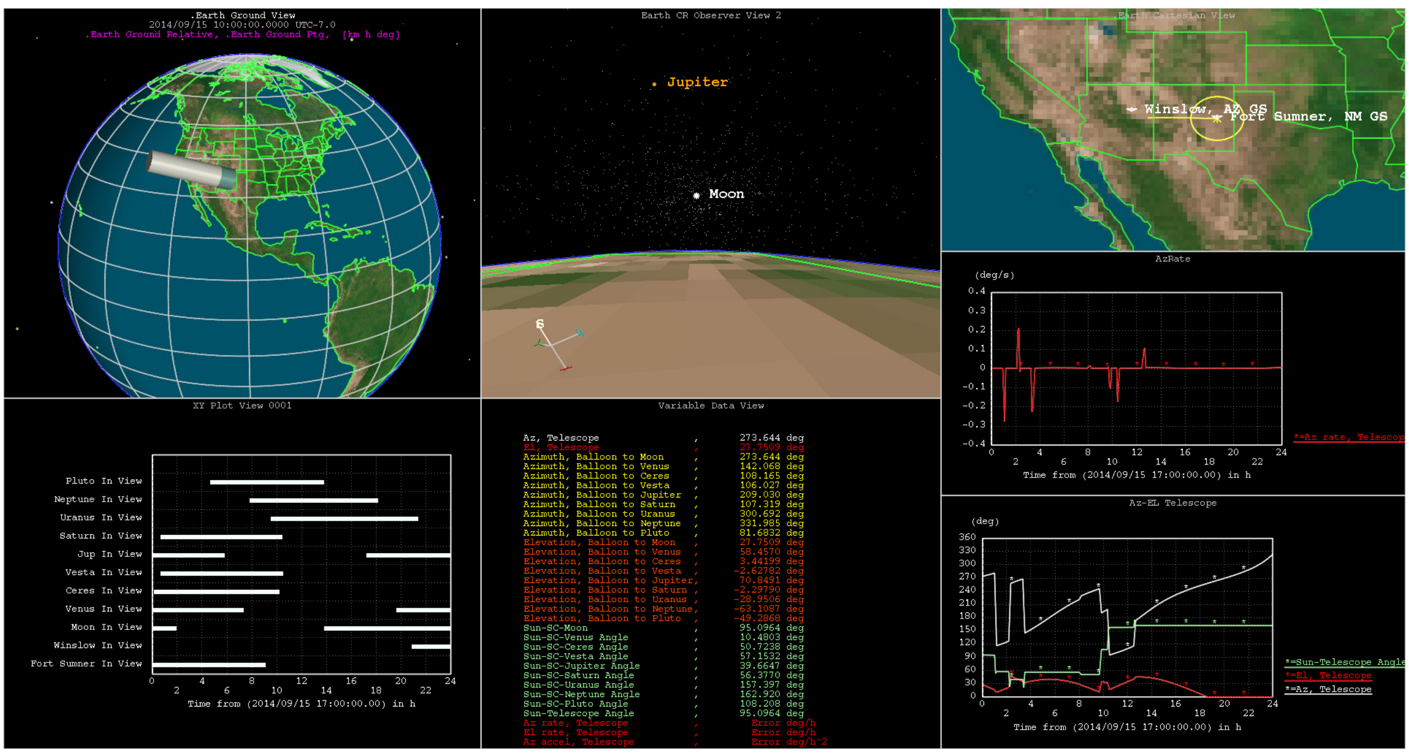


Figure 6.2.—SOAP Screen shot for the short-duration mission.

The science definition process identified several high-priority targets. The baseline science from a single flight from Fort Sumner includes more than 150,000 images of the Galilean satellites and Jupiter; the Saturnian, Uranian, and Neptunian systems' Ceres, Vesta, and Pluto. Observations include mapping atmospheric circulation patterns; searching for OH emission at Ceres; addressing the prevalence of CO_2, IR characterization of water, organics, and volatiles of airless bodies; and the characterization of the spectral nature of hydroxyl on Vesta to improve understanding of its origin. A notional observation schedule was derived based on visible targets for the launch date, and example targets were simulated using the mission visualization and orbital simulation tool, Space Orbit Analysis Program (SOAP). A SOAP screenshot is shown in Figure 6.2 and illustrates the telescope angle of elevation, azimuth, ground track, and viewing times of science targets. The BPO provides tracking for the mission and recovery of the gondola at Fort Sumner. The recovered gondolas are placed on a flatbed truck and returned to the launch location for the team to disassemble and take back to the holding institute. As mentioned earlier, the gondola will be designed to withstand the nominal landing scenarios, and be readily dissembled in a way that protects the high-value elements such as the OTA, instruments, and other components.

6.3 Flight System Design

6.3.1 Science Payload

The baseline science payload is a 1 m class classical Cassegrain or variant, telescope with dual-band optical bench and two instruments for observations over 300 nm to 5 µm and described in detail in Sections4.1.1 to 4.1.5. The requirements for the mirror (Figure 6.3) include a 15-Å RMS micro-roughness and a surface figure less than 10 nm RMS total. New hardware is assumed in the development schedules provided in Section 6.4. Notional cost estimates for a primary mirror only are shown in Table 6.1.

6.3.2 Science Data

The mission includes several hours of observations during the day followed by a night observations. The baseline observations include up to 4,000 images of the Moon; 4,000 images of Vesta; 36,000 images of Jupiter and Galilean satellites, Saturn, and its satellites; 2,000 images of Ceres; 2,000 images of Pluto; 36,000 images of Uranus and its moons; and 36,000 images of Neptune and its moons and targets of opportunity. Altogether, the baseline includes 400,000 images and 185 GB of data. Even with LOS communications, the data volume is too much to transmit during flight. Instead, one percent of the images will be transmitted to the ground for checking data quality and all of the images will be stored on solid-state drives and recovered after flight termination. All planetary science data will be entered into the appropriate node(s) of the Planetary Data System for future use and access by the broader community. This will typically occur within six months of data recovery, but could vary from mission to mission based on factors such as volume of data returned and number of targets observed.

6.3.3 Structures and Mechanisms

The primary structure of the gondola was sized using a heritage design. Secondary structures were checked and sized according to the anticipated loads and various standards. Crushable honeycomb blocks were sized for landing on land. Analytical methods utilizing a spreadsheet tool were employed to analyze the displacements and stresses from operations and landing (Figure 6.4).

Figure 6.3.—A 1-m class Cassegrain telescope primary mirror.

TABLE 6.1.—F/3 PRIMARY MIRROR COSTS ($K) AND SCHEDULE ESTIMATES

Blank Diameter	91 cm	100 cm	150 cm
Cost $k/Time	~$200/6m	~$250/6m	~$550/9m

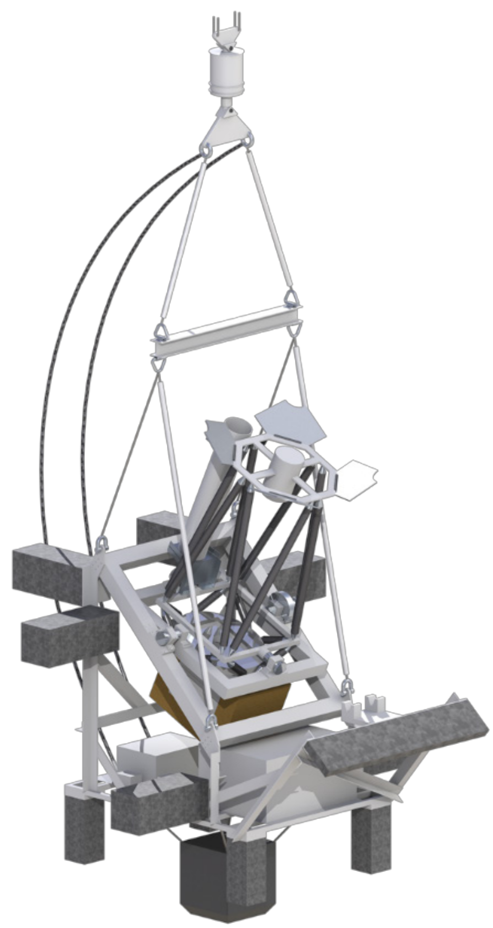


Figure 6.4.—Gondola

The gondola mass is supported by four tethers. Commercial nylon rope with a diameter of 19 mm (0.75 in) is specified. The requirements presented in the NASA Columbia Scientific Balloon Facility User Handbook (2006) (Ref. 16) were applied to determine the size of the rope needed. In addition, D-rings are used to tie to the gondola bus.

Commercial aluminum honeycomb is specified for the landing hardware to accommodate dry landing. An approach velocity of 7.6 m/s (25 ft/s) is anticipated. To limit the acceleration of the gondola to a maximum of 10 g, a minimum crush displacement of 29.6 cm (11.66 in.) is needed. Ten percent additional height was added to the minimum for a height of 33.0 cm (13.0 in.). The crush strength of the honeycomb is 170 kPa (25 psi). The landing load is assumed to stress the crush pads at the crush strength. Using a landing mass of 1000 kg (2200 lb), the needed total cross-sectional area of the crushable honeycomb for the gondola is 0.568 m^2 (880 in^2). With four pads the individual pads are 0.142 m^2 (220 in^2) divided equally. Using 33.0 cm (13.0 in.) tall by 37.6 cm (14.8 in.) square pads results in a mass of 0.752 kg (1.66 lb) per pad.

To size the side crush pads the gondola was modeled as a vertical beam falling over with an initial velocity of zero. An approach velocity of 12.7 m/s (41.7 ft/s) was calculated. Limiting the acceleration to a maximum of 10 g requires a minimum crush distance of 82.3 cm (32.4 in.). Ten percent additional height was added to the minimum for a height of 35.0 cm (13.8 in.). Assuming a mass of 500 kg (1100 lb) and a crush strength of 170 kPa (25 psi), the necessary total cross-sectional area for the crush pads is 0.284 m^2 (440 in^2). With two equal pads of rectangular cross section, the side dimension necessary is 37.6 cm (14.8 in.). The resulting mass of each side pad is 2.02 kg (4.454 lb).

The rear crush pads are identical to the side crush pads. The front crush pad is a single unit mounted to a protective frame cross member. The approach velocity is assumed to be the same as with the side crush pads at 12.7 m/s (41.7 ft/s). The minimum crush distance needed is 35.6 cm (14.0 in.). Adding approximately 10 percent yields a crush pad height of 38.1 cm (15.0 in.). The available width is 215.3 cm (84.75 in.). With a crush strength of 170 kPa (25 psi), the necessary cross-sectional area is 0.284 m^2 (440 in^2). The resulting depth is 9.4 cm (3.7 in.), and the resulting mass is 1.23 kg (2.704 lb).

Vertical members of the gondola were assumed to share the total load with 10 g acceleration shared between the two members. The load per vertical member would be 48.9 kN (11000 lb). The resulting stress is 37.9 MPa (5500 psi). The aluminum alloy 6061-T6 has a yield stress of 241 MPa (35 ksi) as per the Federal Aviation Administration's Metallic Materials Properties Development and Standardization (MMPDS) (2012) (Ref. 17). Applying a safety factor of 1.25 on the yield stress as a protoflight hardware per "Structural Design and Test Factors of Safety for Spaceflight Hardware" NASA STD 5001A (2008) (Ref. 18) provides an allowable stress of 193 MPa (28 ksi). There is a positive margin of 4.1.

The four support tethers were assumed to support a total of approximately 1770 kg (3900 lb). Assuming the four tethers share the load evenly, applying the payload factor of 10 per the NASA Columbia Scientific Balloon Facility User Handbook (2006) (Ref. 16), and factoring in the angle of the support, the load per tether is 5695 kg (12530 lb). A nylon rope of 19 mm (0.75 in) diameter, with a minimum breaking load of 5809 kg (12780 lb), is recommended. The linear density of the rope is 0.213 kg/m (0.143 lb/ft), resulting in a total weight of approximately 3.0 kg (6.6 lb).

The greatest structural risk for this design is the potential for excessive g-loads from impact of a foreign object, launch loads, or harsh landing process, which may cause excessive deformation, vibrations, or fracture to sections of the support structure. Consequences include lower performance from mounted hardware to loss of mission.

6.3.4 Thermal

The thermal system for the short-duration high-altitude balloon for planetary science applications mainly involves insulating the main telescope body to insure it can maintain its desired operating temperature. The main objective of the system was to regulate the temperature of the main collection mirror and insure that it would be at temperatures near 200 K (~ –70 °C) for at least part of the mission operation time. Insulating the telescope and utilizing radiators to remove heat from any electronics located within the insulated telescope enclosure accomplished this.

The telescope operation will take place in the upper atmosphere (~35 km). The thermal system is sized to operate in this environment. Solar Intensity and view angle as well as the view to warm bodies such as the Earth are used to determine the worst-case hot and cold conditions. The worst-case warm conditions will occur during the day, whereas the worst-case cold will be during the night. The primary elements of the thermal control include radiator panels, telescope insulation, avionics heating and cooling, temperature sensors, etc. The thermal components are illustrated in Figure 6.5.

The operating temperature of the telescope was determined through an energy balance between the heat input and loss to and from the surroundings. The main mechanisms for heat transfer to and from the telescope are listed below and shown in Figure 6.6:

- Solar radiation
- Radiation from Earth
- Radiation heat transfer to deep space
- Convective heat transfer to the atmosphere

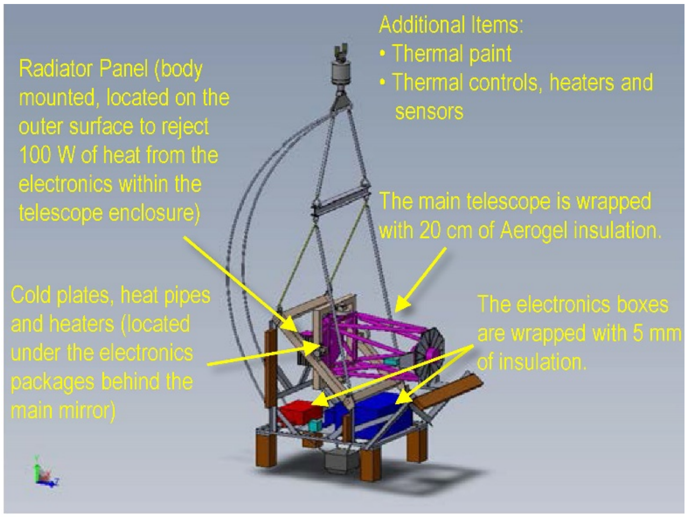


Figure 6.5.—Thermal system elements.

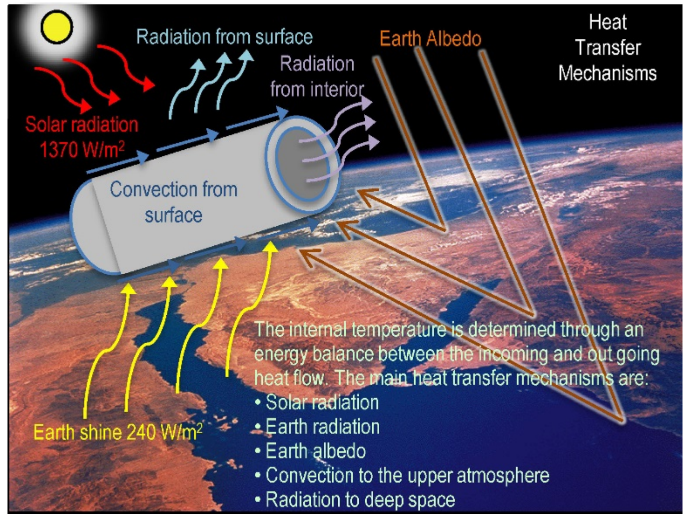


Figure 6.6.—Heat-transfer mechanisms for the system.

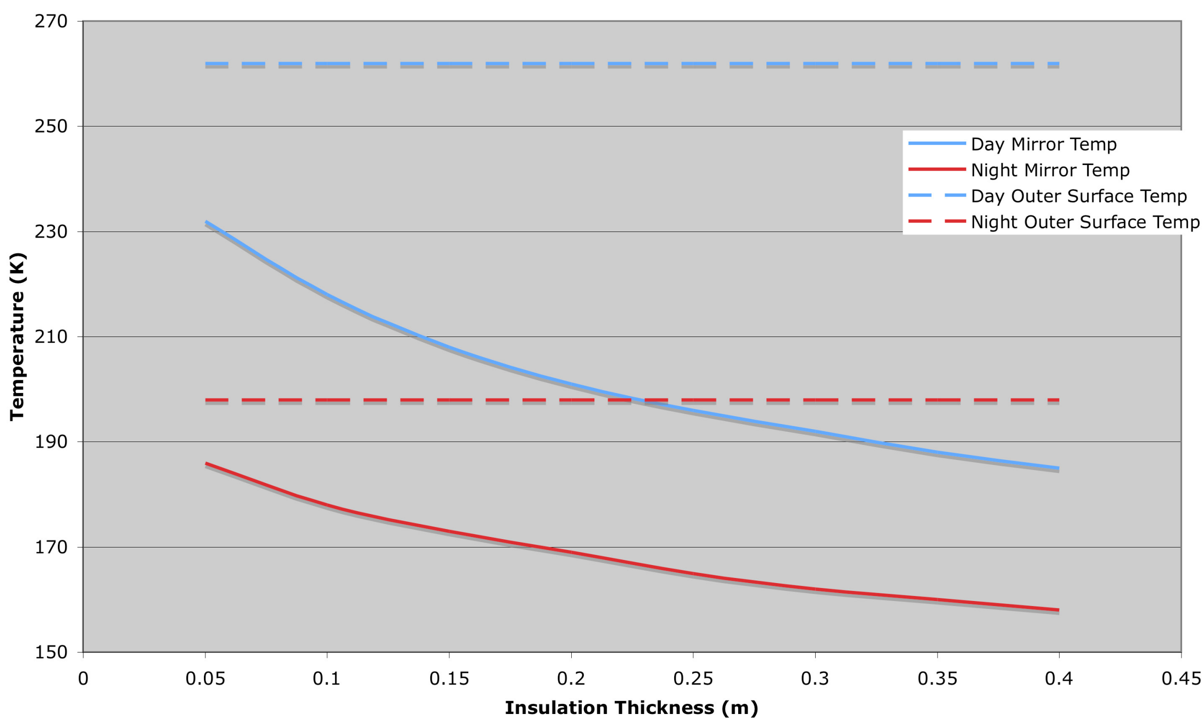


Figure 6.7.—Steady-state temperature versus insulation thickness.

Insulation is used to regulate the temperature of the telescope. The insulation thickness will determine the steady-state operating temperature of the telescope based on the energy balance. Although the atmosphere at the operating altitude is rarefied (0.0085 kg/m^3 density, 5.75 mBar pressure), there is still sufficient gas to prevent the use of multi-layer insulation (MLI); so Aerogel insulation was selected. If no insulation was utilized, the telescope's interior temperature would be the same as the outer surface temperature shown by the dashed lines in Figure 6.7. These results show that approximately 20 cm of insulation will enable the telescope's interior and primary mirror to remain at or below the desired –70 °C (~203 K) operating temperature throughout the mission. This insulation thickness was selected as the baseline for sizing the insulation mass and volume.

Waste heat from the internal components as well as electric heaters is used to provide heat to the platform components if needed to maintain the electronics above –20 °C. Flat plate heaters are used on the cold plates and within the electronics boxes to provide heat to the electronics if necessary. The heaters utilized are flexible Kapton resistance heaters. The heaters have an aerial mass of 0.05 g/cm^2. Thermal control is accomplished through the use of a network of thermocouples whose output is used to control the power to the various heaters. A data acquisition and control computer is used to operate the thermal system. The heaters will be strip heaters evenly distributed along the inside of the insulation of the launch tube. An example of these heaters is shown in Figure 6.8. Electric heaters were selected because their output can be easily controlled, and they provide reliable thermal control.

6.3.5 Power

Due to the short-duration mission, the power for the system is provided by primary batteries. Table 6.2 provides the power and energy requirements for the mission. The calculations assume both a 30 percent power-growth allowance and a 30 percent power-duration growth allowance consistent with the maturity of the design. The total energy requirement for the entire mission is 8,554 W-hr. The system is designed to operate at 28 Vdc. Batteries will be maintained at temperatures between 0 and 55 °C and enclosed by a 1-in.-thick layer of aerogel insulation.

The battery is made of 15 off-the-shelf Li-SO_2 battery packs. An aluminum enclosure houses the battery regulation and power distribution cards. The power system components are all TRL 9 from the CSBF.

The long duration missions will require solar power based system. This is addressed in Section 7.3.5.

6.3.6 Guidance, Navigation, and Control (GN&C)

The GN&C design consists of a two-stage pointing system with coarse and fine components. Developed at the WFF, the coarse azimuth rotator serves as the course pointing system, pointing the entire gondola in azimuth with an accuracy in both pointing knowledge and control of ±1°. For fine-pointing control, the WASP then points the telescope to the desired target to within ±1 arcsec. The WASP essentially consists of an orthogonal pair of pitch and yaw gimbals that are mounted on the gondola via an outer and inner frame respectively. The arcsecond pointing accuracy is enabled by the mechanical design of the WASP gimbal hubs. A pair of hubs on opposing sides of the gimbal is used to establish each articulated axis of rotation. Each hub uses high-precision angular contact bearings to float the rotor side and stator side of the hub on a central shaft. The central shaft in each hub is itself rotated by a small-diameter

Figure 6.8.—Strip heaters for heating required elements.

TABLE 6.2.—F/3 POWER AND ENERGY REQUIREMENTS BY MISSION MODE

	Power Mode 1	Power Mode 2	Power Mode 3	Power Mode 4	Power Mode 5	Power Mode 6	Power Mode 7	Power Mode 8
	Pre-Launch	Launch	Ascent	Commissioning	Science Float, day	Science Float, Night	Descent & Termination	Recovery
Duration (hr)	1.3	0.01	2.0	2.0	6.5	6.0	0.67	6.0
Duration with growth (hr)	1.7	0.01	2.6	2.6	8.5	7.8	0.87	7.8
Power required with growth (W)	250	290	290	380	380	380	120	21
Energy required with growth (W-hr)	430	4.2	746.99	980	3200	2900	100	170

torque motor through a gear-reduction box to eliminate static friction. The shafts in each hub pair are counter-rotated in an attempt to reduce the residual kinetic friction that must be corrected by the control system. Pointing knowledge of the telescope is provided by a WFOV star tracker that is capable of operating during the day along with an LN251 integrated INS/GPS navigation system. The star tracker is mounted to the top of the telescope allowing it to be pointed in the same direction as the telescope. The placement of the GN&C components for the design can be seen in Figure 6.9, and Figure 6.10 shows notional pointing system architecture.

6.3.7 Mass Equipment List (MEL) and Configuration

The MEL shown in Table 6.3 captures the bottoms-up estimation of the current best estimate (CBE) and growth percentage of the gondola system that the subsystem designers calculated for each subsystem. For this balloon study, an allocation to meet the 30 percent system-level growth is necessary only on the basic dry mass of the gondola hardware. The system level growth is in addition to the growth calculated on each of its individual subsystems. The additional system-level mass is counted as part of the total mass to be lifted by the balloon. For the gondola, with the bottoms-up 16 percent growth on dry mass, an additional 14 percent is carried to reach a total growth of 30 percent. For the payload, the aggregate growth is 39 percent; no additional growth is carried at system. As for the balloon, the balloon material and systems carry only four percent growth, and no additional system-level growth is added due to hardware maturity of a basic system. Light weighting of structure and other subsystems are not considered as mature.

The lift capability was calculated in order to measure whether the design fits within the balloon performance of the 29.47 MCF zero-pressure high-altitude balloon. The gondola system included the ballast container, the structure, communications, WASP, and SIPS system. The ballast itself is the material released as the balloon altitude drops below required limits. The planetary payload system is an assumed system provided by the customer, and has no additional growth added at the system level. It is assumed to already contain 40 percent growth on the systems. The balloon systems contain everything in the balloon work breakdown structure (WBS) aside from the balloon material (also referred to as skin) and the He gas. Summary of the lifted systems is provided in Table 6.4.

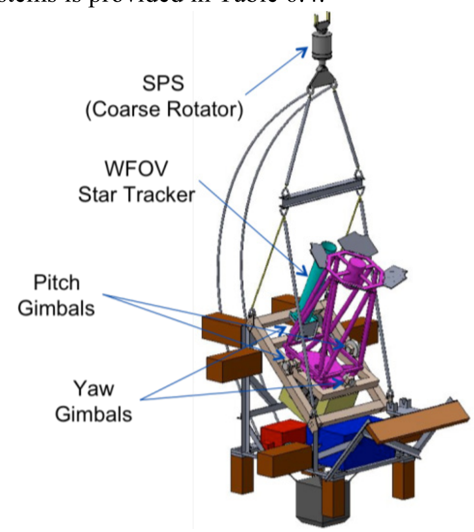


Figure 6.9.—GN&C Components.

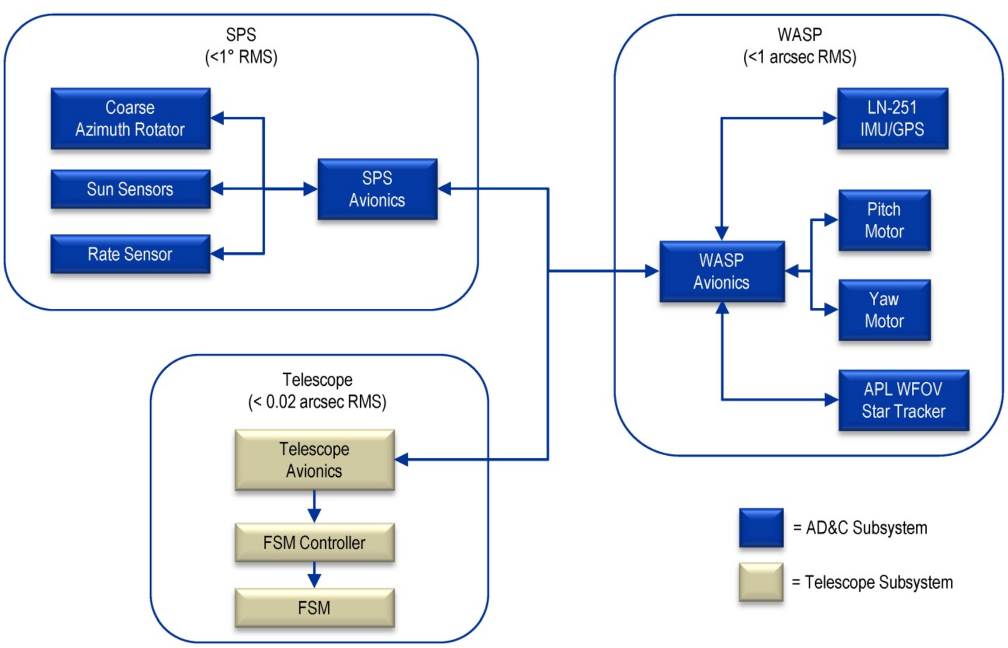


Figure 6.10.—Notional Pointing System Architecture

TABLE 6.3.—MASS BREAKDOWN OF THE BALLOON ELEMENTS

(a) Main subsystems

WBS	Main Subsystems	Basic mass, kg	Growth, kg	Predicted mass, kg	Aggregate growth, %
06	High Altitude Balloon for Planetary Science	4210.8	311.3	4522	
06.1	Gondola System	1170.9	135.3	1306	12%
06.1.2	Attitude Determination and Control	360.3	45.4	406	13%
06.1.3	Command & Data Handling	123.5	16.2	140	13%
06.1.4	Communications and Tracking	0.0	0.0	0	TBD
06.1.5	Electrical Power Subsystem	94.2	18.4	113	20%
06.1.6	Thermal Control (Non-Propellant)	10.9	1.6	13	15%
06.1.11	Structures and Mechanisms	295.3	53.1	348	18%
	Element 1 consumables (if used)	0		0	
	Estimated Spacecraft Dry Mass (no prop, consumables)	1171	135	1306	12%
	Estimated Spacecraft Wet Mass	1171	135	1306	
System Level Growth Calculations Gondola System					Total Growth
	Dry Mass Desired System Level Growth	1171	351	1522	30%
	Additional Growth (carried at system level)		216		18%
	Total Wet Mass with Growth	1171	351	1522	
06.2	Planetary Payload System	238.8	93.2	332	39%
06.2.1	Payload	221.4	90.6	312	41%
06.2.6	Thermal Control (Non-Propellant)	17.3	2.6	20	15%
	Element 2 consumables (if used)	0.0		0	
	Estimated Spacecraft Dry Mass	239	93	332	39%
	Estimated Spacecraft Wet Mass	239	93	332	
System Level Growth Calculations Planetary Payload System					Total Growth
	Dry Mass Desired System Level Growth	239	72	310	30%
	Additional Growth (carried at system level)		–22		–9%
	Total Wet Mass with Growth	239	72	310	
06.3	High Altitude Balloon	2801.1	82.8	2883.9	3%
06.3.2	Attitude Determination and Control	0.0	0.0	0.0	TBD
06.3.3	Command & Data Handling	0.0	0.0	0.0	TBD
06.3.5	Electrical Power Subsystem	0.0	0.0	0.0	TBD
06.3.7	Propulsion (Balloon)	2069.9	82.8	2152.7	4%
06.3.8	Propellant (Balloon Gas)	731.2		731.2	0%
06.3.9	Propulsion (Aux Hardware)	0.0	0.0	0.0	TBD
06.3.10	Propellant (Aux)	0.0		0.0	TBD
06.3.11	Structures and Mechanisms	0.0	0.0	0.0	TBD
	Element 3 consumables (if used)	0.0		0.0	
	Estimated Spacecraft Dry Mass	2070	83	2153	4%
	Estimated Spacecraft Wet Mass	2801	83	2884	
System Level Growth Calculations High Altitude Balloon					Total Growth
	Dry Mass Desired System Level Growth	2070	621	2691	30%
	Additional Growth (carried at system level)		538		26%
	Total Wet Mass with Growth	2801	621	3422	

(b) Summary Mass Calculations

	Basic mass, kg	Growth, kg	Predicted mass, kg	Aggregate growth, %
Total dry mass	4211	311	4522	
Total wet mass	3480	311	3791	16%
Dry mass desired system level growth	3480	1044	4523	30%
Additional growth (carried at system level)		733		14%
Total useable propellant	0		0	
Total trapped propellants, margin, pressurant	0		0	
Total inert mass with growth	4211	1044	5254.64	
Total wet mass with system level growth	4211	1044	5255	

TABLE 6.4.—EARLY ESTIMATE OF BALLOON SYSTEM MASS SUMMARY

WBS		Basic mass, kg	Growth, kg	Predicted mass, kg	Growth on dry, %
06	High Altitude Balloon for Planetary Science				
	Gondola + Ballast + Payload + Balloon Systems (Lift Capability)	1812	378	2190	
	Gondola + Ballast + Payload (aka Suspended Mass)	1410	362	1772	32%
06.1	Total Gondola System, Growth	896	269	1165	30%
	Total Ballast (in gondola)	275	0	275	N/A
06.2	Total Planetary Payload System, Growth	239	93	332	39%
06.3	Balloon Total Mass (Material, Systems, Gas)	2801	83	2884	4%
	Balloon material	1668	67	1735	4%
	Balloon Systems	402	16	418	4%
	Total Balloon Gas (in balloon)	731	0	731	N/A
	Gross Mass (Gondola + Payload + Balloon - He)	3480		3924	kg

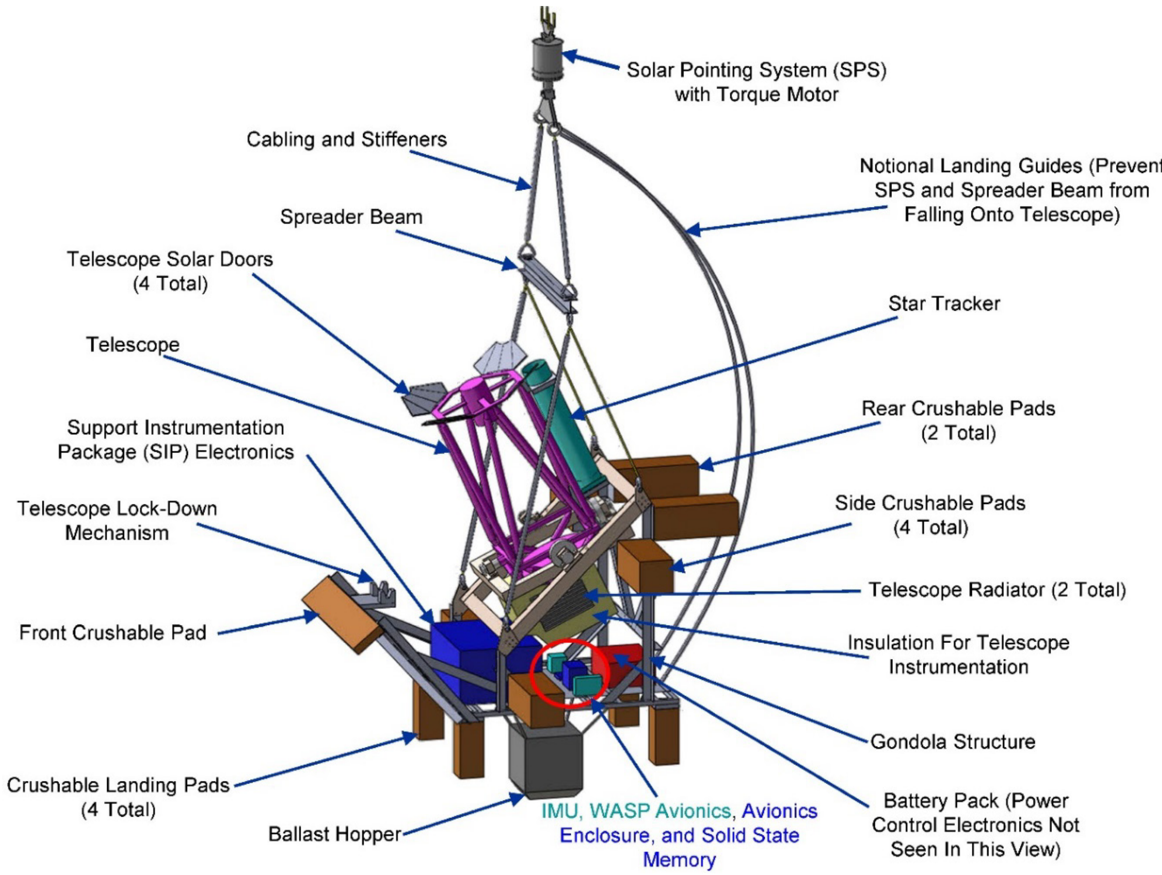


Figure 6.11.—Configuration design of the short-duration flight system.

The bottoms-up design of the gondola lift mass was required to fit inside of the balloon's lift performance. For the design, the balloon performance had a margin of 532 kg above the total mass assuming 29.47 MCF with 30 percent growth on the dry elements of the design. Configuration of the baseline design is shown below in Figure 6.11. Note: this mass estimate is one concept only, and may not include all solutions/system elements.

6.4 Development Schedule

An aggressive development schedule was created to determine the ability to rapidly develop and fly a planetary science gondola. Even if pre-procuring a primary mirror is likely to occur, the ability to procure, test, and integrate the telescope with a new gondola system was not faster than 1 year. In fact, estimates to design and build a non-light-weighted optical telescope assembly (OTA) are generally in the 12 to 18 month range. BRRISON demonstrated that the platform can be a rapid response tool assuming the main elements (like the telescope) are available. BRRISON instruments and structure was designed and fabricated in under a year, but that pace was enabled by an existing telescope, pointing system and general avionics. A more comfortable development period is in the 24-month range. However, preparing for a reflight is expected to take under a year assuming no major rework items.

6.5 Development Cost

The rough order of magnitude (ROM) costs of a planetary science balloon mission were estimated as an early part of this study using basic parametric tools.

However, the best estimates of a balloon platform development for planetary science is in the actual costs of recent missions namely the Balloon Rapid Response for ISON (BRRISON) and the Balloon Observation Platform for Planetary Science (BOPPS). The BRRISON and BOPPS missions and their costs are described in Section 9.3. The details of the parametric cost estimates are provided for reference in Appendix A. It should be noted that the parametric cost models reflect a lower estimate than what was experienced on the recent missions. This is due to tight schedule constraints, the procurement/development approaches, and lack of accurate cost data in the parametric databases for this type of system. It should also be noted, there has not been a gondola developed for planetary science observations for over 40 years.

7.0 Science Optimized Mission Implementation

7.1 Mission Overview

The study team evaluated the potential of a light-weighted long duration planetary science balloon mission after fine pointing has been demonstrated and long-duration sites are available for nighttime science campaigns. The biggest single differentiator for the long-duration flight is the need to use light-weighted optics and systems to meet the mass limitations of super-pressure long-duration balloons. This mission would capture more than two-thirds of the decadal survey objectives identified and serve as a multi-flight high-value asset. The decadal class science objectives required additional thermal control, an advanced optical bench to provide a cooled optical path for IR observations, and overall improved optical performance.

The target mission design begins with a launch from New Zealand with a planned 100 days of time aloft. This long duration, while requiring longer term systems such as a pressurized balloon, solar arrays, and satellite communications, provides unique cost effective science. Additionally, placed above 99 percent of the atmosphere, it provides planetary science at resolutions approaching HST and MIR spectroscopy over a broader wavelength range than possible from SOFIA. The planned science includes near-UV to MIR observations of gas giant and ice giant systems, Pluto, Ceres, Vesta, the Moon, and other targets of opportunity (such as comets and asteroids) for 12 hr at night and 2 hr during daylight. Daytime science has thermal and power limitations as discussed in Section 7.3.4 and 7.3.5.

The nominal 100-day mission is expected to net 26 million 1-Mpixel visible and IR images that will be stored on a 12 TB drive; one percent are transmitted to ground for sampling, while the remaining science is recovered on landing. Key to the design is accurate and stable pointing of the telescope, which is accomplished by use of daytime star trackers, an azimuth pointing system, and a proven WASP pointing platform capable of subarcsecond accuracy. Finer pointing is provided within the optical path itself.

The power system for the science operations utilizes a fixed solar array that charges lithium-ion batteries for 100-day fall/winter operations. The fixed solar array design greatly simplified the mass of the design—the azimuth pointing system pointed the solar array during daytime battery charging operations, but then was used to point the telescope for primarily night-time science operations. The balloon control system has its own independent power system using solar arrays wrapped around the periphery of the bottom of the gondola.

The thermal system used 20 cm aerogel insulation and a pumped-looped radiator system to maintain the telescope at sufficiently low temperatures to allow IR imaging during the nighttime and short daytime operations. The structural system used an aluminum frame and honeycomb Al shock absorption for safe recovery of telescope optics assuming 10 g shock at balloon separation and 5 g shock at landing up to 25 ft/s. The balloon systems are assumed to be procured from the NASA Balloon Office, and CSBF included an ~18 MCF super-pressure He balloon, a ~250 kg ballast/hopper, and off-the-shelf balloon control, parachute recovery, navigation, satellite communications, and gondola control systems.

7.2 Mission Description and CONOPS

Much of the mission operations will be similar to the short-duration flight described in Section 6.0. However, there are a few unique aspects of the long-duration super-pressure balloon flight. The long-duration mission CONOPS, shown in Figure 7.1, launches the mission from Wanaka, New Zealand, ascends to an altitude of 110,000 ft, and then remains at a relatively stable altitude. The gondola performs a ballast maneuver to rapidly transit the troposphere, but does not require significant ballast drops each day/night cycle to return to float altitude. The

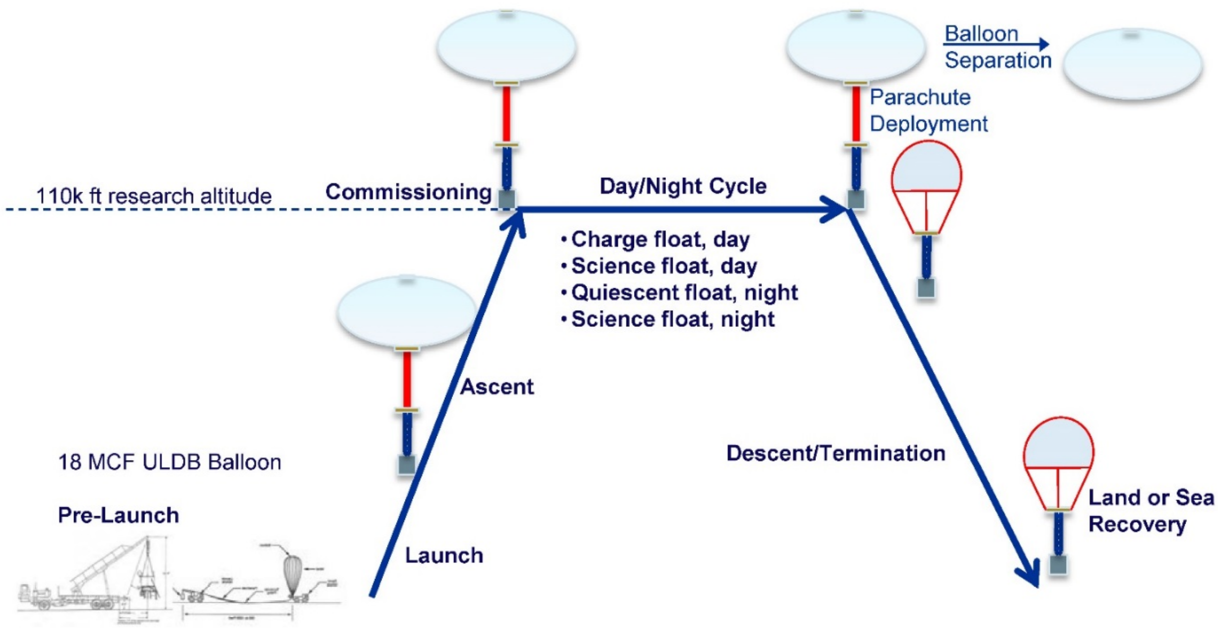


Figure 7.1.—Top-level CONOPS for the long-duration mission.

balloon will circumnavigate the Earth multiple times before a planned flight termination over South America. A visualization of the notional balloon trajectory is shown in Figure 7.2.

The Space Orbit Analysis Program, or SOAP, was used for mission simulation and visualization during the mission operations planning. A ground station representing Wanaka, New Zealand (–44.7° S latitude, 169.15° longitude) was created in SOAP along with a "SOAP platform" that represented the telescope, and this platform was placed at the nominal altitude of 33.5 km above the ground station. To obtain a reference trajectory, an assumption was made that the telescope would simply have a constant velocity equal to the wind speed at the altitude of the telescope. The wind speed was assumed to be constant in both magnitude and direction throughout the mission. The magnitude and direction of the winds were obtained from the Earth Global Reference Atmospheric Model (GRAM) 2007 program and was equal to 80.5 km/h due east. As a result, the telescope followed a trajectory of constant latitude (–44.7°) with a velocity of 80.5 km/h due east.

Each science target was simulated with SOAP to determine the time and pointing requirements. Representative small bodies were included: Make as a representative KBO, Hektor as a representative Jupiter Trojan, etc. The telescope was then commanded to each target to define the mission operations, slew rates, required elevation angles, angles from the Sun, etc. Figure 7.3 illustrates a snapshot of April 1, 2016. The pane in the lower left represents the time that the targets are in view of the telescope for a 24-hr period. The pane in the top middle portion represents the current view from the telescope. The pane in the lower middle shows the current azimuth and elevation of the telescope along with the current angle from the telescope to the Sun. The large pane on the right shows current values for the azimuth and elevation of all of the targets from the telescope and the angle from the telescope to the Sun if the telescope was pointing at that target.

During daytime CONOPS planning, a constraint was placed on observations that the telescope cannot look within 40° of the Sun. Several targets are often available; however, when the system is not performing science, the telescope will rotate for maximum power generation to store energy for the nighttime science observations.

As with short duration flights, the BPO provides tracking for the mission and recovery of the gondolas. Depending on locations and conditions, the recovered gondolas are returned in different degrees of assembly. The design reference mission developed here is intended to be disassembled into masses and volumes that recovery teams can readily transport back to the launch location. The gondola will be designed to withstand the nominal landing scenarios, and be readily dissembled in the expected environmental conditions such that the high-value elements such as the OTA, instruments, and other components are protected.

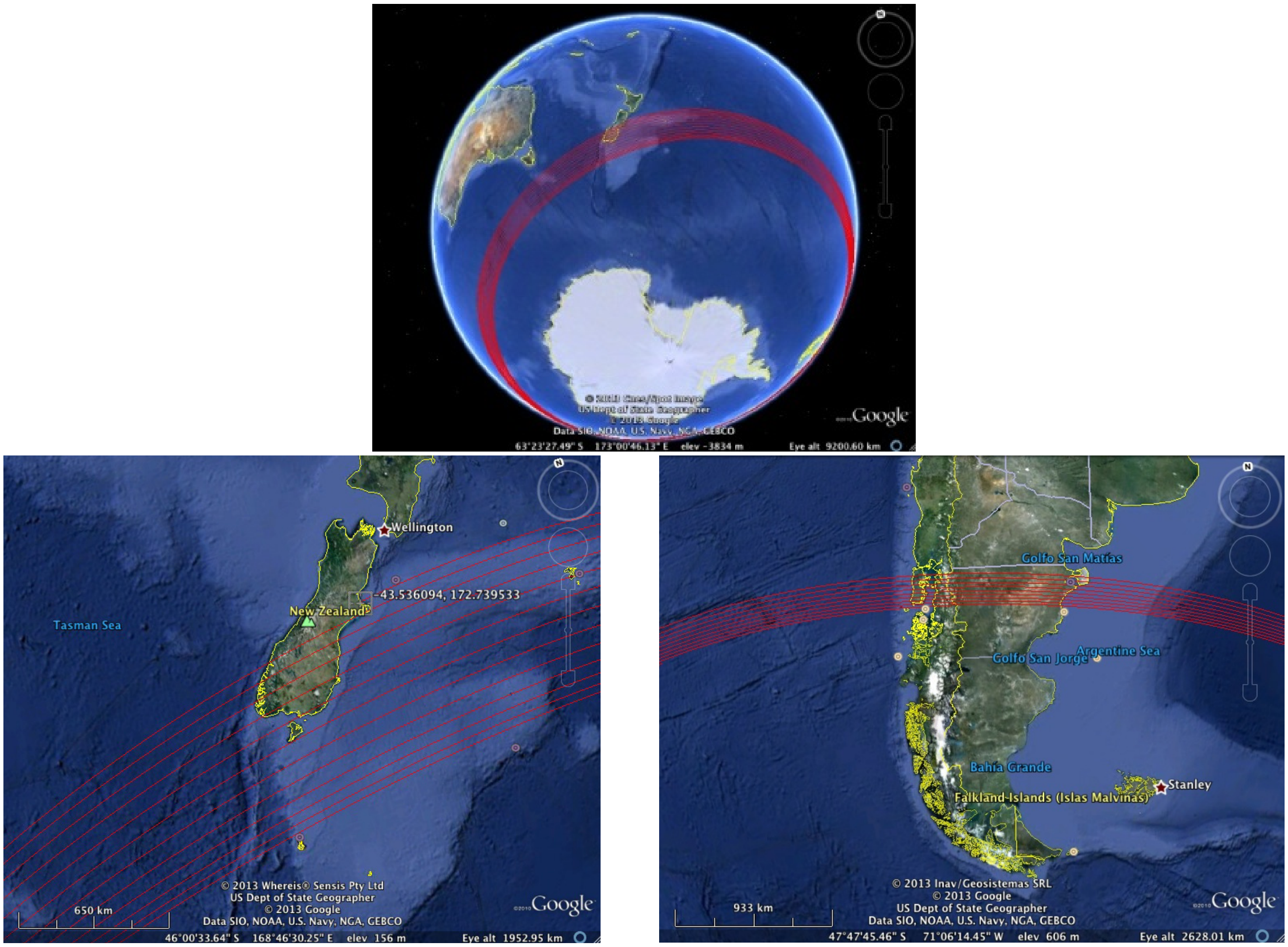


Figure 7.2.—Notional balloon ground track from a New Zealand launch.

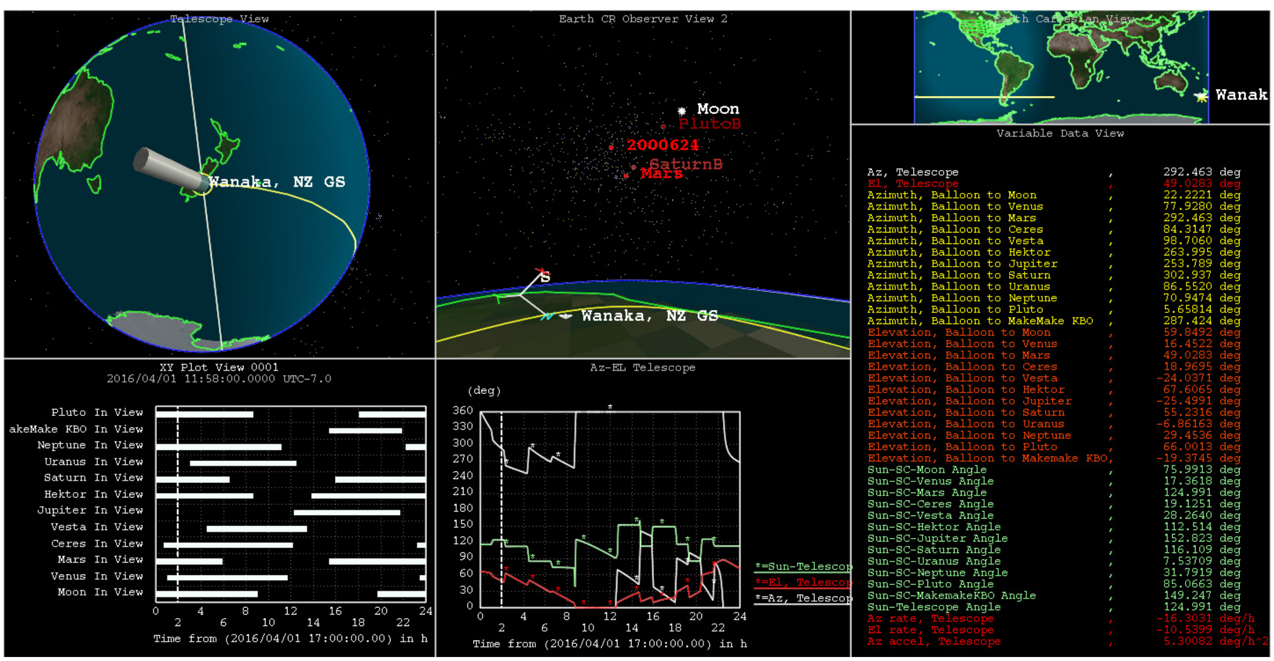


Figure 7.3.—Top-level CONOPS for the short-duration mission.

7.3 Flight System Design

Most of the elements of the flight system design are identical to those described in the short- duration zero-pressure balloon mission in Section 6.3. A system block diagram is shown in Figure 7.4. The diagram shows three main subsystems: the planetary telescope, the gondola including science support systems, and the balloon systems. These three systems are based on functional separations rather than spatial; thus, one can have items that are from the balloon systems that actually mount to the telescope or gondola. This approach allows for a cleaner WBS and cost assignments by supplier (e.g., the Balloon Office may provide the balloon systems). The balloon systems' main functional items include the balloon, vent system, SPS, SIP, with dedicated battery and communications antenna, navigation instruments, and ballast systems. The telescope incudes the telescope itself and its fine-pointing mechanism as well its command and data handling system, thermal control system, and power interfaces. The telescope also carries the science memory device, which is recovered at landing along with all of the science data. The telescope has the WASP gimbal control electronics. The gondola is primarily the structure and science power system along with the WASP gimbal because it is integrated into the gondola structure.

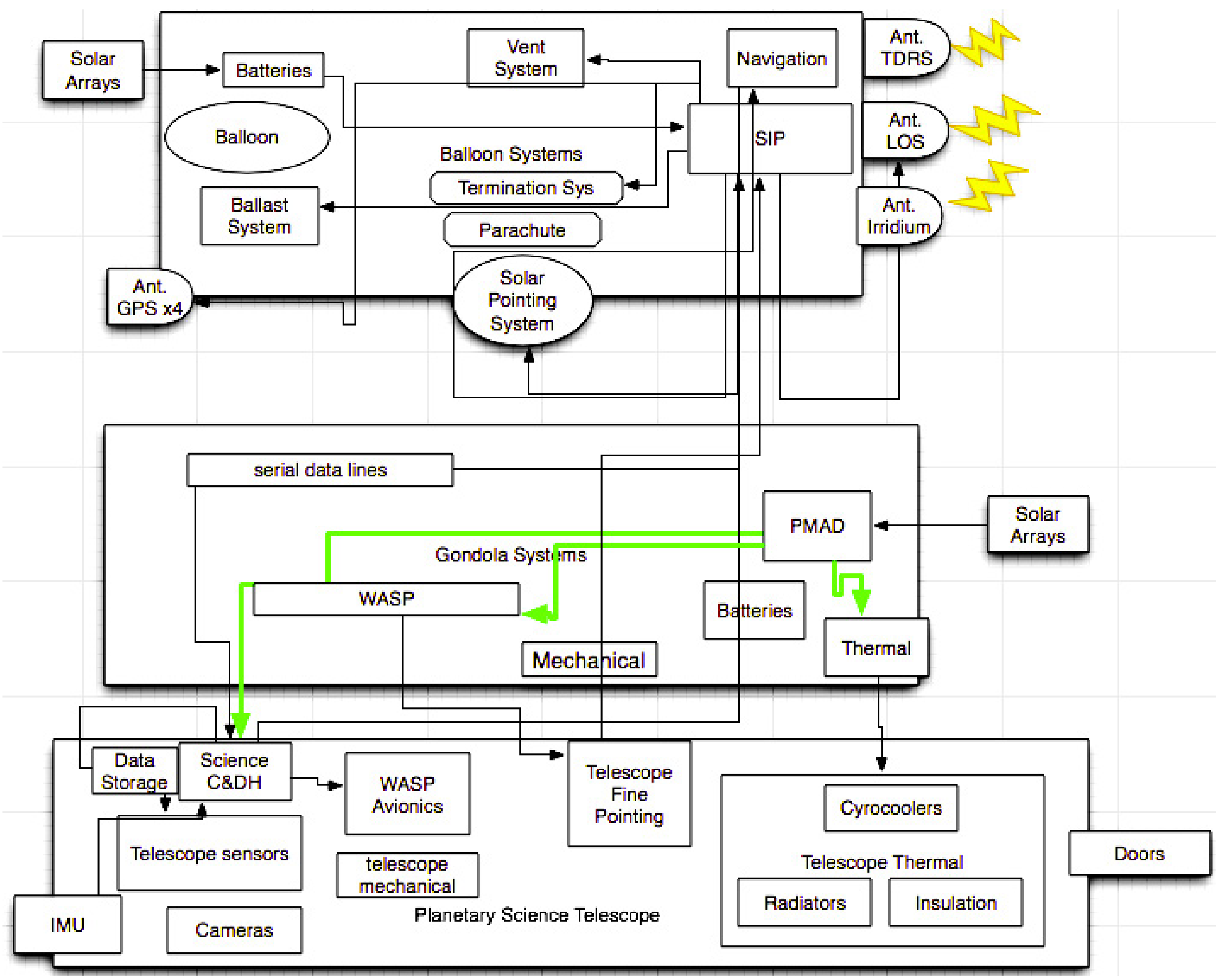


Figure 7.4.—Top-level CONOPS for the short-duration mission.

Figure 7.5.—Light-weighted Zerodur blank.

TABLE 7.1.—LIGHT-WEIGHTED PRIMARY MIRROR (ONLY) COSTS ($K) AND SCHEDULE ESTIMATES.

Blank Diameter	110 cm	160 cm	210 cm
F/1.5–3.0	$1,000/6m	$2000/10m	$3000/15m

7.3.1 Science Payload

The biggest change to the science payload to enable long-duration flights is the necessity for the telescope design to be based on a light-weighted telescope. The mirrors must be polished from an 80 percent light-weighted Zerodur blank, shown in Figure 7.5. Other low thermal expansion materials were considered, primarily for cost advantages, but only Zerodur is expected to yield the optical performance desired. Quotes for primary mirror costs and schedules were requested from this study. Additional schedule required for polishing and testing the surface is provided in Table 7.1. A Magneto-Rheological Finishing (MRF) process is assumed, which should yield savings for higher quality optics. A faster telescope design was expected to have a large cost penalty; however, using the MRF process, the quotes for an F/1.5 mirror of the desired optical quality was estimated to cause less than a 10 percent cost increase. Due to reduced system length and packaging advantages, the faster optics is selected. Note that the schedule times shown below are the manufacturing and testing times assuming the Zerodur blank is available. Otherwise, an additional 9-month allocation is necessary to deliver the lightweight blank.

While the telescope is light-weighted, the general design is fundamentally the same as the short- duration mission. The telescope is a Serrurier truss design classical Cassegrain telescope, or variant, mounted to the WASP with the primary mirror placed in front of the inner gimbal, and the secondary mirror mounted on a hexapod. The optical bench and instruments are placed behind the gimbal to counterbalance the mass, and place the center of gravity near the center of the WASP. The telescope includes several baffles to minimize the stray light entering the telescope. The telescope includes 20 cm of insulation around the OTA to maintain the desired temperatures and to minimize thermal gradients. An illustration of the telescope assembly without the insulation is shown in Figure 7.6.

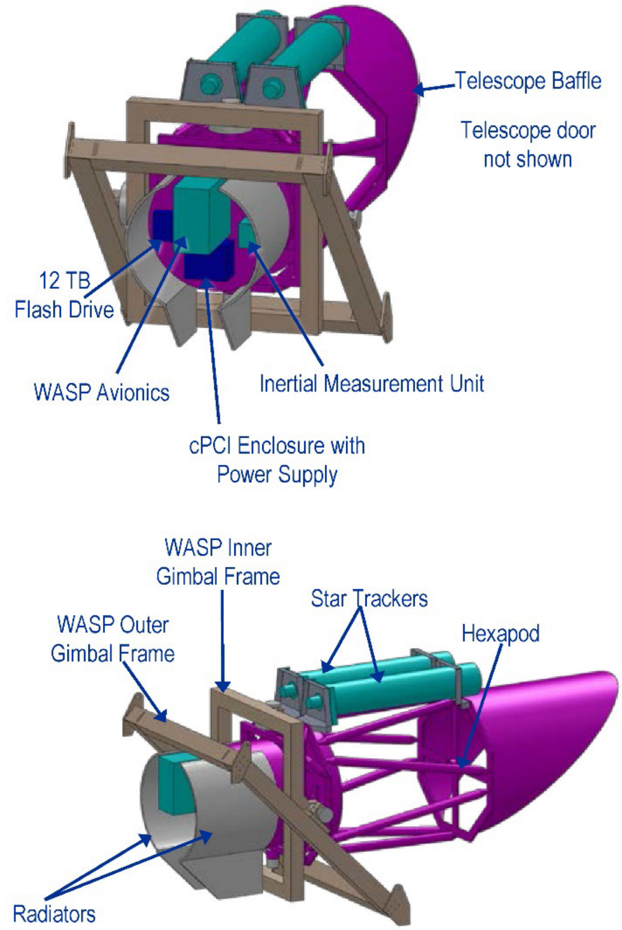


Figure 7.6.—Telescope assembly without insulation shown.

7.3.2 Science Data

Over a 100-day mission, the science targets available depend on the observation windows with many targets having potential repeated observations over the 100-day span to capture temporal variations. The baseline science assumes 10-min transition and settling time between targets. The mission could include images of the Moon, Venus, main belt asteroids, Jupiter Trojan asteroids, Kuiper Belt Objects, icy satellites of Uranus and Neptune, Io global heat flow mapping, Mars for transient or localized methane, Mars dust clouds, etc. Based on integration times and science operations scheduling, it is estimated to produce on the order of 26 million images. Like the short-duration mission, one percent of the images will be transmitted through the communication system while 12 TB of solid-state drives will store all images to be recovered after flight termination. The science data will be enclosed in a waterproof "black box" container to allow recovery in the event of a catastrophic failure.

7.3.3 Structures and Mechanisms

The structures are very similar to the short-duration balloon, although many of the elements are sized for the lower mass requirements. The initial assumption was to use steel for its low cost and simple welding. In an effort to reduce weight, the gondola was specified with aluminum with the majority of the components being riveted.

The primary structure of the gondola was sized using a heritage design. Secondary structures were checked and sized according to the anticipated loads and various standards. Crushable honeycomb blocks were sized for landing on land. Analytical methods utilizing a spreadsheet tool were employed to analyze the displacements and stresses from operations and landing.

The gondola mass is supported by four tethers. Commercial steel cable with a diameter of 13 mm (0.50 in) is specified. The requirements presented in the NASA Columbia Scientific Balloon Facility User Handbook (2006) (Ref. 16) were applied to determine the size of the wire rope needed. In addition, D-rings are used to tie to the gondola bus.

Commercial aluminum honeycomb is specified for the landing hardware to accommodate dry landing. An approach velocity of 7.6 m/s (25 ft/s) is anticipated. To limit the acceleration of the gondola to a maximum of 10 g, a minimum crush displacement of 29.6 cm (11.66 in) is needed. Ten percent additional height was added to the minimum for a height of 33.0 cm (13.0 in) to provide some margin. The crush strength of the honeycomb is 170 kPa (25 psi). The landing load is assumed to stress the crush pads at the crush strength. Using a landing mass of 2500 kg (5500 lb) the needed total cross-sectional area of the crushable honeycomb for the gondola is 1.42 m^2 (2200 in^2). With four pads, the individual pads are 0.355 m^2 (550 in^2) divided equally. Using 33.0 cm (13.0 in.) tall by 59.7 cm (23.5 in) square pads results in a mass of 1.9 kg (4.14 lb) per pad.

The mass of the vehicle is shared equally at the corners of the gondola base. As a result, each vertical member bears approximately one-fourth of the mass under a potential 10 g acceleration. The load per vertical member would be 61.2 kN (13750 lb). The resulting stress is 47.4 MPa (6880 psi). The aluminum alloy 6061-T6 has a yield stress of 241 MPa (35 ksi) as per the MMPDS (2012) (Ref. 17). Applying a safety factor of 1.25 on the yield stress, as a protoflight hardware per NASA STD 5001A (2008) (Ref. 18), provides an allowable stress of 193 MPa (28 ksi). There is a positive margin of 3.1.

The four support tethers were assumed to support a total of approximately 2500 kg (5500 lb). Assuming the four tethers share the load evenly, applying the payload factor of 10 per the NASA Columbia Scientific Balloon Facility User Handbook (2006), and factoring in the angle of the support, the load per tether is 6650 kg (14630 lb). A steel wire rope of 13 mm (0.5 in.) diameter, with a minimum breaking load of 95.2 kN (21400 lb), is recommended. The linear density of the rope is 0.63 kg/m (0.42 lb/ft), resulting in a total weight of approximately 9.5 kg (21 lb).

7.3.4 Thermal

The thermal environment is nearly the same at float altitude as the short-duration mission; however, the lower thermal inertia, the desire to maintain lower temperatures, and most importantly, the duration of the mission has driven several thermal design changes. The thermal system for the high-altitude balloon for planetary science applications mainly involves insulating the main telescope body to insure it can maintain its desired operating temperature. The main objective of the system was to regulate the temperature of the main collection mirror and insure that it would be at temperatures down to approximately 200 K (~–70 °C) for at least part of the mission operation time. Insulating the telescope and utilizing radiators to remove heat from any electronics located within the insulated telescope enclosure accomplished this. An illustration of the thermal control elements is shown in Figure 7.7.

In addition to the standard steady-state analysis as provided in Section 6.3.4, a more detailed transient analysis was performed to determine the mirror temperature throughout the day with sunlight entering the mirror opening and to help define the requirements for observing targets near the Sun. These results are shown in Figure 7.8. In the figure, 90° represents the case where no sunlight is entering the mirror opening at 0; the mirror opening is pointed directly at the Sun. These results were generated with no insulation surrounding the mirror tube. They match the steady-state results fairly well without insulation, i.e., the dashed lines in Figure 7.8. These results show the quick drop-off in the mirror temperature from the daytime to nighttime operation.

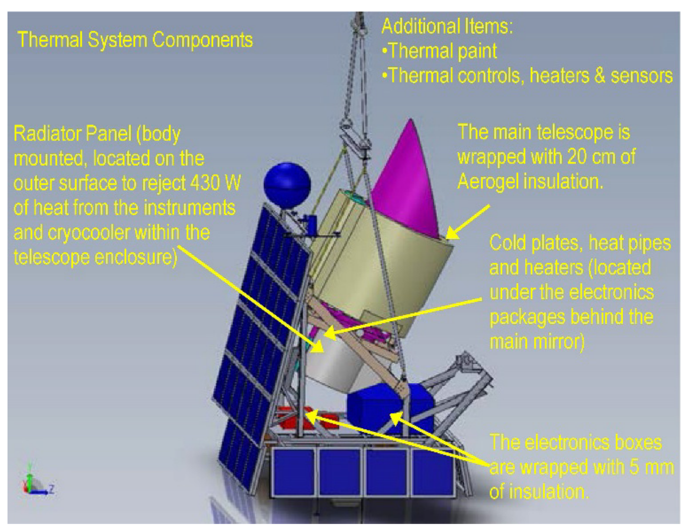


Figure 7.7.—Thermal control elements of the long-duration system.

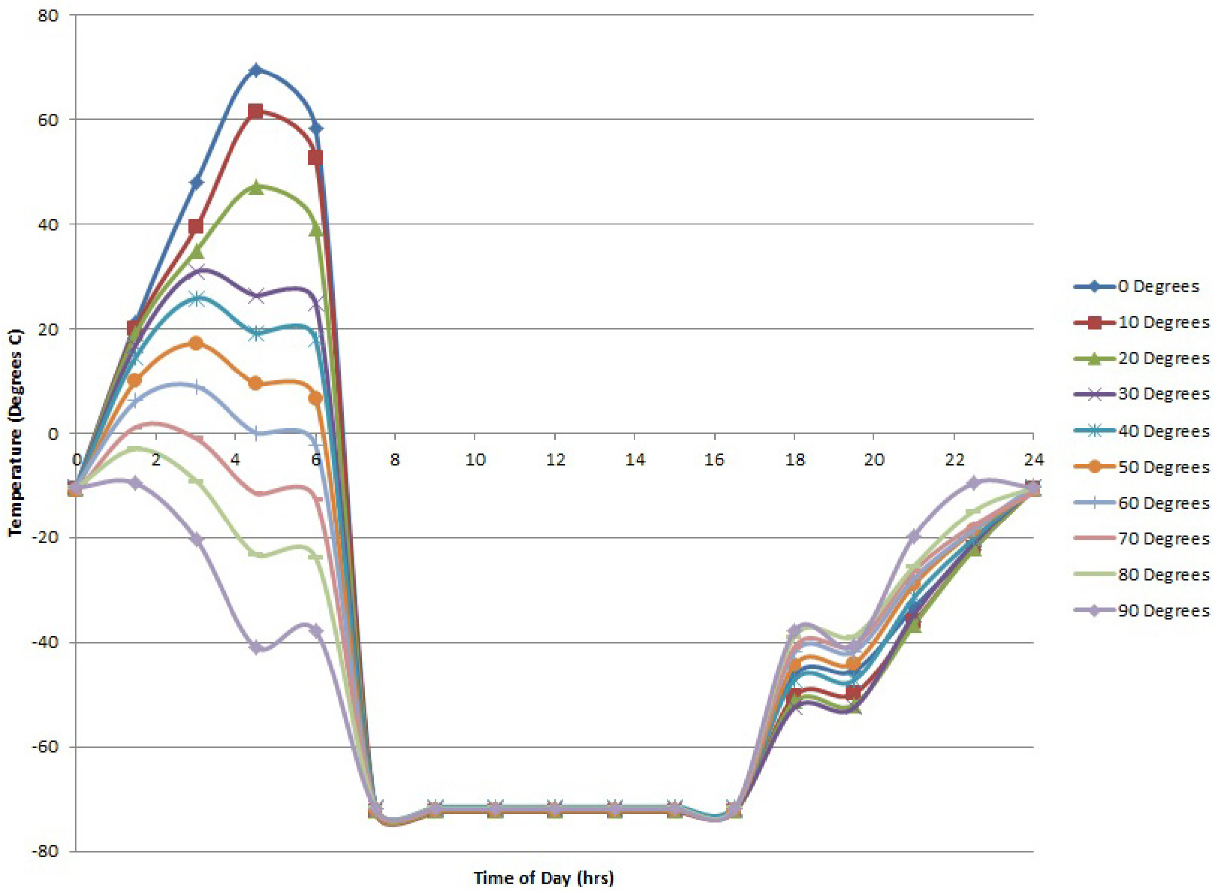


Figure 7.8.—Mirror temperature versus Sun angle.

In addition to the aerogel insulation, heat pipes and radiators are used to remove heat from the system. Heat pipes transfer heat from the cold plates to the radiator, which radiates and convects the excess heat to the surroundings. The radiator rejects heat by radiating to space and convecting to the atmosphere through heat transfer between its surface and the surroundings. Items that are higher temperature than the radiator will provide an energy input to the radiator and must be accounted for in its sizing. The radiator is sized based on an energy balance between the incoming radiation from these "hot" sources and the view to deep space. Because the desired temperature of the telescope interior was low, the radiator had to be sized to reject heat at a low temperature. The lower the rejection temperature of the radiator the larger its size has to be to remove a given amount of heat. A tradeoff was made between the available area for the radiator and its rejection temperature. Based on this, the rejection temperature, of –3 °C was selected. Because this is higher than the internal operating temperate of the telescope, it was assumed that the cold plates and internal heat generating electronics were thermally isolated from the main mirror to reduce their heat transfer into the telescope.

Figure 7.9.—Baseline COTS cryocooler.

A trade was conducted to compare liquid nitrogen and/or electric cryocoolers to maintain the low temperatures required for the IR path of the optical bench. Due to physical constraints and power limitations, only the IR path is cooled and not the entire optical bench. The baseline design uses a Ricor Stirling Cryocooler, as illustrated in Figure 7.9.

7.3.5 Power

The power system is entirely new relative to the short-duration mission. Primary batteries have been replaced with solar power and secondary batteries. Power is supplied by solar arrays during insolation periods and lithium-ion batteries during night periods. Power management and distribution electronics process and deliver the power to the loads. In all cases, heritage hardware is available from CSBF for long-duration balloon flights. The power system is sized for low mass while allowing sufficient power for continuous observations during the night, and maximum daytime science operations while providing sufficient time to point the gondola for charging the batteries.

Several assumptions were made to size the electrical power system. JPL's HORIZONS Ephemeris Computation Service was used to generate the Sun elevation data needed to size the solar array and battery. The data assume the balloon is stationary over New Zealand at a 33.5 km altitude, 40° S latitude, and 172° E longitude. The optimum solar array tilt angle was determined to be 12.5° off the vertical, and corresponds to the average Sun elevation angle on the shortest day of the year. It is assumed that the solar array is not shadowed by any structures on the balloon, gondola, or payload. The solar array is assumed to always be azimuthally pointed within 5° of the Sun during insolation periods, except during daylight science. It is assumed that the battery will provide all power during daylight science because Sun pointing cannot be guaranteed. When pointed at the Sun during the shortest insolation period of the year (9.6 hr daylight, 14.4 hr night), the solar array is sized to provide a continuous 261 W to essential loads (after overcoming system inefficiencies) and to recharge the battery. The battery is sized to provide the required energy throughout the mission at no more than 60 percent depth of discharge.

The solar array design consists of one 2 kW stationary 13.7 m^2 rigid panel solar array. The array consists of 24 SunCat solar panels; these are the same solar panels that are used for the SIP power system, shown in Figure 7.10. Each panel is 0.803- by 0.714-m in size, covered in 20 percent efficient solar cells (BOL, 25 °C), and weighs 0.9 kg. The expected array operating temperature is 83 °C; as temperature increases, solar cell efficiency decreases, and so the cells are only 16 percent efficient during operations at altitude. According to engineers at the Columbia Scientific Balloon Facility, each panel generates 90 W in the operating environment for this mission. This results in a solar cell packing factor of 72 percent.

The battery design consists of one 14.1 kW-h lithium-ion battery. Over the course of the mission, the battery will operate between 50 to 60 percent depth of discharge. The battery can tolerate the approximate 100 cycles over the mission with minimal impact to battery capacity for this depth of discharge range. The battery in this design was sized using 30 A-h space-rated cells (15 parallel strings of 8 series Lithion NCP25-1 cells), similar to the cells used by the Columbia Scientific Balloon Facility. The Columbia Scientific Balloon Facility uses 1.4 A-h Valence IFR 18650e LiFeMgPO4 cells, but there was not enough data available for these cells to perform a rigorous sizing analysis. Additionally, the capacity of the Valence cells may be too low for this application. Approximately 3,000 of the Valence cells would be required to meet the energy demands for this mission, which would result in an approximate 156 kg battery (assuming a 30 percent packing factor). However, there are risks associated with using such a large number of cells in a battery. The space-rated battery sized for this study weighs around 140 kg.

The power electronics design consists of three Terma Space Battery Charge/Discharge Regulators, nine Terma Space S3R Shunt Regulation Modules (for solar array regulation), and three Terma Space Equipment Power Distribution Modules. All electronics cards are housed in a single box.

On the shortest day of the year (shortest insolation period), the power system can support up to 2 hr of daylight science without requiring a nighttime load shed. If longer daytime science durations are required, the power system will not be able to support a full night of science. Figure 7.11 illustrates the trade of night science time lost as a result of conducting daytime science. A full night of science must be sacrificed to complete 4.35 hr of daytime science. If additional daytime science is required, essential loads will need to be shed or additional arrays incorporated.

The 100-day mission's power system mass (with growth) is 219 kg. The 1-day mission's power system mass (with growth) is 113 kg. A 106 kg mass increase in the power system is required to fly the long-duration mission.

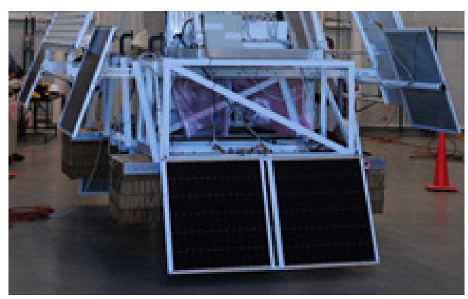


Figure 7.10.—SunCat Solar Panels.

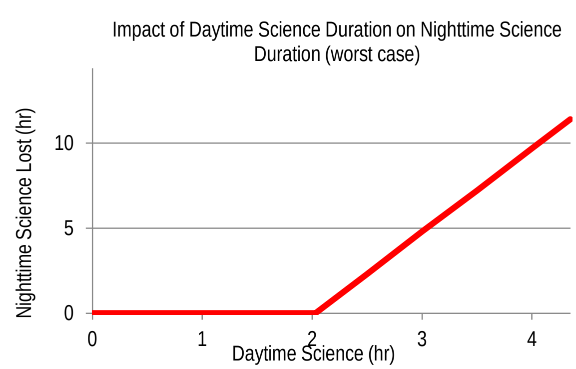


Figure 7.11.—Trade of day and night science.

7.3.6 Technology Needs

The optical bench and active cooling are the highest technical risk elements of the decadal science long-duration mission. Detectors alone should not be a challenge. Ball Aerospace has developed a cryostat for the 100-day Galactic/Xgalactic Ultralong-duration balloon Spectroscopic Stratospheric THz Observatory GUSSTO balloon mission proposal. The mission will use approximately 100 liters of He and a cryocooler to maintain a temperature of 4 K for up to 150 days. Cooling the IR path of the optical bench, albeit at warmer temperatures, requires thermal isolation, thick insolation, and significant consumables and/or significant power for cryocoolers. Lower power instruments and more efficient cooling options are enhancing. While not required, if an investment will be made for a light-weighted system, a higher performance optical bench is likely warranted. A higher performance optical bench will require significant system optimization, tight tolerances of the components, and significant up front thermal and mechanical design, but no new technologies are required for the nominal mission.

7.3.7 Mass Equipment List and Configuration

The system is required to fit within the mass allocation of the super-pressure long-duration balloon. The MEL contains the CBE and the mass growth allowance per item. The three major elements of the MEL include the gondola system with the ballast container and consumables; the planetary payload system with the telescope, optical bench, and mechanical and thermal system for the telescope; and the high-altitude balloon element with the balloon, helium, cabling, etc. The system was designed to fit within 2,495 kg lift capability of the 18 MCF balloon. The top level MEL is listed in Table 7.2.

Three mass definitions are important to the balloon: suspended mass, gross mass and, lift capability. The calculations for these masses used in this study were with the following equations:

Suspended mass = Gondola System + Ballast + Planetary Payload system

The suspended mass is calculated as the gondola system (WBS 06.1), which included the ballast container, the structure, communications, WASP, and SIPS system. The ballast itself was the material released as the balloon altitude drops below the required limits. The planetary payload system (WBS 06.2) is an assumed system provided by the customer and has no additional growth added at the system level. It is assumed to already contain 40 percent growth on the systems.

Gross mass = Gondola + Ballast + Planetary Payload
+ High-Altitude Balloon – He gas

The gross mass, used by the mission analysis balloon flight modeling, is calculated above, and is the suspended mass plus the balloon system. The entire structure and material contained in the balloon (WBS 06.3), aside from the He gas contained within the balloon itself, is used in this calculation.

Lift capability = Gondola + Ballast + Planetary Payload
+ Balloon Systems

The lift capability was calculated using the equation above in order to measure whether the design fits within the balloon performance of the 29.47 MCF zero-pressure high-altitude balloon (see Table 7.3). As before, the gondola system (WBS 06.1) included the ballast container, the structure, communications, WASP, and SIPS system. The final design fits within the balloon capability with 77 kg (3 percent) margin in addition to the 30 percent standard system design margin.

TABLE 7.2.—TOP LEVEL MEL FOR THE LONG DURATION SYSTEM

WBS no.	Balloon Cases High Altitude Balloon PSD CD-2013-85	Basic mass, kg	Growth, %	Predicted mass, kg	Aggregate growth, %
06	High Altitude Balloon for Planetary Science	6074.9	7.9%	479.57	6554.46
06.1	Gondola System	801.2	11.6%	92.54	893.71
06.1.1	Science	0.0	0	0.00	0.00
06.1.2	Attitude Determination and Control	277.2	3.0%	8.32	285.51
06.1.3	Command & Data Handling	0.0	0	0.00	0.00
06.1.4	Communications and Tracking	0.0	0	0.00	0.00
06.1.5	Electrical Power Subsystem	188.7	15.9%	29.98	218.69
06.1.6	Thermal Control (Non-Propellant)	3.5	15.0%	0.52	4.01
06.1.11	Structures and Mechanisms	331.8	16.2%	53.73	385.50
06.2	Planetary Payload System	329.5	22.2%	73.20	402.71
06.2.1	Payload	194.0	26.2%	50.84	244.81
06.2.2	Attitude Determination and Control	19.4	3.0%	0.58	19.99
06.2.3	Command & Data Handling	20.9	29.4%	6.15	27.05
06.2.6	Thermal Control (Non-Propellant)	50.2	15.0%	7.52	57.68
06.2.11	Structures and Mechanisms	45.1	18.0%	8.11	53.19
06.3	High Altitude Balloon	4944.2	6.3%	313.83	5258.03
06.3.2	Attitude Determination and Control	65.8	3.0%	1.97	67.74
06.3.3	Command & Data Handling	262.7	30.0%	78.80	341.45
06.3.7	Propulsion (Balloon)	2557.0	5.1%	130.12	2687.16
06.3.8	Propellant (Balloon Gas)	1825.0	5.0%	91.25	1916.25
06.3.9	Ballast Hardware	233.7	5.0%	11.69	245.43

TABLE 7.3.—BALLOON SYSTEM MASSES

(a) Subsystem breakdown

WBS	Main subsystems	Basic mass, kg	Growth, kg	Predicted mass, kg	Aggregate growth, %
06	High Altitude Balloon for Planetary Science	6074.9	479.6	6554	
06.1	Gondola System	801.2	92.5	894	12%
06.1.2	Attitude Determination and Control	277.2	8.3	286	3%
06.1.3	Command & Data Handling	0.0	0.0	0	TBD
06.1.4	Communications and Tracking	0.0	0.0	0	TBD
06.1.5	Electrical Power Subsystem	188.7	30.0	219	16%
06.1.6	Thermal Control (Non-Propellant)	3.5	0.5	4	15%
06.1.7	Miscellaneous	0.0	0.0	0	TBD
06.1.11	Structures and Mechanisms	331.8	53.7	385	16%
	Estimated Gondola Dry Mass (no prop, consumables)	567	81	648	14%
	Estimated Gondola Wet Mass	801	93	894	
System Level Growth Calculations Gondola System					Total Growth
	Dry Mass Desired System Level Growth	567	170	738	30%
	Additional Growth (carried at system level)		89		16%
	Total Wet Mass with Growth	801	170	971	
06.2	Planetary Payload System	329.5	73.2	403	22%
06.2.1	Payload	194.0	50.8	245	26%
06.2.2	Attitude Determination and Control	19.4	0.6	20	3%
06.2.3	Command & Data Handling	20.9	6.2	27	29%
06.2.6	Thermal Control (Non-Propellant)	50.2	7.5	58	15%
06.2.11	Structures and Mechanisms	45.1	8.1	53	18%
	Estimated Spacecraft Dry Mass	330	58	388	18%
	Estimated Spacecraft Wet Mass	330	73	403	
System Level Growth Calculations Planetary Payload System					Total Growth
	Dry Mass Desired System Level Growth	330	99	428	30%
	Additional Growth (carried at system level)		40		12%
	Total Wet Mass with Growth	330	99	428	
06.3	High Altitude Balloon	4944.2	313.8	5258.0	6%
06.3.2	Attitude Determination and Control	65.8	2.0	67.7	3%
06.3.3	Command & Data Handling	262.7	78.8	341.5	30%
06.3.5	Electrical Power Subsystem (EPS in SIP)	0.0	0.0	0.0	TBD
06.3.7	Propulsion (Balloon)	2557.0	130.1	2687.2	5%
06.3.8	Propellant (Balloon Gas)	1825.0		1916.3	0%
06.3.11	Structures and Mechanisms	0.0	0.0	0.0	TBD
	Gondola Ballast consumables	234	11.7	245	5%
	Estimated Spacecraft Dry Mass	3119	211	3330	7%
	Estimated Spacecraft Wet Mass	4944	314	5258	
System Level Growth Calculations High Altitude Balloon					Total Growth
	Dry Mass Desired System Level Growth	3119	211	3330	7%
	Additional Growth (carried at system level)		0		0%
	Total Wet Mass with Growth	4944	314	5258	

(b) Summary Mass Calculations

	Basic mass, kg	Growth, kg	Predicted mass, kg	Aggregate growth, %
Total dry mass	6075	388	6463	
Total wet mass	4250	388	4638	16%
Dry mass desired system level growth	4250	1275	5525	30%
Additional growth (carried at system level)		887		14%
Total useable propellant	0		0	
Total trapped propellants, margin, pressurant	0		0	
Total inert mass with growth	6075	1275	7349.85	
Total wet mass with system level growth	6075	1275	7350	

7.4 Development Schedule

Much like the 1-day flight mission, the telescope procurement, development and test, drives the schedule for a light-weighted long duration balloon flight. Using advanced manufacturing techniques, the quality and speed of the mirror does not significantly drive schedule (as it has historically) rather the procurement of the blank material and general process of grinding the mirror and validating performance. The development and test effort would take 2.5 to 3 years but could potentially be longer depending on the amount of flight and integration testing assumed.

7.5 Development Cost

The rough order of magnitude (ROM) costs of a planetary science balloon mission were estimated as an early part of this study using basic parametric tools.

However, the best estimates of a balloon platform development for planetary science is in the actual costs of recent missions namely the Balloon Rapid Response for ISON (BRRISON) and the Balloon Observation Platform for Planetary Science (BOPPS). The BRRISON and BOPPS missions and their costs are described in Section 9.3. The details of the parametric cost estimates are provided for reference in Appendix A. It should be noted that the parametric cost models reflect a lower estimate than what was experienced on the recent missions. This is due to tight schedule constraints, the procurement/development approaches, and lack of accurate cost data in the parametric databases for this type of system. It should also be noted, there has not been a gondola developed for planetary science observations for over 40 years.

8.0 System Evolution

8.1 Science Payload

8.1.1 Telescope

Based on the science return, the minimum-diameter primary mirror should be 1 m class. Significant science is achievable with a 1-day flight, and therefore, the mirror does not need to be light-weighted. However, a significant science increase is only possible through the use of long-duration flights, and long-duration flights are only possible with light-weighted mirrors. The highest cost component is the primary mirror, and the rest of the components are proportional: OTA, whiffle tree, etc. No new technology is required for larger mirrors or for light-weighting mirrors. However, the mass of the 1.5 m primary telescope is viable, but pushes the limits of the mass capability of a super-pressure balloon. Apertures evolving larger than 1.5 m may require either mass reductions from other subsystems or mass increase capabilities through future super-pressure balloon capabilities. It should be noted that the potential exists for having to insulate and perhaps actively cool the telescope itself as demand grows for observations beyond wavelengths of 5 μm.

In addition to a larger diameter OTA, more advanced mirror coatings are also desired. The wider the range of reflectance and emissivity the broader range of science that can be done on a single mission.

8.1.2 Wide Field-of-View Option

As discussed earlier on telescope options, very few science objectives require a wide FOV. However, multiple high-value science objectives can still be met with a wide FOV capability. Missions such as surveys including near Earth objects (NEOs) Trojans, TNOs, or even Oort cloud options with occultation are possible with wide FOV telescopes. Space-based telescopes are simpler for longer wavelength observations due to thermal constraints or for multi-year campaigns, but balloons may still offer high-value science return. After the successful use in narrow field planetary science balloon missions, an additional wide-field or single TMA telescope may be a viable option to capture the remaining missions possible through balloon-borne observations.

8.1.3 Optical Bench

A notional development cost and schedule for a mid-term, decadal-class, optical bench was completed for reference. The schedule shown in Figure 8.1 is meant to describe duration of the development and not when it will occur.

8.1.4 Science Instruments

The science instruments necessary for high-value science can be relatively low cost and simple. Higher performance instruments will always be desired, and a modular approach to the payload system would encourage the newer-advanced instruments. An instrument with good potential for planetary science may be a high-performance imaging spectrometer such the JPL Moon Mineralogy Mapper (M^3) over the wavelengths of interest. The spectrometer is small and lightweight with little to no distortion in either spatial or spectral direction. Lower mass and especially lower power can also increase science by enabling a higher duty cycle for additional observations.

ID	Task Name	Duration	Start	Finish
1	Project Kickoff	0 days	Tue 10/1/13	Tue 10/1/13
2	Requirements Definition	1 emon	Tue 10/1/13	Thu 10/31/13
3	Preliminary Optical, Mechanical, Thermal Design, STOP Analysis	2 emons	Thu 10/31/13	Mon 12/30/13
4	Preliminary Design Review	0 days	Mon 12/30/13	Mon 12/30/13
5	Detailed Optical, Mechanical, Thermal Design, STOP Analysis	4 emons	Mon 12/30/13	Tue 4/29/14
6	Critical Design Review	0 days	Tue 4/29/14	Tue 4/29/14
7	Order Long Lead Items (Custom Optics, Fine Guidance Sensor, Optical Bench)	6 emons	Mon 12/30/13	Sat 6/28/14
8	Mechanical Component, GSE Fabrication	3 emons	Tue 4/29/14	Mon 7/28/14
9	Remaining Procurements	3 emons	Tue 4/29/14	Mon 7/28/14
10	UDB Integration and Test	2 emons	Mon 7/28/14	Fri 9/26/14
11	Pre-Ship Review	0 days	Fri 9/26/14	Fri 9/26/14

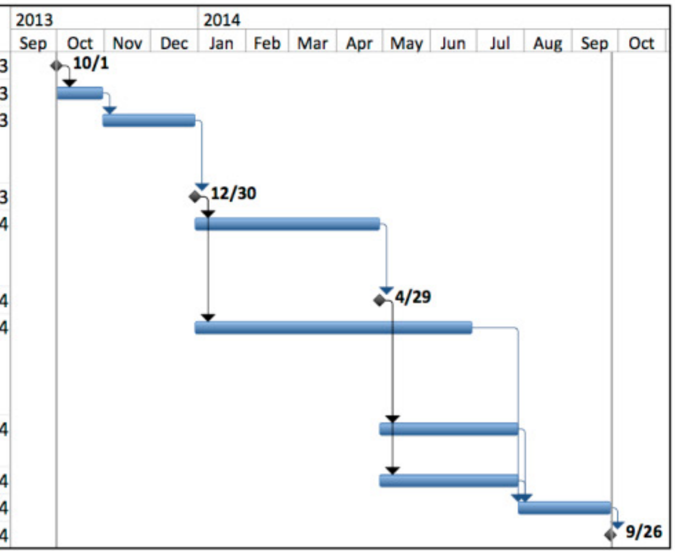


Figure 8.1.—Notional Optical Bench Development Schedule.

8.1.4.1 Near UV/Visible and Near-IR

A high-performance imaging spectrometer with over 300 nm to 2.5 µm is the ideal instrument for this application. Another instrument from 2.5 to 5 µm with a high-performance imaging spectrometer is also desired. A modified M^3 could meet all of the desired science objectives.

8.1.4.2 Far-IR

Imaging asteroids and objects in the far IR is not within the existing capabilities of balloon-based systems. It may be possible to perform science observations from 5 to 9 µm, 12 µm, or even 14 µm with various levels of increased system complexity. Instruments have been developed with multiple detectors to range from 5 to 100 µm. The challenge for balloon-based far-IR observations is not limited only to the instruments themselves. The cooling requirements for the optical bench, thermal IR, and the telescope itself add complexity and mass beyond the mid-term implementation options. Investments in higher capability balloons; increased mass and altitudes, would increase the viability of observations further in the IR spectrum. Trade studies for coating, dichroic materials, and additional design options for longer wavelength implementation would also be required.

8.1.5 Gondola Subsystems

BPO is currently responsible for continuous improvement to balloon subsystems that have multi-mission applicability. CSBF submits proposals for evaluation, and they are selected by the BPO as funding is available. Improvements may include new power technologies, improved communication systems, and miscellaneous capability upgrades. At this time, no new gondola subsystems are required to enable planetary science missions. Enhancements for low-mass power systems and other incremental subsystem improvements are desired, but none are required or unique to planetary science beyond those already under development.

8.1.5.1 Modular Structures

Typical balloon systems are designed with “expendable” structural elements. It is anticipated and considered acceptable for structural components to be damaged during landing or in some cases, intentionally cut after flight to accommodate the equipment recovery and return shipping process. In general, the gondola systems cannot be returned as integrated units, and some level of disassembly is required. It is possible to design a modular structural system for reusable disassembly. Additional trade studies are recommended to determine the life cycle cost and risk advantages of a modular reusable architecture as opposed to the replacement of damaged components over multiple flights.

8.1.5.2 Trajectory Control

The desire to control trajectory of balloon missions has been discussed for some time. Multiple concepts have been conceived for control of the balloon, but little has been done to date to develop systems that may yield a viable practical long-duration solution. Fort Sumner launches are limited in duration by the wind speeds and turnaround until the flight system approaches a populated area; the ability to “hover” over a very large area would add significant value to domestic flights. Long-duration flights can also benefit significantly from even limited control. Antarctic flights could benefit from the ability to maintain the gondola over the ice sheet; the natural winds will force the system to spiral to high latitude and over the ocean. Similarly, flights launched from New Zealand or any number of sites could benefit from the ability to transfer to desired latitudes for maximum science potential, but especially to control the overflight of populated areas and even to minimize the potential recovery zone. NASA should continue to explore concept designs and potential solutions for gondola trajectory control. While trajectory control is desirable and can offer significant return, the balloon community has successfully implemented missions for decades without such systems using knowledge of winds and controlling altitudes, to influence trajectory. Such approaches can continue to be used until better options become available.

8.1.5.3 Super-Pressure Balloons

The BPO has been performing flight tests of an 18 MCF super-pressure balloon for long-duration flights at altitudes of 110,000 ft and suspended mass capabilities of approximately 2,500 kg. The lower altitudes cause higher daytime sky brightness by a factor of 1.5 over 120,000 ft, and increase telluric opacity especially approaching the ultraviolet. Planetary science observations would be improved by higher altitudes and by increased mass capabilities. Increased mass can enable larger telescopes, larger power systems, and increased thermal control consumables.

8.1.5.4 Zero-Pressure Balloons

There are known ongoing development efforts to augment the capabilities of zero-pressure balloons. However, significant capabilities are already available. Zero-pressure balloons are typically used over an altitude of 60,000 to 135,000 ft, but higher altitude capability is available at the expense of lower mass.

8.1.5.5 WASP

The Wallops Arcsecond Pointer (WASP) has already demonstrated sufficient performance for many planetary science missions. The current system as demonstrated does not allow for clear apertures greater than 39 in. to be placed behind the inner frame. There may be system-level benefits to placing the primary mirror behind the WASP frame, but the WASP would need to be increased in size. Increasing the dimensions is possible, though manufacturing would need to be demonstrated to the required tolerances. Additionally, the WASP is one of the largest mass elements of the system. Increasing the dimensions of the WASP frames may allow the primary mirror to be behind the inner frame to simplify the center-of-gravity management, but the mass would increase. Mass reductions of the WASP would be highly desired either through simple material reduction or through a material change. Initial studies show that the WASP mass could be decreased by around 100 lb, but it would require substantial engineering changes.

8.1.5.6 Power

The BPO, through CSBF, is currently making investments in lithium-ion battery options for long-duration balloons. The CSBF is actively performing life-cycle testing on improved cells. The balloon flight options are lower energy density then commercially available systems. Additional life testing and infusion of state-of-the-art power systems is highly desired, and is already planned to continue through BPO investments. The investments will benefit all future balloon missions, and do not have any unique requirements for planetary science missions.

8.1.5.7 Advanced Communications and Command and Data Handling (C&DH)

As with other subsystems, the BPO is actively pursuing investments to enhance avionics and communication options to future balloon missions. Investments currently under consideration include a lower cost TDRS antenna, enhanced packaging, and a dual-modem Iridium configuration. Higher data rate systems will be highly desirable, especially for ULDB flights over oceans, where recovery options may be limited for the time being.

8.1.5.8 Structures

Compared to spacecraft, balloon gondola structures have been relatively simple configurations. The structural elements have often been considered sacrificial. The structure is often damaged during landing or intentionally cut for transport after the mission. Replacement structures are considered low cost. However, it may be advantageous to develop a modular frame that can be both integrated and disassembled quickly to allow for easier transportation and also for field recovery without sacrificing any hardware. This may improve turn-around time and cost and offer system level flexibility. As structures become more expensive to build, in an effort to reduce their mass for long duration missions, the ability to reuse the structure becomes highly desirable.

8.1.5.9 Semi-Controlled Landing

Another area of interest is the ability to perform controlled or semi-controlled landings. Options have been considered that use parachutes, or other means, that can be controlled for both landing location(s), and reduce the vertical and horizontal velocities. This may lower the risk of damage at impact and reduce future system requirements.

8.1.6 Areas of Concern

Several areas of concern remain, but most are minor for near-term and mid-term implementation paths. It is desirable to maintain the optical path at low temperatures, yet condensation remains a risk when going through the tropopause while actively cooled. Cooling cannot be achieved on the ground

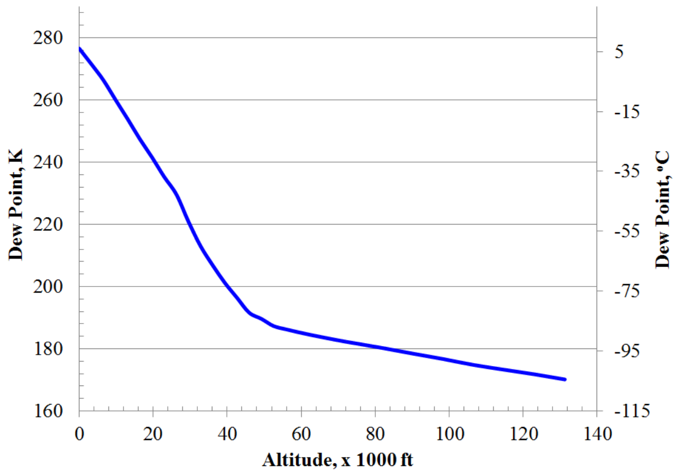


Figure 8.2.—Predicted dew point as a function of altitude.

without condensation forming (unless the OTA is purged), but can be achieved at float without condensation. Preliminary estimates suggest the frost point will be less than 180 K. Unpurged surfaces should remain frost free above that temperature. The actual humidity at float, which does control the dew point/frost point, would need to be verified, but is promising for passively cooling options. This is model dependent and has yet to be verified. This risk can be tested during the 1-day flight demonstration. Figure 8.2 illustrates predicted dew points vs. altitude.

The sky is also very bright near the desired near-UV observations. The quality of the observations and noise are concerns.

A new concern associated with potential New Zealand launches is the ability to recover from an ocean landing. The nominal mission is expected to launch from New Zealand and terminate for recovery on land in South America. With a large portion of the mission occurring over the ocean, there is the potential for an unplanned water landing. Currently BPO has no plans for ocean recoveries. The plan for ocean landings is to force the gondola and parachute to sink to the bottom of the ocean. This is driven by environmental concerns. However, if BPO does begin ocean recoveries of payloads, protecting the data for recovery is relatively simple; the data can be stored in a "black box." As the balloon, parachute, and other materials must be recovered, a challenge will be the logistics of an unplanned water landing given the large distances possible between the recovery resources and the final unknown landing location. The gondola will be exposed to salt water for an indeterminate duration. Protecting any high-value science instruments may be practical. While protecting the telescope and optical bench may prove challenging, approaches for their protection have not been assessed to date. Based on the limited mass margins available, the first flights may require accepting a risk of payload damage should an unplanned balloon failure occur. As mass capability is increased or systems are flown to higher maturity mass estimates, options may become available for flotation and payload protection.

Finally light weighting a high performance observatory to the degree needed for current super pressure balloons may prove challenging. However, careful design from the onset, mass focused design trades along the development phase is expected to yield a compatible system.

9.0 Demonstration Flights

9.1 Balloon Rapid Response for ISON (BRRISON)

The BRISSON (Ref. 19) mission idea was conceived in the winter of 2012, during the initial development of this report, and in response to the discovery of Comet2012 S1 (ISON) on September 21, 2012, by the International Scientific Optical Network (ISON) near Kislovodsk, Russia. Comet ISON was an Oort cloud comet on its first, and to be only, pass through the inner solar system. As such, this traveler was considered scientifically interesting and, having been discovered a year before its close approach to the Sun, the international science community, including NASA, prepared an observational campaign. This campaign included many ground based observatories, and for the first time, NASA SMD funded the development of a high altitude stratospheric observation platform instrumented with a multispectral MIR camera and multispectral UVVis camera. The BRRISON mission was approved in February 2013. Launch was September 28, 2013. The science motivation for making measurement from a platform 30 to 35 km above the ground followed directly from Section 3.1 in this report and is similar to a DRM1, DRM2, and DRM3 mission concept. Relevant to this mission, the absence of telluric absorptions from the atmosphere at that altitude enables measurements of important cometary volatile species: in this case, carbon dioxide (CO_2) and water.

9.1.1 Mission Objective

The objective of the BRISSON mission was to observe comet C2012 S1 (ISON) in the 2.5 to 5 µm region, wavelengths corresponding to those of water and CO_2 emission not available to ground-based observatories and with a goal to demonstrate subarcsecond pointing stability at ultraviolet and visible wavelengths (see the Table 9.1). The MIR measurement objectives were developed to demonstrate the value of MIR observations at 'float altitude' where the absence of telluric spectral features enable new measurements not possible with ground-based or even aircraft-born telescopes and to conduct new unique science on Comet ISON (Ref. 1). Also, this flight would be the first demonstration from a scientific balloon of using a fine-steering mirror to correct residual low amplitude motion (a few arcseconds or less) in the gondola thereby acquiring

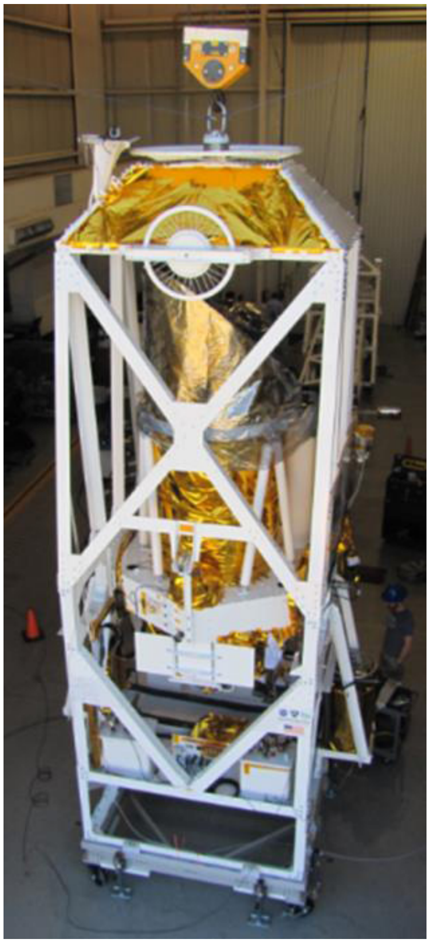


Figure 9.1.—Fully integrated gondola and payload during a hang test in Fort Sumner, New Mexico. Telescope is stowed pointed vertically up.

TABLE 9.1.—BRRISON LEVEL 1 REQUIREMENTS

ID	Requirement
L1-1	BRRISON shall launch before October 15, 2013 (predicted last day of launch service availability) to observe Comet C2012 S1 (ISON)
L1-2	BRRISON shall launch on a stratospheric zero pressure balloon from Fort Sumner, NM
L1-3	BRRISON shall observe H_2O and CO_2 emissions from Comet C2012 S1 (ISON), at wavelengths 2.7 and 4.3 µm, respectively
L1-4	BRRISON shall launch with a reusable gondola meeting the CSBF mechanical requirements outlined in OF-600-10-H
L1-5	BRRISON shall launch with a gondola capable of accommodating a telescope with >1 m aperture
L1-6	BRRISON shall document science results and engineering performance of gondola and payload and submit results for publication in the peer-reviewed literature, within six months after the flight
L1-7	BRRISON shall fly a fine pointing system with visible imaging
G1	Quantify the ability to produce an optical tracking error signal at the 10 milliarcsec level at a rate of 20 Hz, during day or night conditions
G2	Quantify the performance of the fine steering mirror at 10 mas level when commanded at 5 Hz
G3	Target a launch readiness date of September 17, 2013

diffraction limited imaging from a meter-class telescope over several seconds. Such a capability would demonstrate the ability to acquire high-spatial acuity imaging of dim astronomical objects in future missions. In this way, this mission was both a scientific investigation and a proof-of-concept flight. Until the flight of BRRISON, the previous planetary science balloon mission to fly was 40 years ago, with the series of Stratoscope flights that lofted a 1 m telescope to take visible wavelength images of (bright) planets in the outer Solar System under diffraction limited conditions, but very short integration times.

Many areas of technology have improved since the 1970s and the BRRISON mission carried extremely sensitive and large format CCD and CMOS cameras for UVVis imaging, and an IR system based upon the Teledyne H2RG 2k x 2k cryocooled HgCdTe MIR detector. Both instrument suites were capable of long integration time observations of many seconds, if not minutes, and require a platform that can maintain arcsecond stability for the IR, and subarcsecond stability for the visible, over that time. Thus, after 40 years of technology development, a major objective of BRRISON was to demonstrate that these platforms will make unique and valuable observations for the planetary science community not possible from other platforms.

9.1.2 Mission Development

The BRRISON platform consisted of multiple subsystems: the gondola frame, the pointing system, the telescope, the infrared and ultraviolet-visible instruments (payload), the power distribution system, communications, and an instrument package for tracking and ground communication that is provided by the Columbia Scientific Balloon Facility (CSBF) (Figure 9.1).

1. Gondola. The gondola carries and protects the telescope and attached dewar and detectors and houses the command and control systems. The frame is made of standard aluminum angles bolted together and painted with a white thermal coating. The structure is strong enough to support up to 2000 kg even under the 10 g shock experienced at the end of the flight when the parachute inflates.

2. Telescope. The APL telescope is a gold-coated Cassegrain, with an f/1.5 hyperboloid primary 80 cm in diameter, made of honeycombed Ultra Low Expansion titanium silicate glass and weighing just 50 kg. The effective focal length is f/17.5. The full FOV of the Ø80 cm telescope is 3 arcmin, and the spatial extent of the f/17.5 primary image is defined by a Ø12.7 mm field stop. A hexagonal support ring surrounding the telescope, and placed at the center of mass of the telescope near the primary mirror, acts as the interface between the elevation pointing control system and the telescope, including the instrument payload. This cradle is attached to the instrument payload through low CTE struts (Figure 9.2).

3. Payload. The instrument payload consists of the BRRISON InfraRed Camera (BIRC) and the UVVis camera systems (Figure 9.3). Each are mounted separately along the optical axis behind the telescope to the cradle through low CTE struts. A modular approach was taken to enable instrument development, testing, and to some extent integration to be accomplished in parallel. While this resulted in a volumetrically larger and more massive instrument payload than a single integrated optical/mechanical payload design, it enabled the development of this payload in the limited time frame available. The UVVis instrument is immediately behind the telescope, perpendicular to the telescope axis so that the light from the telescope passes through the center of the UVVis optical bench and comes to a focus above the UVVis optical bench. At that point, to support UVVis measurements, it is picked off by moveable fold mirror and passed through the UVVis optical train (described in Section 4.1.1). If IR measurements are to be obtained, the fold mirror is moved out of the way and the now expanding beam continues on to pass through the center of the IR optical bench, that is also positioned perpendicular to the optical axis of the telescope. This 'wedding cake' configuration enabled nearly completely separate development, testing, of the two instruments, and required the UVVis instrument to be delivered and integrated ~1-month prior to the delivery and integration of the IR instrument.

The BIRC instrument is described in detail by McMichael et al., 2013 (Ref. 20), and is briefly summarized here. BIRC acquires multispectral images in 8 bands from 2.47 to 4.6 µm, and one band in the astronomical R band, near 660 nm. The instrument is comprised of three subsystems: a collimator, a camera, and a cryogenic filter wheel (shown in Figure 9.2 as part of the camera). The primary image from the telescope propagates through a CaF2 window at the aperture hole in the cold box and passes into the collimating subsystem of BIRC. This subsystem is a cooled, nitrogen-purged enclosure which contains a collimating mirror and three fold mirrors, all of which are coated with protected gold and are maintained ~200 K or colder to eliminate thermal self-emission at these MIR wavelengths. The collimated beam then passes through the filter wheel and into the camera subassembly where it is focused by a small all-aluminum, 2-in. aperture Ritchey-Chretien telescope onto the cryogenic H2RG Teledyne detector. Both the filter wheel and the RC telescopes are maintained colder than the box, at ~150 K and 100 K, respectively

4. Pointing system. The BRRISON pointing system is derived from > 15 years of development and many flights on heliophysics and astrophysics missions including the Solar Bolometric Imager (SBI) and the Stratospheric Terahertz Observatory (STO). The approach is fundamentally different from WASP. The pointing system is an integral part of the gondola structure. There are three components: the elevation control, which interfaces with the cradle to move the telescope and instrument payload vertically, and two flywheels to control gondola motion against forces input from residual balloon motion transmitted to the gondola through the tether and to compensate for effects of winds. One flywheel controls rotational motion, including azimuthal pointing, and the other maintains the gondola in more or less vertical position during pendulation so that the elevation and rotational controls can maintain pointing. There is no intermediate 'coarse' pointing control such as the Solar Pointing System (SPS) used for WASP. These three mechanisms alone achieve arcsecond stability of the gondola during float.

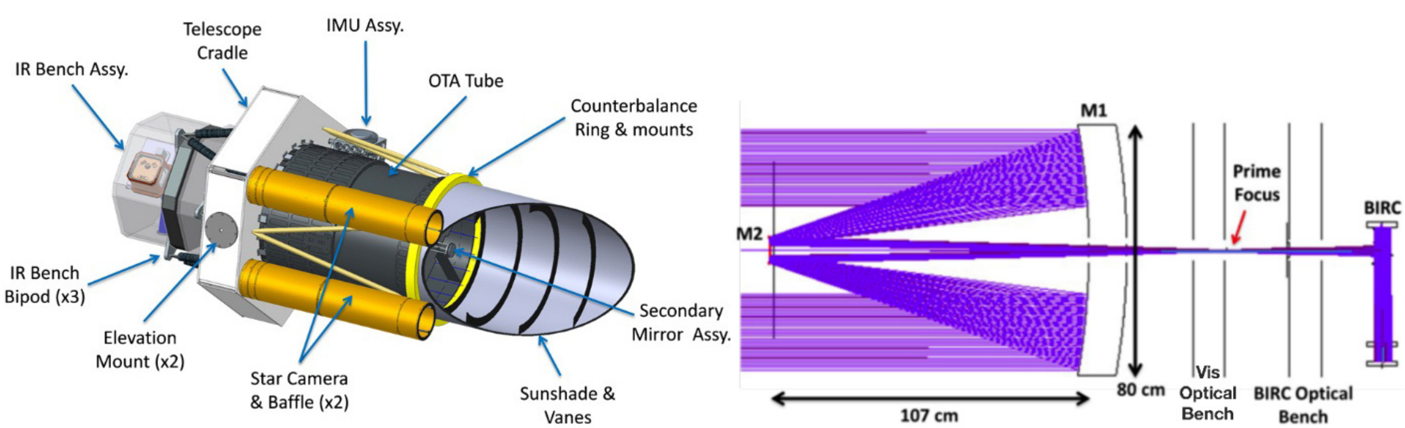


Figure 9.2.—(Left) Full telescope assembly CAD model. (Right) Raytrace cross-section of the Ø80 cm telescope. The BIRC instrument is located beyond the prime focus of the telescope.

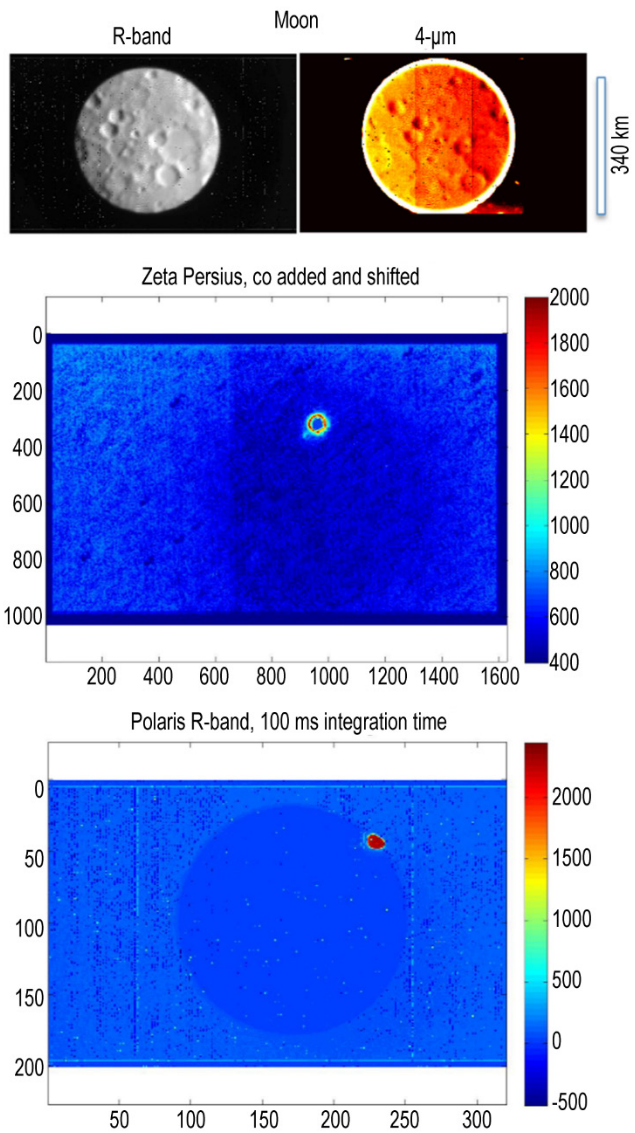


Figure 9.3.—BIRC observations of (top) the Moon, (middle) dim star, (bottom) Polaris.

9.1.3 Flight Summary

The BRISSON mission launched in the afternoon on September 28, 2013, after several days of waiting for weather to clear. It was the first afternoon launch from Fort Sumner in several years. The gondola ascended to operational altitude (90,000 ft) within 2 hr and commissioning commenced. That included operating the pointing system and determining the alignment between the star cameras and the FOV of the UVVis and IR payloads. However, the science payload suffered an anomaly about 2.5 hr after BRRISON's launch, preventing the payload from collecting mission data. The 0.8-m telescope on the gondola returned to a stowed position too rapidly, driving the telescope past a stow latch. The telescope was unable to be redeployed despite numerous attempts.

9.1.4 Results

The results from the UVVis system are summarized earlier (Section 4.1.1); results for BIRC are summarized here. During nighttime ground hang tests days prior to launch, the BIRC instrument obtained 4 μm images of the Moon demonstrating the successful operation of BIRC. At float, during gondola commissioning, the BIRC also obtained images of the multiple star system αUMi, commonly referred to as Polaris. The observations were obtained during commission while attempting to refine knowledge of the alignment relationship between the star trackers and the telescope, which had shifted from that determined on the ground due to minute differences in the thermal contraction between the two subsystems. A relatively long integration time of 100 ms was used to ensure high signal, resulting in significant saturation of the central pixels. Additionally, during ground hang tests, the BIRC instrument demonstrated the ability to detect faint targets, in this case a magnitude 10 star, using a jitter correction algorithm that corrects for the residual gondola instability of ~1 arcsec, by using IMU pointing knowledge to shift the image position in consecutive images so the images align when coadding to build SNR.

9.2 Balloon Observation Platform for Planetary Science (BOPPS)

The BOPPS mission was essentially a reflight of the BRRISON system, occurring almost exactly 1-year later and after identifying and correcting the issues that led to the anomaly. In the future, the year from October 2013 to October 2014 could be considered the year of comets. Comet ISON broke apart after its encounter with the Sun only to be replaced by another even more spectacular Oort Cloud comet, C/2013 A1 (Siding Spring). Discovered when it was 7.2 AU from the Sun by Robert McNaught at the Australian Siding Spring Observatory, it was quickly realized the comet would make a grazing flyby of Mars on October 19, 2014. The Oort Cloud is a distant repository of material little changed since the early solar system. Oort Cloud comets are pristine, icy bodies that have never been heated by passing close to the Sun. Again, NASA and astronomical communities around the world established an observing campaign, and a second stratospheric balloon mission was approved. As fortune would favor, a second and third comet were also available for observation at the same time period. Comet C/2012 K1 (PanSTARRS) is a retrograde Oort Cloud comet that would make an apparition in the southern hemisphere during September and October 2014, after passing through perihelion at 1.05 AU on August 27. It would be observable close to the horizon at lower and mid latitudes in the northern hemisphere, and observable in the mornings beginning on September 15 as its solar elongation reached 40°. A third Oort cloud comet, C/2014 E2 (Jacques), was discovered on

TABLE 9.2.—BOPPS MISSION LEVEL 1 REQUIREMENTS

L1-1	BOPPS shall launch before the close of the 2014 fall CSBF Fort Sumner campaign	Achieved
L1-2	BOPPS shall launch on a stratospheric zero pressure balloon from Fort Sumner, NM	Achieved
L1-3	BOPPS shall re-fly the BRRISON gondola which meets the CSBF mechanical requirements outlined in OF-600-10-H	Achieved
L1-4	BOPPS shall observe H_2O and CO_2 emissions from either comet Siding Spring or Pan-STARRS, at wavelengths 2.7 and 4.3 μm, respectively	Achieved (Comet Jacques)
L1-5	BOPPS shall document science results and engineering performance of gondola and payload and submit results for publication in the peer-reviewed literature, within six months after the flight	In Process
L1-6	BOPPS shall fly a fine pointing system with visible imaging and make observations to demonstrate performance	Achieved
G1	Quantify the ability to produce an optical tracking error signal at the 10 mas level at a rate of 20 Hz, during day or night conditions	Achieved
G2	Quantify the performance of the fine steering mirror at 10 mas level when commanded at 5 Hz	Achieved
G3	Target a launch readiness date of September 15, 2014	Achieved
G4	Observe additional science targets including Ceres and Vesta	Achieved

March 16, 2014, by the SONEAR Observatory in Brazil. Fainter than the other two, Jacques was to fade to about magnitude 10 by the time of the BOPPS launch (see Table 9.2).

9.2.1 Mission Objective

The main objective of BOPPS was to observe an Oort Cloud Comet, first preference, if possible, was C/2013 Siding Spring, shortly before its extraordinary close encounter with Mars which was also to be observed by a fleet of spacecraft at Mars and at Earth. Comet Siding Spring passed within 100,000 km of Mars on October 19, 2014; BOPPS observed the comet on September 26, 2014, when the comet was 114 million km from Mars. Again, this mission would attempt to measure the emissions from both water and CO_2 from a comet—preferably Siding Spring—as this would be the most heavily observed comet at the time because of its upcoming close approach to Mars. However, water and CO_2 measurements of PanSTARRS or Jacques would also meet the intent of the level one objectives. In addition to the goals set for BRRISON, the BOPPS mission assumed an additional goal of measuring the IR water-related absorption feature in a bright asteroid—either Vesta or Ceres. The goal related to the UVVis instrument, to demonstrate the ability to conduct subarcsecond imaging over many seconds remained the same as for BRRISON. Additionally, the BOPPS mission would carry a rideshare instrument—a miniature Gamma-Ray spectrometer—to raise its TRL for operating in Mars-like conditions.

9.2.2 Missions Description

BOPPS was developed in 8 months by a team from NASA Glenn Research Center, Johns Hopkins Applied Physics Laboratory and the Southwest Research Institute. The payload on BOPPS was identical to that on BRRISON. BOPPS was launched from Fort Sumner, New Mexico, on September 26, 2014. The Siding Spring observations were obtained at altitudes above 120,000 ft prior to sunset in twilight conditions, with the comet at low elevation, approximately 10° elevation angle. BOPPS also obtained observations of a second bright Oort Cloud Comet, C/2014 E2 (Jacques), the dwarf planet Ceres which is by far the largest member of the asteroid main belt, and several bright stars including Polaris. BOPPS observed Comet Siding Spring with the BIRC instrument in the midst of an outburst. The comet was observed in R-band near 660 nm wavelength and in near infrared filters at wavelengths of 2.47 and 2.7 μm for measuring water vapor emissions. The UVVis instrument on BOPPS successfully demonstrated the capability of the fine pointing system while imaging Polaris in daytime. UVVis achieved 33 and 58 mas stabilization on Polaris in the instrument azimuth and elevation directions, respectively. During this observation the RMS spread in centroid positions due to gondola motion was 2 to 3 arcsec, which is a measure of the BOPPS gondola pointing stability during that time in daylight conditions. The gondola pointing stability of the telescope improved at night with pointing errors < 1 arcsec over minutes while guiding on a sidereal target.

9.2.3 Results

The BOPPS mission was both a successful science flight and a successful technology demonstration. At the time of completing this study, the mission team is still analyzing the data from the BIRC instrument. However, some results are clear and a list of observations made is provided in Table 9.3.

TABLE 9.3.—BOPPS SCIENCE OBSERVATIONS WITH BIRC

Target	r_H, AU	δ, AU	Phase, deg.	Calibration star (type) mag	Detections, band center in μm
Siding Spring C/2013 A1	1.46	1.12	43	HD163761 (A0V) V=6.69	R, 2.7, 2.47, 4.0
Jacques C/2014 E2	1.72	1.15	34	HD196724 (A0V) V=4.82	R, 2.7, 2.47, 3.05, 3.2, 2.85, 4.0, 4.27, 4.6
1 Ceres	2.75	3.37	15	HD133772 (A0V) V=7.47	R, 2.7, 2.47, 3.05, 3.2

Current overall assessment of the science accomplishments are:

- BIRC observed two Oort cloud comets including Siding Spring.
- BIRC observed water and dust emission from both comets, and CO_2 from Comet Jacques.
- BIRC observed the asteroid Ceres and measured its water absorption band.
- UVVis and BIRC observed several stars.
- Technical achievements are currently:
  - UVVis demonstrated the ability to correct residual gondola instability using a fine-steering mirror, to enable imaging at a subarcsecond level (67 mas rms).
  - The gondola demonstrated pointing stability over several minutes at 1 arcsec RMS or better.

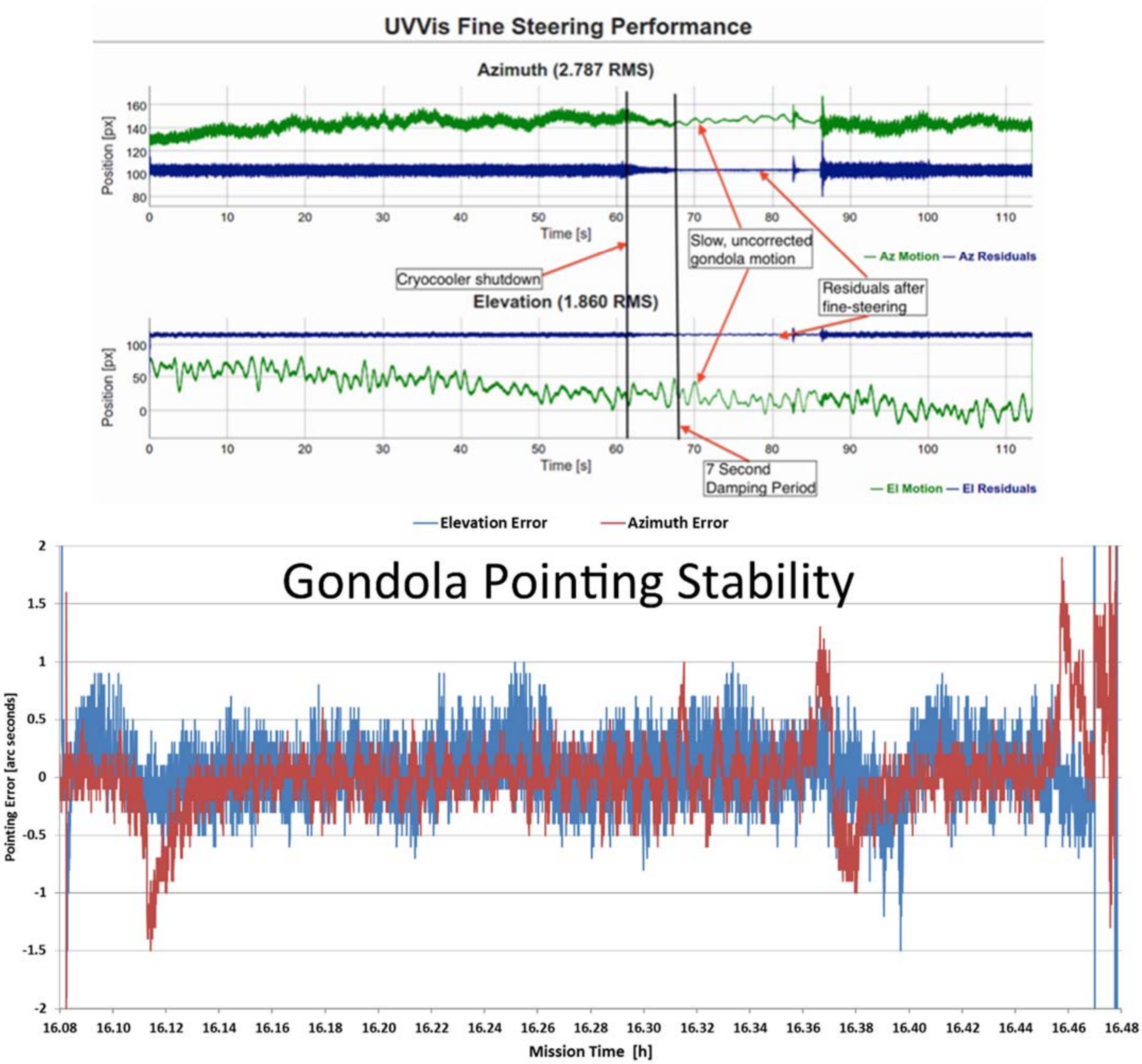


Figure 9.4.—Pointing results from (top) UVVis and (bottom) gondola. Units are pixels, 96 mas/pixel. (bottom) BOPPS gondola pointing errors in azimuth and elevation over a period of 24 min beginning ~16 hr after launch (~ 1:30 a.m. MST) when pointing had stabilized. The telescope was tracking a sidereal object located at ~56° elevation over the horizon. Units: arcseconds.

9.2.4 BOPPS Lessons Learned

BOPPS was a successful mission. It demonstrated the value of these platforms for enabling new planetary science measurements, and made new and unique science measurements of an Oort Cloud comet and the asteroid Ceres. This mission also provided many learning opportunities for future missions. There were several lessons learned that were captured as part of a formal lessons learned process. One of BOPPS' goals was to serve as a stepping stone for future planetary science balloon missions, and it is recommended that future missions pay special attention to those lessons. Section 9.2.4.1 summarizes the lessons learned that were deemed of greatest importance and broadly applicable to planetary science balloon missions.

The BOPPS lessons learned can be broken down into three primary categories: 1) project management/structure; 2) design, manufacture, and test; and 3) field and flight operations.

9.2.4.1 Project Management Lessons Learned

In the area of project management and structure, there were two main lessons learned. First it is important to plan and budget for the development of the hardware and software simulators. For second and later flights, it is important that sufficient time and budget is allocated for enhancing existing simulators. It is expected that as the flights mature the design, and the development of the software and simulators will taper off, but it will remain important to include budget and time to maintain those simulators. This may seem like standard practice in many areas, but ballooning is a low-cost, rapid development environment, and the temptation may exist to overlook these aspects of the project. The second lesson learned relates to staffing techniques. With stratospheric ballooning, the teams are typically small and need to be very nimble in their ability to respond to project needs and schedule movement. As a result, the need to have dedicated staff, rather than staff that are splitting their time between multiple projects, becomes of greater importance.

9.2.4.2 Design, Manufacture, and Test

The area of design, manufacture, and test had many lessons learned. At the system level there were two major lessons. First, when utilizing subcontractor workforce, the way in which the subcontractor is integrated, or not integrated, into the anomaly reporting process is critical. It is critical that subcontractors utilize a process for reporting anomalies and issues during their development. This will be especially important as instrument developers continue to develop instruments to fly on existing planetary balloon assets. Second, the project should use a requirements management package (e.g., DOORS), even if it seems like the number of requirements could be small. The process to setup the requirements in the requirements management tool for the mission may seem cumbersome, but it makes maintenance of requirements and development of verification much easier and will reduce the overall cost to the project.

The mechanical design of the BOPPS gondola presented a unique lesson. The gondola was built primarily using spacecraft tolerances. This is important in maintaining the platforms ability to maintain alignment. However, due to the way in which a gondola is suspended (from a single point beneath the balloon), the tolerances in some areas needed to be adjusted to account for structure shifting. In the case of BOPPS, a latch that was designed to hold the telescope when the telescope was stowed, worked as expected when the gondola was sitting on the ground. However, when the gondola was suspended from cable, a small shift in the structure resulted in a flat-on-flat contact that prevented the latch from working properly. This was found during test and was modified before flight. The lesson learned is that the appropriate levels of tolerances need to be determined and applied appropriately.

The thermal environment that the gondola sees can vary drastically from day to night, and this needs to be accounted for in the structural design as well as the thermal control. If possible, pre-flight testing of the entire system and the optical performance in the various thermal environments is recommended. This was done to limited degree on some gondolas in NASA Glenn's Plum Brook Station's B2 chamber or Space Power Facility. Heaters used to keep particular components warm should have the ability to be shut down when no longer needed rather than relying only on thermostatic control. This could prolong a mission or prevent draining of batteries.

The ballooning community usually utilizes COTS electronics components. During development of BOPPS, there were instances where the electronics boards that were purchased (PC104) were not actually capable of performing at their rated temperatures even though they were advertised as such. Special attention should be paid in board and vendor selection and a minimum number of thermal cycles should be run on all electronic components to assure there will be no issues that arise during flight. This testing proved to be invaluable on the BOPPS project as it was able to catch issues with COTS products that would have only been found in flight had thermal testing not taken place on the ground.

With regards to software, the main lesson learned is that due to the unique nature of ballooning, it is best to have the software team doing both development and testing. This can become cumbersome if the software becomes too large, but in general, having people within the project test each other's code is a more efficient use of the software team's limited resources. It should be noted that it is important to use the standard software development processes of the developing organization. They should, however, be tailored to meet the needs of the ballooning community. This includes the process for which code freezes, and post-freeze changes occur, as well as the way in which software bugs are tracked, resolved, and tested.

During test, assure that all critical hardware is placed on uninterrupted power supplies so that in case of facility power issues, the hardware is not damaged. Also verify, before testing, that the GSE meets the needs of the hardware being testing (i.e., assure that circuit breakers aren't exceeding their load limits, etc.). The cost of hardware under test, and time to replace it, should be considered when deciding to conduct unattended testing, or have personnel support the test 24/7. During testing of BOPPS, there were two instances where unattended testing caused damage to hardware. In one of those instances, the environmental chamber being utilized had been used many times prior by other projects with no issues.

9.2.4.3 Field and Flight Operations

Training of personnel is critical. Having backups in key areas is also critical as missions from Fort Sumner can be up to 24 hr and missions from other BPO sites can be multiple days. In addition to training, key command sequences should be done when possible. This includes items such as star camera operations, computation of drift factors, etc.

Lastly, planning for contingencies is critical, and should be done early especially for short duration flights where there is little opportunity to recover. Plan for the case in which the flight launch may be delayed 2 hr or 2 weeks. These delays can greatly impact the ability to collect the science the mission is trying to capture. These contingencies should be considered when developing the projects science requirements and goals.

9.3 Actual Costs for the BRRISON and BOPPS Missions

Actual costs for the both the BRRISON mission and BOPPS missions are provided, and should be primary components for developing a cost estimate for a platform such as GHAPS.
Table 9.4 shows the top level actual costs for the BRRISON mission. There are several factors that need to be considered if it is to be used in predicting development of other planetary payloads. First, the BRRISON mission was on a very aggressive schedule. The Sun-grazing comet ISON, was on a one time visit into the solar system, and the team had only one opportunity for observation. The encounter opportunity was measured in months not years like typical planetary missions. This resulted in significant amount of overtime, extra purchases, and other tactics to ensure readiness. These tend to drive costs higher than a standard development effort. On the other hand, there were several key components of the system that already existed and needed only refurbishment or verification testing. These included the telescope itself, most of the pointing system hardware and software, and the gondola avionics. This, of course, would reduce costs from what would be a complete new build.

TABLE 9.4.—BRRISON MISSION COSTS.

BRRISON Mission Costs	Total, M$
Management / S&MA	$1
Engineering and Test	$2.5
Instruments	$5
Gondola	$2.5
Science and Operations	$1
Total	$12

TABLE 9.5.—BOPPS MISSION COSTS

BOPPS Mission Costs	Total, M$
Management / S&MA	$1
Engineering and Test	$1.5
Instruments	$1
Gondola	$1
Science and Operations	$1
Total	$5.5

BRRISON experienced an anomaly during flight, namely the telescope got trapped in a position that prevented any science observations. Therefore, the goal of taking science observations of an Oort cloud comet were not achieved, nor was the characterization of the instruments and gondola for future missions. Many engineering goals were achieved in ground tests and flight.

Another Oort cloud comet, Comet Siding Spring, was identified in 2013, one that was would pass very near Mars in fall of 2014. The payload on BRRISON had the capability to measure water and CO_2 emissions in the infrared. Because that is a highly desired measurement to make for comets (especially Oort cloud comets), because viewing performance of balloon based platforms still needed to be demonstrated, and because the BRRISON hardware experienced little damage on landing, it was decided to refly the mission with the name BOPPS. The BOPPS mission goals were to observe an Oort cloud and characterize the payload's performance.

The work required to accomplish these objectives was to refurbish the gondola, address the issues that caused the BRRISON anomaly, and implement a more rigorous test plan to better prepare for science success.

The BOPPS actual costs, in many ways, fills in soft areas of the BRRISON costs when it comes to using the values to predict the future develop costs for a new platform The top-level BOPPS mission costs are provided in Table 9.5. Neither mission, however, provides actual costs data for the OTA or the pointing system, two key and relatively significant cost elements to a new platform. To predict these costs, cost estimates were obtained from industry.

Table 9.6 provides the current best cost estimate for the development of a 1 m class observatory with 1 arcsec and better pointing capability and platform features such that it could fly long-duration planetary observation missions. These costs rely heavily in the BOPPS and BRRISON costs and incorporate industry cost estimates for the key components.

9.4 Observatory for Planetary Investigations from the Stratosphere (OPIS)

The Observatory for Planetary Investigations from the Stratosphere (OPIS) was an internal Goddard Space Flight Center (GSFC) effort in cooperation with the Balloon Program Office (BPO) to demonstrate the capability of the Wallops ArcSecond Pointing (WASP) system. The OPIS flight was supported by the BPO through the funding to build the OPIS imaging system and mount it in a WASP system at Wallops Flight Facility (WFF). GSFC provided FTE for the OPIS team to build the OPIS imaging system and to interface with the WASP team. NASA Headdquarters provided some funds to support team operations at Fort Sumner, New Mexico.

9.4.1 OPIS Mission Goal and Objectives

The main goal of the OPIS mission was to demonstrate the WASP system and assess its capability to enable planetary investigations from a high-altitude balloon platform. To address this goal, several observational objectives were defined for the OPIS mission (Table 9.7).

The primary objective was to assess the short-term stability of the WASP system. The WASP system constantly updates its pointing solution to try to maintain an exact pointing even as the platform moves. These small adjustments cause the pointing to randomly "jitter" about a fixed location. If the jitter is too large or fast, extended objects will exhibit smear in their images. To assess the short-term stability, the OPIS mission observed Jupiter with the objective of imaging it without any jitter induced smearing.

The secondary objective was to assess the long-term stability of the WASP system. The WASP system can track a target over the longer term. Many sensitive observations will require tracking a target and keeping that target in the same position on a CCD detector. To assess the ability of the WASP system to track a target long-term and maintain a precise pointing of that target, the OPIS mission planned for a long-term observational target. This target could be either 1) an exoplanet host star (preferably one with a transiting planet), 2) a bright star or 3) a bright asteroid target.

9.4.2 OPIS Imaging System

The OPIS team built the OPIS imaging system, which be mounted in the WASP system for the demonstration flight. Figure 9.5 shows the OPIS imaging system. It was built using a 21 arcsec telescope that was repurposed from the CIRS project. At the focal point of the telescope an Alta F32 CCD imager was mounted on a translation stage. A filter wheel was also placed in front of the CCD camera to allow imaging with a few different filter options (Table 9.8). The camera and translation stage were controlled with a custom built avionics system that was mounted next to the WASP avionics system. All imaging data was stored onboard, and only a select number of images were downlinked for verification of system performance. The OPIS imaging system was powered from the same batteries as the WASP system.

9.4.3 OPIS Mission Description

On October 8, 2014, the OPIS mission was launched from Fort Sumner. Because its flight was late in the season, the duration of the mission was expected to be short. As a result, a smaller balloon, which allowed for a lower maximum altitude was chosen in order to extend the flight duration and allow less

TABLE 9.6.—ESTIMATE OF DEVELOPMENT COST FOR NEW PLATFORM

New Platform Development Cost Estimate	Total, M$
Management / S&MA	$1.5
Engineering and Test	$2.5
Instruments (re-using some of BOPPS)	$3
OTA	$6
Flight Software and Attitude Control	$4
Gondola structure, avionics, power and thermal	$4.5
Total	$21.5

TABLE 9.7.—OPIS MISSION GOALS AND OBJECTIVES

Goal	Objective	Target
Demonstrate the ability of the WASP system to enable planetary science observations	Assess the short-term stability of the WASP system through observations of an extended planetary object	Jupiter
	Assess the long-term stability of the WASP system extended observations	Exoplanet host star, bright star or bright asteroid target

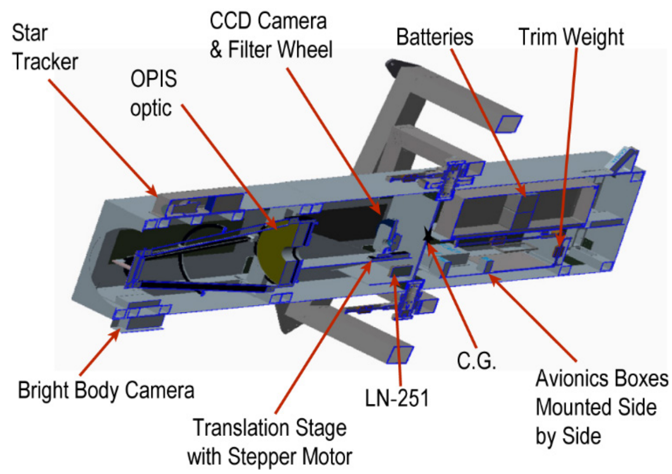


Figure 9.5.—Cut away of the OPIS imaging system as mounted in the WASP system.

TABLE 9.8.—OPIS MISSION FACTS

Observatory for Planetary Investigations from the Stratosphere (OPIS)	
Launch date	October 8, 2014, 8 a.m.
Launch site	Fort Sumner, New Mexico
Flight altitude	105,000 ft
Float duration	~8 hr
Observation targets	• Jupiter • Bright Star
OPIS optics	21 arcsec (0.533 m) refurbished Cassini CIRS telescope
Imager	Apogee Alta F32 CCD system
Platescale	0.25 arcsec/pixel
Wavelengths	• Clear Filter 300 to 900 nm • 50% neutral density 300 to 900 nm • Edge filter 600 to 900 nm • H_2O band pass 720 nm • H_2O continuum 750 nm • Grating Filter

TABLE 9.9.—BRIEF TIMELINE OF THE OPIS/WASP FLIGHT

Time, local time	Activity
10/8/14 08:01	Launch
10/8/14 09:05	58,384 ft
10/8/14 09:53	92,128 ft
10/8/14 10:22	First OPIS Images taken
10/8/14 12:29	Jupiter Imaging with ND filter, 0.02 s exposure
10/8/14 12:53	Jupiter Imaging with 720 nm filter, 0.15 s exposure
10/8/14 12:57	Jupiter Imaging with 750 nm filter, 0.15 s exposure
10/8/14 13:05	Jupiter Imaging with 720 nm filter, 0.25 s exposure
10/8/14 13:09	Jupiter Imaging with 750 nm filter, 0.25 s exposure
10/8/14 15:46	Star tracking with edge filter, 0.02 s exposure
10/8/14 17:15	Star imaging with grating filter, 0.03 s exposure
10/8/14 17:26	Star imaging with grating filter, 0.06 s exposure
10/8/14 18:23	Tried to acquire Neptune
10/8/14 19:00	End of mission

stringent launch conditions. Table 9.8 summarizes the mission facts.

While flight times were expected to be around 4 hr, favorable conditions around Clovis, New Mexico, allowed the flight to last at the float altitude of ~105,000 ft for 8 hr. Table 9.9 summarizes the mission activities during the 8-hr flight.

9.4.4 OPIS Mission Results and Assessment

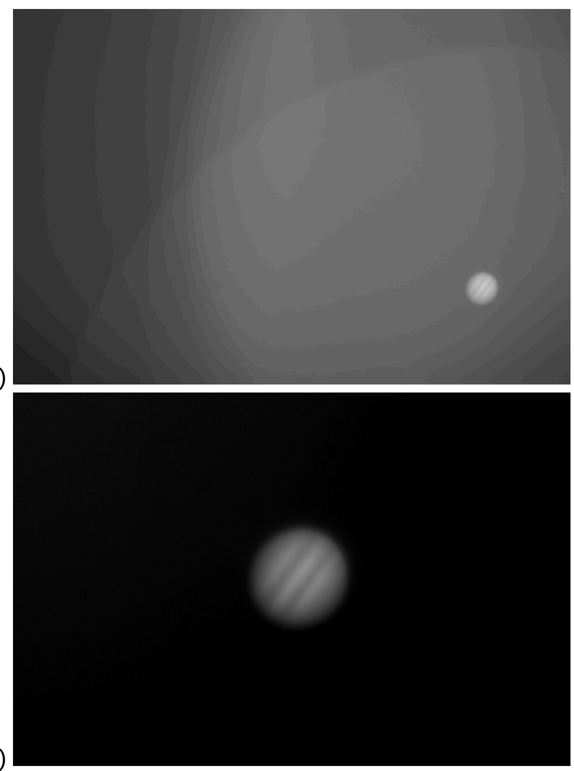
The OPIS/WASP mission was able to make observations to address both of its main objectives.

9.4.4.1 Assessment of the Short-Term Stability of the WASP System

Observations of Jupiter were planned to assess the short-term stability of the WASP system. In September and October of 2014, Jupiter would be about 32 arcsec in diameter. The OPIS imaging system with its sub-arcsecond plate scale would be able to image Jupiter as an extended object that would by 131 pixels in diameter on the CCD detector.

In order to image Jupiter with no effects of image smear due to WASP jitter, the OPIS imaging system imaged Jupiter with exposure times of 0.02 s. Analysis of jitter from previous test flights indicated that only 1 out of 3 images would be smear free even with this short exposure time. However, the OPIS system can image Jupiter at a rate of 2 images per second, thus about 40 images a minute should exhibit no image smear.

Figure 9.6(a) shows an unprocessed image of Jupiter. The images acquired show significant amounts of scattered light. Observations of Jupiter were taken during daylight hours, as Jupiter was setting in the sky. Moreover, the Sun was about 40° away from Jupiter in the sky, allowing plenty of sunlight to enter the barrel of the OPIS telescope, although not directly onto the OPIS primary. Figure 9.6(b), shows the same image processed to remove the scattered light levels near Jupiter. The scatter light level is nearly constant and easily removed. The resulting image of Jupiter exhibits no smear due to WASP jitter, successfully showing that the short-term stability of the WASP system can allow observations of extended Solar System targets.



(a)

(b)

Figure 9.6.—Image of Jupiter as seen from the OPIS imaging system. (a) The image exhibits the effects of scattered light in the telescope optics. (b) Processing of the image of Jupiter can remove the stray light levels and reveal that the image quality does not show any smearing by the jitter of the WASP system.

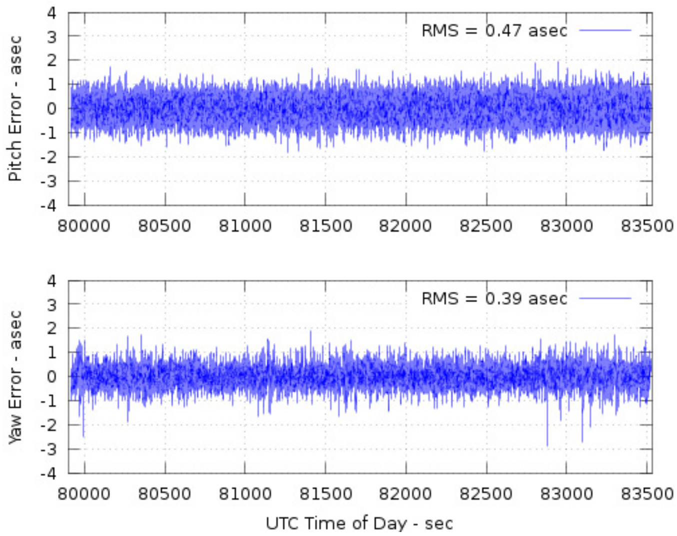


Figure 9.7.—Results for the WASP pointing accuracy from a long-duration stare measurement during the OPIS flight. WASP achieved overall stability of <0.5 arcsec.

9.4.4.2 Assessment of the Long-Term Stability of the WASP System

In order to assess the long-term stability of the WASP system, observations of an exoplanet host star were planned. It was hoped that a host star with an active transiting planet could be observed during this point test. However, at the time of the flight no suitable transits were active. Moreover, the exoplanet host stars available were not bright enough to be observed due to the stray light issue into the OPIS telescope. Therefore, a bright star served as the source for the long-term stability demonstration. The OPIS flight demonstrated the capability of the WASP system to deliver sub-arcsecond pointing control with control residual RMS <0.5 arcsec (Figure 9.7).

9.4.5 OPIS Lessons Learned

9.4.5.1 Flight Software

Off the shelf components allow for quick, cost effective missions, which are great for lower-class missions that can be flown on high-altitude balloon platforms. However, off-the-shelf electronics still need a lot of work to modify for flight purposes. While mechanical modifications may be straight-forward and relatively simple, the digital modifications may be more extensive. Key components need to be commanded and used by the mission avionics system. The OPIS avionics system was custom built based on RTD computers previously flown by the WASP team. The mission flight software was built around NASA Goddard Space Flight Center's core flight software (FTS), which needed to be customized for the OPIS applications. Specific science commands were written, utilizing the commercial software libraries supplied with the off-the-shelf CCD camera, filter wheel and translation stage. It should be noted that commercial drivers supplied for these components may not always represent tools built with the best source code practices. Thus, it is key to have resources available to make these drivers more useful and capable of completing the required tasks.

9.4.5.2 Mechanical

OPIS' aggressive schedule and budget present unique challenges for the mechanical effort to design and build the OPIS imaging structure. The team employed a technic that sent all mechanical structural pieces out for competitive bids. This allowed the fabrication of the OPIS imaging structure to be as cost effective as possible. Also, a time consuming PR process wasn't required. However, the job of assembling the OPIS structure was complicated by the fact that parts made by different vendors didn't always work together. Thus, the OPIS/WASP mechanical engineer proved key to the assembly of the structure and the modification of parts as needed. In the future, more time and healthier budgets should allow for an easier fabrications process.

9.4.5.3 Scattered Light

Scattered light into the optics was an issue for OPIS. Jupiter was only about 40° away from the Sun, and had it been any closer, sunlight would have been able to reflect off the primary. As it was (see Figure 9.6), sunlight was able to enter the barrel of the OPIS telescope and reflect into the optical path. The OPIS team was aware that scattered light would be an issue, but because of the limited budget of the OPIS project it wasn't able to be fully mitigated. However, it did not limit the success of the mission. In the future, more work needs to be done to limit the effect of stray light on observations. The OPIS team now more fully respect the other possible sources for stray light, such as off clouds below the telescope (if observation elevations are low) or the balloon itself (if observation elevations are high).

10.0 Project Implementation

10.1 Existing Programs

The Balloon Program Office is implemented out of Wallops Flight Facility, and has a successful history of conducting a large number of science campaigns. The BPO makes strategic investments for new balloon technology (e.g., new super-pressure balloons, WASP, etc.), and awards technology investment projects to enhance future balloon missions. It is recommended that a representative for planetary science balloon missions participate in the solicitation and strategic investment planning discussions by BPO for the identification and advocacy of investments for the planetary science division. There is a Balloon Working Group with scientists to represent heliophysics, Earth science, and astrophysics. It is recommended that a member be added to the working group to represent planetary science. The BPO does not develop gondolas nor implement the science missions. The observatory model being assessed in this study, and the fact that it has planetary specific mission objectives, will require that the suggested gondola be develop primarily with planetary science funds and mechanisms.

10.2 Science Mission Opportunities

There are existing solicitation opportunities for planetary astronomy on balloons, suborbital launches, and hosted payloads. However, the solicitations/programs funded from the Research and Analysis (R&A) program elements do not have sufficient resources to support competed balloon missions. Further, R&A programs are generally not structured to develop a NASA "observatory" such as GHAPS. In addition, the Small Bodies Assessment Group (SBAG) noted that R&A funds should not be used for development of a platform such as GHAPS. Such developments are rather unique, and therefore, development approach must consider long term factors such as sustainability, ownership and proprietary hardware, software or other intellectual property factors as well as future enhancements, repairs and maintenance. For these and other reasons, the typical science mission opportunities are not well suited to development and implementation of repeated flights for an asset such as GHAPS. The development of such a sustained NASA asset is more suited to development through a directed project to be implemented by a field center familiar with the specific challenges and opportunities of the application. The field center would assess and recommend the best acquisition approaches to the various elements and the sustaining activities. There are a number of acquisition approaches possible, and assessing and providing a specific acquisition approach is outside the scope of this study. Having said that the general recommended approach is competition balanced with the need for long term open access and enhancement. This suggests acquiring major gondola elements or subsystems and integrating with a core team, perhaps at a field center. The team would be charged with ensuring the platform remains viable for several flights and for a host of potential science in an unbiased manner.

Clearly though, once the asset, GHAPS, has been developed, it is recommended that the science for a given mission be selected competitively through the annual ROSES call, perhaps the best fit being the Solar Systems Observations (SSO) program. It is envisioned that a "standard" payload and flight characteristics/interfaces can be provided to potential proposers, who will then propose the science they intend to accomplish and or other instruments they may have available to incorporate. Flights could be offered on a regular basis from various locations and be driven by availability of funds, facilities, BPO launch schedules, or the science targets themselves. This approach has the advantage of a regular science cadence, opportunity for engagement by the broader community, and a relatively stable cost profile for the Planetary Science Division (PSD).

10.3 Balloon Instrument Development

Instruments for balloon missions should be a fraction of the cost of space-based missions, yet they would offer frequent opportunities for technology advancement and instrument upgrades and to mature them for space applications where the cost and risk are higher.

The instruments from the BOPPS mission, the UVVIS and BIRC, should be available and have been shown to offer the needed capability to capture some decadal science data. These can be offered as standard suite of instruments that can come with the platform. Over time, the decadal important questions and the respective measurement requirements suggest that eventually other instruments, like a full spectrometer, will be desired.

There are several options for developing the instruments that will be used on the planetary gondola. One, of course, is to direct the effort to the organization developing the gondola/telescope. This option would increase the likelihood of better coordination and smoother integration. It would simplify interfaces and establish a single point of responsibility. The disadvantage of this option is that gondola systems experts may not be instrument experts, so there would be a risk of not getting the best instruments possible. This approach would also preclude the competitive process, which is desired.

A second option is to compete the development of the instruments. This would require careful development and documentation of interfaces between the OTA, the gondola systems, and the instruments themselves. Advantages of this approach are that the instrumentation community can propose the products, and PSD may get a better instrument at a lower cost. Potentially it could allow a broader set of people to participate in the development efforts. The disadvantages are the increased risk that the sensitive interfaces in the optical system will not work as hoped. This approach increases the number of interfaces in the development effort, thereby increasing the risk of delays and the risk that the systems not work together as needed.

There is a third approach, a hybrid of the prior two, which maximizes the advantages and minimizes the disadvantages of the two approaches discussed above. In this approach, a basic set of instruments is developed in concert with the development of a gondola and its systems. These would become an available suite or "standard" set of instruments as are available on SOFIA or other observatory models. Over time and as science needs evolve, later instrument additions or upgrades would be selected through a competitive process, or possibly contributed by international partners, etc. This approach maximizes the likelihood that the first system will work together cohesively and perform the desired science out of the gate with the best chance of schedule, cost, and technical success. A couple of flights with the "standard" suite will allow the gondola, systems, and interfaces to be well understood. Then as science needs change, better or different instruments can be developed through competitions in ROSES or mission-of-opportunity projects contributed as part of a flight/mission proposal, or provided through other mechanisms.

10.4 Recommended Approach to Enable Planetary Science From Balloons

Based on the options for planetary science balloon program implementation discussed above, the following multi-step approach is offered for planning purposes. It must be noted that this recommended approach assumes the continued support of NASA's BPO at WFF for launches and the leveraging of their developments of multi-mission gondola systems such as the command and control devices, pointing systems, long-duration balloons, and so on. The plan relies on NASA's BPO to establish future launch options and enhance balloon capability in the future.

1. **Leverage the BOPPS and BRRISON flights and the associated instrument development efforts.** Ensure that the NUV/Vis and IR instruments, optical benches, and other hardware as well as the respective engineering and test data are fed forward and provided to PSD for incorporation into future planetary balloon systems and missions. The recovered BOPPS instruments would essentially become the initial "standard" suite of instruments offered on the early planetary balloon missions.
2. **Leverage expertise and resources wherever possible, particularly in-house resources if available.**
3. **Continue planning for the development of the Gondola for High-Altitude Planetary Science (GHAPS).** This gondola should be based on the recommendations outlined in this study, and designed for repeated flights including with super-pressure long-duration balloons, which will require light-weighting the OTA and the gondola systems as much as possible. It implies that the frame and systems should be designed to survive landings and be reused even when recovered by smaller planes. Eventually, recoveries from the ocean may be targeted. The instruments are being removed from the BOPPS gondola and delivered and stored at GRC for incorporation into GHAPS when required. A specification, with strong technical support from MSFC and industry input, was developed for the OTA. A Request for Information (RFI) was then generated. Responses to the RFI for OTA development have been solicited and assessed. The 1 m OTA is recommended and should be optimized for observations in the NUV through MIR. The RFI responses help better understand cost and schedule impacts. Another RFI was released by GRC to assess interest and capabilities for the GHAPS pointing-system with the requirement of coarse pointing the gondola at 1 arcsec or better for at least 10 min. That input should be incorporated into overall planning as well.
4. **Develop and present plan to PSD for initiating the GHAPS development.** This study, results of BOPPS and BRRISON missions, the RFI responses, and other factors will contribute to the decision. As with most ongoing programs, it is recommended that development and maintenance of GHAPS be managed through a directed effort to a field center for the reasons that have been described earlier. This does not imply that all work will be done by the one field center. For example, the field center may competitively source much of the gondola build or repair activities, and would leverage skills and capabilities at field centers to provide the best value for PSD. The ownership by the field center is important for maintaining government insight and expertise as the system evolves, ensuring future advancements and capabilities are readily implementable, and that all potential users have equal opportunity to propose and use GHAPS and its future variants. Assuming a decision is made to implement GHAPS, a goal would be to launch GHAPS for first flight as early as possible. The earliest year to launch is 2019 due to long lead items such as the delivery of the OTA. The goal would be to launch annually or as refurbish schedules allow, and target longer flights where possible to maximize observing time/science return. It should be noted that 100 day flights on an annual basis with a single copy of GHAPS would not be possible due to the flight, transit, and refurbishment times required. If all or most flights are long-duration flights, then either two copies of the GHAPS gondola would be required (one set of instruments and one OTA may be adequate though), or flight cadence would need to be extended.
5. **While GHAPS is being developed, consider possible reflights of the BOPPS' gondola and payload.** The science will be limited compared to what GHAPS is expected to accomplish, but there is unique science that can still be realized with BOPPS and shorter flights. Assuming the telescope survives the STO2 landing, it can be refurbished and flown again. The science to be realized can be competed through SSO selections or a separate call as most practical for the community and PSD. This would allow for earlier engagement of the planetary science community, and give them their first opportunity to propose science on a balloon-based observatory. APL owns the pointing system

and telescope for BOPPS, and this must be considered in this approach. Figure 10.1 summarizes the characteristics of BOPPS, its reflights, and GHAPS. There are science, cost, and schedule implications to utilizing one or both hardware elements.

6. **Once GHAPS is complete and in operations mode, science missions would be competed as driven by science contribution and resource availability**. Competitions are expected to be through ROSES, either in the current elements or as a new element as dictated by PSD and SMD needs. It is envisioned that this would be similar to proposals for using Keck or other major terrestrial observatories. The standard suite of instruments would be made openly available to future users as government-furnished equipment for the flight proposals, similar to terrestrial observatories. All data collected would be made openly available to the entire planetary science community, after a short delay to allow the principle investigator the opportunity for first publication.

7. **Continued replacement and upgrades to instruments will need to be considered.** Development of these sub-orbital flight instruments should be competed and can occur through enhancing current PSD instrument programs, e.g., MaTISSE or a new ROSES element, as suggested earlier. With the right gondola design, it is conceivable that instruments can be contributed, perhaps even by international partners, and readily plugged into the payload system. This would be another goal for GHAPS. Maintaining and upgrading GHAPS will be required and there are several options that have been mentioned as viable approaches. Figure 10.2 illustrates the planned flight and development schedule.

8. **If observation demand remains high and science results prove successful, the possibility exists for a second copy of GHAPS to be built to enable more observations or allow multiple flights per year from various locations**. Another option would be to build an enhanced version of GHAPS with a larger telescope or even better pointing performance. Such a possibility is another reason for strong government insight and cognizance of the GHAPS system, its capabilities, and performance.

BOPPS Reflights

BOPPS Mission/System Characteristics

- Upfront low cost
- Utilizes APL telescope and pointing system (APL) proprietary
- Can re-use BOPPS instruments
- Due to STO2 missions, earliest next flight is 2017
    - Compete science in Roses 15 SSO or other solicitation
- For the long term:
    - Quick response, non-ULDB flights.
    - Use as back-up or to enable multiple flights/year
    - As GHAPS evolves could be a second gondola (not suitable for ULDB flights)

GHAPS Development and Flights

GHAPS Mission/System Characteristics

- New light-weighted gondola & telescope
- Can re-use BOPPS instruments (planned for first flight)
- Due to development time, first flight not until 2019
    - Assumes 2015/16 OTA start, compete science in ROSES17 SSO
- Leverage interest and contributions from Centers
    - OTA, WASP, other components and labor
- Optimized for science and ULDP: high optical performance (fainter targets, better resolution), long flights, regular cadence, and temporal science.

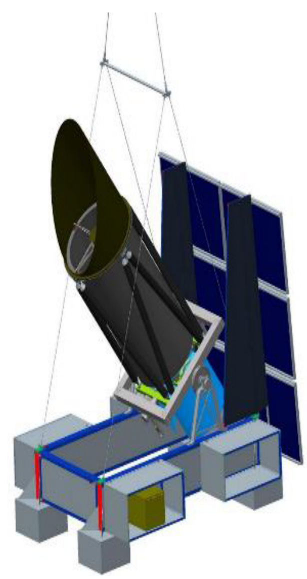


Figure 10.1.—Summary characteristics for BOPPS and GHAPS.

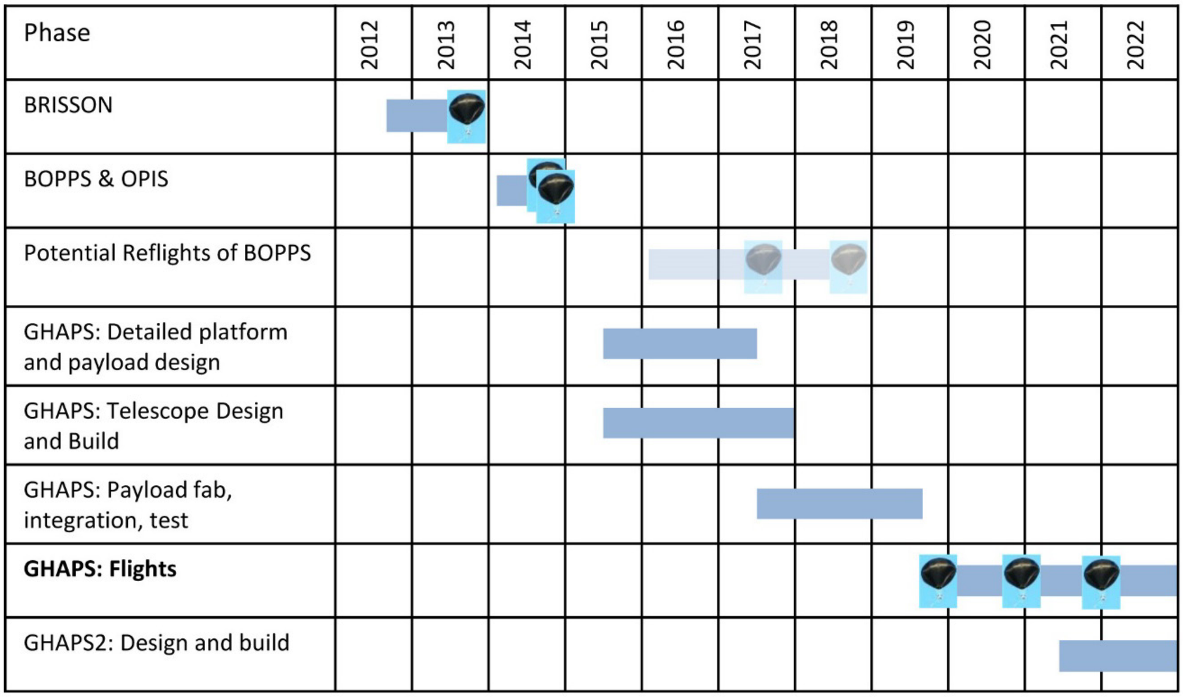


Figure 10.2.—Notional development and flight schedule

11.0 Summary

11.1 Science Value

With current or near term capabilities, planetary science from a balloon payload can provide significant science through observations in the 300 nm to 5 µm range and beyond. Each mission could make continued progress towards the important and “top priority” science objectives identified in the planetary sciences decadal survey. The frequent and affordable flight opportunities can offer experience for early-career scientists, yielding future PIs for larger planetary missions. Additionally, balloon missions have demonstrated the ability to progress from concept to observation to publication and distribution of data to the community in years opposed to more than a decade with typical planetary spaceflight missions. Last, the platform is ideal for maturing and demonstrating new technologies.

The cost of the first flight of a 100-day planetary science balloon mission is comparable to the cost of 100 nights on one of the Keck telescopes, and offers an order of magnitude cost reduction over both HST and SOFIA. Future flights would offer observing time at significantly less than the cost of time on Keck, and the cost per observing time is even better when including the daytime science capability. The balloon asset could be dedicated entirely for planetary science and offer tremendous low-cost progress on the objectives of the planetary science decadal survey. The planetary science community would have unprecedented access to space observations.

11.2 Conclusions

This study confirms the science potential, feasibility, and cost-benefit value of stratospheric balloons for planetary science purposes as posited by the National Research Council in the most recent Planetary Science Decadal Survey Report. Planetary science through balloons offers a low-cost and high-value opportunity to make significant progress on the objectives of the planetary science decadal survey. Forty-four important questions of the decadal survey are at least partially addressable through balloon science capabilities, and many of the “Top Priority” questions are part of that set. The cost of observing time, even for the first long-duration flight and the development cost, is expected to be comparable to ground-based assets and factors lower than from SOFIA or the HST while providing unique capabilities and science. Future flights will show further cost reductions. The balloon can be dedicated solely to planetary science initially, and options may exist in the future to cost-share with other programs. The strengths of balloon observations are in the 300 nm to 5 µm range, but can be extended further in the IR with increasing complexity. A narrow FOV can address all but the survey-type missions in the decadal survey, and therefore, a classical Cassegrain, or variant, trades well for the primary payload.

It is recommended that a baseline system (GHAPS) be developed to achieve the planetary science potential, including a 1 m or larger aperture narrow-field telescope and pointing accuracies better than 1 arcsec. The gondola should be designed for multiple flights so it must be robust and readily recoverable. It must be light-weighted to the extent possible to allow for long-duration flights on super-pressure balloons. A relatively low-cost program can enable planetary science balloon missions. The modest investment, however, would result in a dedicated planetary science capability that could collect 12 TB of high-value science per flight at cost-effective rates. A notional approach to development and continued flights of balloon-borne observatory (GHAPS) has been offered through this study. The BOPPS flight provides additional confidence for this new capability to address science decadal questions with low risk.

Appendix A.—Early Parametric Cost Estimating

A.1 Short Duration Flights

In order to estimate an early parametric cost of the balloon gondola mission, the MEL generated by the COMPASS team was used. The subsystem masses and their associated parameters from the design are inputs in two different commercially available cost-estimating models: SEER-H and PRICE Estimating Suite. As a cross-check, estimates are provided using each model.

In order to estimate the design using SEER-H, the pertinent cost-modeling assumptions that apply to this model and mission are as follows:

- Platform: air-unmanned
- Operations & support (O&S) : not included
- Acquisition category: buy and integrate
- Standard : space science; command & control
- Single-unit build
- Design complexity for development: used "low" for this run but would need to be increased when incorporating new features
- Design complexity for production: nominal
- Integration complexity factors (development): low
- Integration complexity factors (production): nominal
- Throughput costs:
  - WASP: $400K
  - CSBF: $1M
  - Balloon (ZP): $300K
  - Balloon gas: $100K
  - Pro rata campaign (Fort Sumner): $50K
  - NASA Direct Campaign Cost: $150K
- Costs in this section are all in FY13$K.

When implemented in SEER-H, the MEL of the COMPASS subsystem WBS is shown in Figure A.1. Each WBS element consists of a roll-up (summation), throughput cost (yellow arrow), an electrical component (plug), or a mechanical component (wrench). The "application" for each component is generally consistent with the name, except the telescope which is "optical." The mass inputs for each component are based on the masses in the COMPASS MEL. Integration costs are included. The input values of the throughput costs have been previously stated in the assumptions. Minimal NASA insight/oversight costs of $450K have been included for program management activities only. Normal PM and oversight costs are expected to be higher. Finally, reserves of 30 percent are added to the estimated total.

The cost estimate for the short mission using SEER-H with integration costs included in the total is shown in Table A.1.

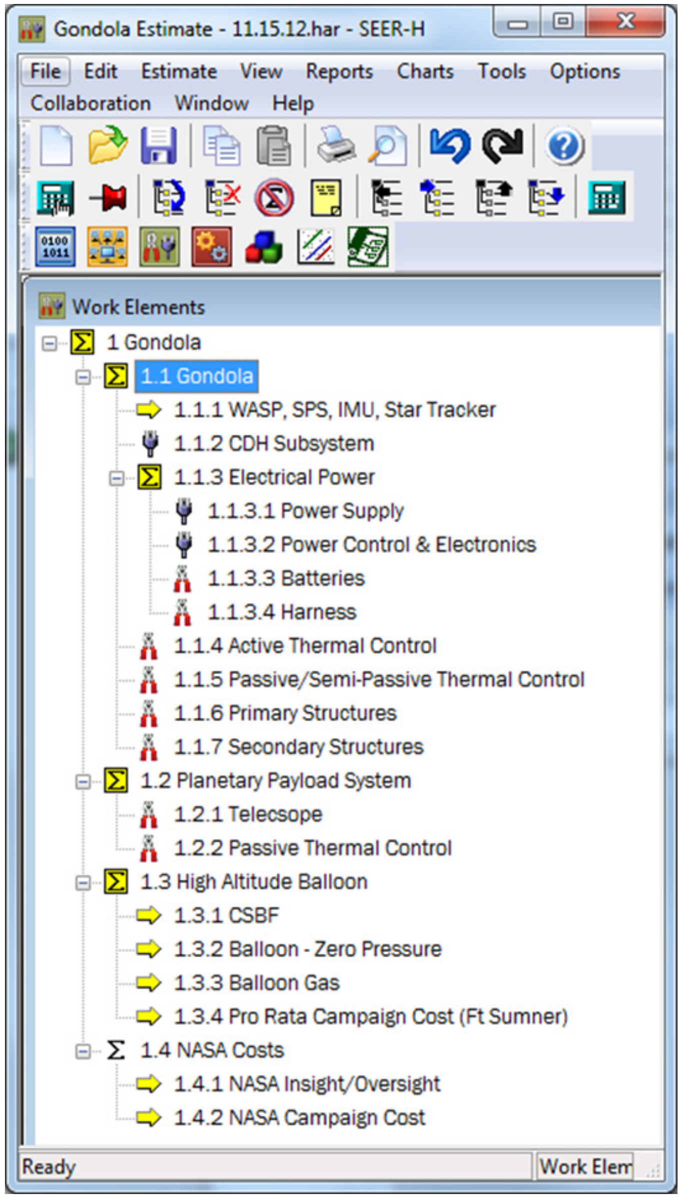


Figure A.1.—Cost ROMs.

TABLE A.1.—MISSION COST ESTIMATE WITH SEER-H

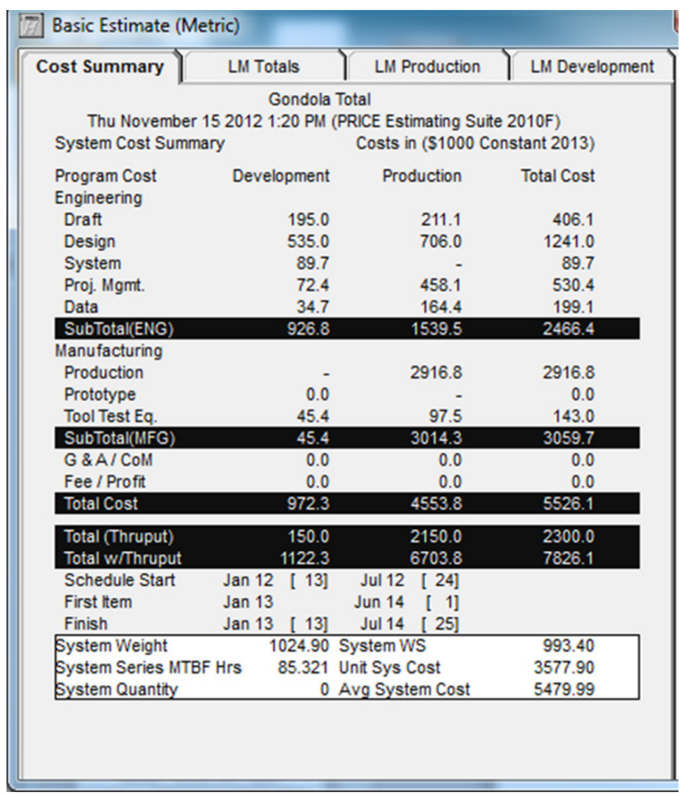
WBS	Work Element Name	Total Development Cost	Total Production Cost	Total
1	Gondola	3646	3874	7520
1.1	Gondola	976	614	1589
1.1.1	WASP, SPS, IMU, Star Tracker	0	400	400
1.1.2	CDH Subsystem	286	19	305
1.1.3	Electrical Power	144	26	170
1.1.4	Active Thermal Control	10	2	12
1.1.5	Passive/Semi-P Thermal Control	13	3	16
1.1.6	Primary Structures	328	55	382
1.1.7	Secondary Structures	7	1	8
1.2	Planetary Payload System	1750	715	2466
1.2.1	Telescope	1281	685	1966
1.2.2	Passive Thermal Control	13	2	15
1.3	High Altitude Balloon	0	1609	1609
1.3.1	CSBF	0	1000	1000
1.3.2	Balloon - Zero Pressure	0	300	300
1.3.3	Balloon Gas	0	100	100
1.3.4	Pro Rata Campaign Cost (Ft Sumner)	0	50	50
1.4	NASA Costs	150	300	450
1.4.1	NASA Insight/Oversight	150	150	300
1.4.2	NASA Campaign Cost	0	150	150
			Reserves (30%)	2256
All costs in FY13$K			Total (with Reserves)	9775

Therefore, utilizing SEER-H and adding a 30 percent reserve, the total mission cost is estimated to be approximately $9.8M in FY13 dollars.

An estimate of the cost of the balloon gondola was also completed with the PRICE Estimating Suite. The subsystem masses from the COMPASS design are used as inputs and the pertinent cost-modeling assumptions that apply for this estimate are as follows:

- Single unit build.
- No ground spares are included.
- The platform selected for this mission is "airborne: commercial."
- Contractor fee is excluded.
- Gondola is modeled using subsystem masses with integration costs included.
- No schedule constraint is imposed on the project.
- Throughput costs (same as SEER).
- Costs in this section are all in FY13 dollars (K).

In PRICE, each WBS element is one of the following: an assembly (tree), throughput (blue arrow), an electrical component (lightning bolt), a mechanical component (gear), or an integration and test element. As in the other cost model, the mass inputs are based on the COMPASS MEL. Again, integration costs are included, and the throughput costs remain the same. The NASA insight/oversight cost consists of 2 FTE at $150K/FTE for program management activities. Finally, reserves (30 percent) are added in post-processing.


Basic Estimate (Metric)
Cost Summary | LM Totals | LM Production | LM Development
Gondola Total
Thu November 15 2012 1:20 PM (PRICE Estimating Suite 2010F)
System Cost Summary — Costs in ($1000 Constant 2013)

Program Cost	Development	Production	Total Cost
Engineering			
Draft	195.0	211.1	406.1
Design	535.0	706.0	1241.0
System	89.7	-	89.7
Proj. Mgmt.	72.4	458.1	530.4
Data	34.7	164.4	199.1
SubTotal(ENG)	926.8	1539.5	2466.4
Manufacturing			
Production	-	2916.8	2916.8
Prototype	0.0	-	0.0
Tool Test Eq.	45.4	97.5	143.0
SubTotal(MFG)	45.4	3014.3	3059.7
G & A / CoM	0.0	0.0	0.0
Fee / Profit	0.0	0.0	0.0
Total Cost	972.3	4553.8	5526.1
Total (Thruput)	150.0	2150.0	2300.0
Total w/Thruput	1122.3	6703.8	7826.1
Schedule Start	Jan 12 [13]	Jul 12 [24]	
First Item	Jan 13	Jun 14 [1]	
Finish	Jan 13 [13]	Jul 14 [25]	

System Weight	1024.90	System WS	993.40
System Series MTBF Hrs	85.321	Unit Sys Cost	3577.90
System Quantity	0	Avg System Cost	5479.99

Figure A.2.—Mission cost estimate with PRICE.

Using the PRICE estimate, shown in Figure A.2, a 30 percent reserve equates to roughly $2.3M on the $7.8M estimate. Therefore, the total mission cost is estimated to be roughly $10.1M in FY13 dollars.

Because a point design was developed in a concurrent engineering design lab, the costs estimates from the process have been presented here; however, limitations of the parametric cost for this platform and application suggest they be used with caution. A better indicator of expected costs are the two recent missions that were flown along with current cost estimates for design and build of the specific OTA required to meet science requirements. Those costs are presented in Section 9.3.

A.2 Long Duration Flights

Just as the short-duration mission, the long-duration mission costs were estimated with two independent tools, SEER-H and PRICE.

For SEER-H, the WBS elements, shown in Figure A.3, consist of a roll-up (summation), throughput cost (yellow arrow), an electrical component (plug), or a mechanical component (wrench). The "application" for each component is generally consistent with the name, except for the telescope which is "optical". The mass inputs for each component are based on the masses in the COMPASS MEL. Integration costs are included. The input values of the throughput costs are previously stated in the assumptions. Minimal NASA insight/oversight cost is included of $900K for program management activities only. Finally, reserves (30 percent) are calculated and added, after the fact, to the estimated total.

The SEER cost estimates, including integration costs within the sub-element, are provided in Table A.2. The SEER estimate is roughly $15.5M.

Two parametric estimates were developed, one using SEER-H and one using PRICE, as described in the Appendix, Section 12.0. The PRICE estimating suite uses the COMPASS design masses as provided in the MEL. For the PRICE calculation, the assumptions include a single one-off build with no ground spares, a commercial airborne platform, integration costs proportional to the subsystem masses, and no schedule constraints. The PRICE MEL is shown in Figure A.4.

Integration costs are included and the throughput costs remain the same. Minimal NASA insight/oversight cost is included for program management activities. Finally, reserves (30 percent) are added after the fact. The estimated costs from PRICE are shown in Figure A.5. The total estimated costs are $12.6M. Reserves of $3.8M are added for a total of $16.4M.

The two estimates show that the total mission cost is estimated to be in the $15.5M–$16.4M range in FY13 dollars. Relative to the short-duration mission, the cost is higher by approximately $6M primarily due to increased science payload cost.

Because a point design was developed in a concurrent engineering design lab, the costs estimates from the process have been presented here; however, limitations of the parametric cost for this platform and application suggest they be used with caution. A better indicator of expected costs are the two recent missions that were flown along with current cost estimates for design and build of the specific OTA required to meet science requirements. Those costs are presented in Section 9.3.

A.3 Cost for BPO Services

At the time of this study, Table A.3 was provided by the Balloon Project Office as a rough order of magnitude costs for their services for a balloon mission, and is used for various throughput values in Appendix A.

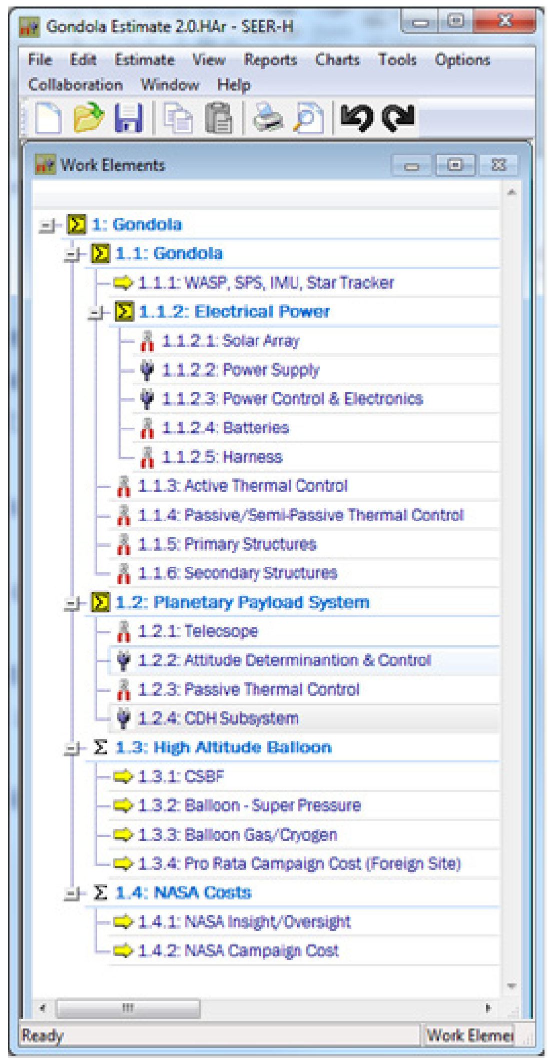


Figure A.3.—SEER WBS.

TABLE A.2.—ROM COST ESTIMATES FOR THE LONG-DURATION MISSION

WBS	Work Element Name	Total Development Cost	Total Production Cost	Total
1	Gondola	4497	7418	11914
1.1	Gondola	1026	633	1658
1.1.1	WASP, SPS, IMU, Star Tracker	0	400	400
1.1.2	Electrical Power	578	79	658
1.1.2.1	Solar Array	7	18	25
1.1.2.2	Power Supply	110	8	119
1.1.2.3	Power Control & Electronics	227	14	240
1.1.2.4	Batteries	54	22	76
1.1.2.5	Harness	27	13	40
1.1.2.6	Integration	153	4	157
1.1.3	Active Thermal Control	10	2	12
1.1.4	Passive/Semi-Passive Thermal Control	3	0	3
1.1.5	Primary Structures	198	32	230
1.1.6	Secondary Structures	62	10	72
1.1.7	Integration	174	109	284
1.2	Planetary Payload System	2405	745	3150
1.2.1	Telescope	1281	685	1966
1.2.2	Attitude Determination & Control	234	9	242
1.2.3	Passive Thermal Control	36	6	42
1.2.4	CDH Subsystem	234	16	250
1.2.5	Integration	620	30	650
1.3	High Altitude Balloon	0	3500	3500
1.3.1	CSBF	0	1000	1000
1.3.2	Balloon - Super Pressure	0	1250	1250
1.3.3	Balloon Gas/Cryogen	0	250	250
1.3.4	Pro Rata Campaign Cost (Foreign Site)	0	1000	1000
1.4	NASA Costs	200	700	900
1.4.1	NASA Insight/Oversight	200	200	400
1.4.2	NASA Campaign Cost	0	500	500
1.5	Systems Level Integration	866	1840	2706
			Reserves (30%)	3574
All costs in FY13$K			Total (with Reserves)	15489

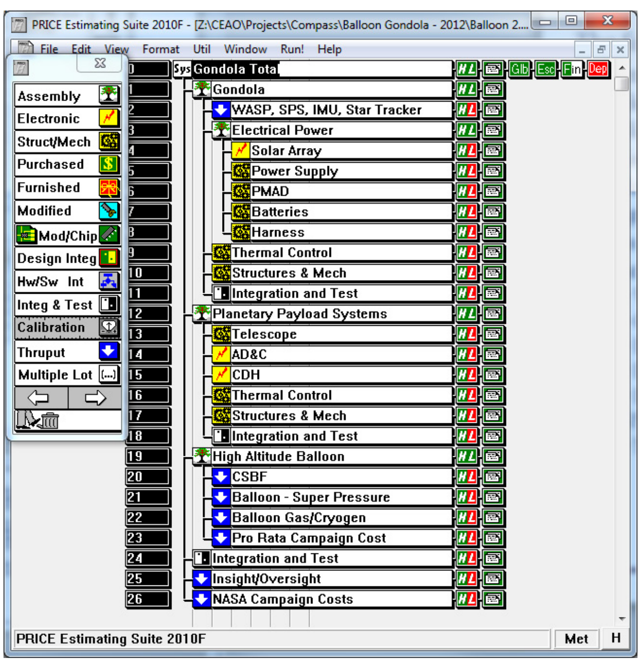


Figure A.4.—PRICE MEL.

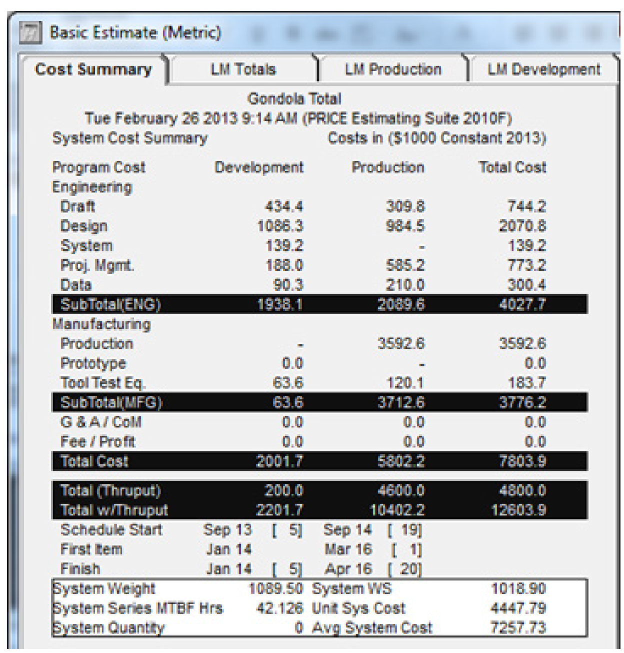


Figure A.5.—PRICE cost estimates.

TABLE A.3.—BPO COST ROMS

Cost Element	Category	$K	Details
Flight Support Hardware	CSBF Flight Hardware (first flight)	1000	Costed when first used, one time purchase, includes LDB SIP, UTP, HGA, rotator
	CSBF Flight Hardware Recurring Cost	150	Each additional flight, includes expendables, refurbish, test
	WASP Flight Hardware (first flight)	400	Costed when first used, one time purchase, includes Hubs, Gimbal Frames, Star Tracker
	WASP Flight Hardware Recurring Cost	100	Each additional flight, includes expendables, refurbish, test
Campaign Costs	Pro Rata Campaign Cost	50 500 to 1000	Fort Sumner launchsite (conventional) Foreign sites (Australia, Antarctica, Sweden)
	Balloon Cost	200 to 300 1200	Zero Pressure 29 to 40 MCF 18 MCF Super Pressure (FY12 dollars)
	Helium Cost (per balloon)	25 to 100	Depending on launchsite
	Cryogen	50 to 100	Depending on launchsite
	Antarctic Personnel Cost	15	Per person, NSF support
	Shipping	40	For Antarctic campaign, from Texas to California

Appendix B.—Acronyms

APL	Johns Hopkins University Applied Physics Laboratory
BLAST	Balloon-borne Large-Aperture Sub-millimeter Telescope
BOPPS	Balloon Observation Platform for Planetary Science
BPO	Balloon Program Office
BRRISON	Balloon Rapid Response for ISON
C&DH	Command and Data Handling
CBE	current best estimate
CCD	charge-coupled device (image sensor)
CIP	Consolidated Instrument Package
CMOS	complementary metal-oxide semiconductor (image sensor)
CSBF	Columbia Scientific Balloon Facility
DEIMOS	Deep Imaging Multi-Object Spectrograph
DRM	Design Reference Mission
ESI	Echellette Spectrograph and Imager
FGS	fine-guidance sensor
FOV	field of view
FSM	fine-steering mirror
FWHM	full width at half maximum
GHAPS	Gondola for High-Altitude Planetary Science
GN&C	Guidance, Navigation, and Control
GPS	global positioning system
HIRES	High Resolution Echelle Spectrometer
HST	Hubble Space Telescope
IR	infrared
KBO	Kuiper Belt Objects
LOS	line-of-sight
LRIS	Low Resolution Imaging Spectrometer
MCF	million cubic feet
MEL	Master Equipment List
MIR	mid-infrared
MIP	Micro-Instrumentation Package
MMPDS	Metallic Materials Properties Development and Standardization
MOC	mission operations center
MOCC	Mission Operations Control Center
NM	Nautical mile
NUV	near-ultraviolet
OAP	off-axis parabolic
OTA	Optical Telescope Assembly
OTH	over-the-horizon
PI	principal investigator
PSF	point-spread function
RMS	root-mean-square
ROCC	Remote Operations Control Center
ROM	rough order of magnitude
SBAG	Small Bodies Assessment Group
SIP	Support Instrumentation Package
SMD	Science Mission Directorate
SNR	signal-to-noise ratio
SOAP	Space Orbit Analysis Program
SOFIA	Stratospheric Observatory for Infrared Astronomy
SPS	solar pointing system
STO	Stratospheric Terahertz Observatory
SwRI	Southwest Research Institute
TDRSS	Tracking and Data Relay Satellite System
TM	Telecommunications monitors
TMA	Three-mirror anastigmat
TNOs	Trans-Neptunian Objects
UHF	ultra-high frequency
UTP	universal termination package
UV	ultraviolet
VeXAG	Venus Exploration Assessment Group
WASP	Wallops Arcsecond Pointer
WBS	work breakdown structure
WFF	NASA’s Wallops Flight Facility
WFOV	wide field of view

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