

NIAC Project:
10 meter Sub-Orbital Large Balloon Reflector
(LBR)

Summary of Research

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1.0 LBR TECHNICAL DESCRIPTION

In Section 1 we summarize the technological approaches to the Large Balloon Reflector (LBR) that are discussed at length in our Phase I Technical report. Within each subsection we highlight how the work was advanced in Phase II. In Section 2 the work and lessons learned from the 3 and 5 meter LBR prototypes are described. In Section 3 the LBR Sensor Package stratospheric flight is described. Section 4 puts LBR in the context of on-going NASA missions. In Sections 5 and 6 the dissemination of results and plans to realize a stratospheric LBR are discussed.

1.1 Technological Approach

Water vapor in the Earth's atmosphere absorbs much of the far-infrared emission and absorption lines from atoms and molecules in space needed to understand the origins of stars, planets, and galaxies. It is for this reason that telescopes designed to observe far-infrared spectral lines are placed on high, dry, mountain peaks or on the frozen high plateau of Antarctica. However, even these 10 to 12 meter class telescopes (ALMA – Atacama desert, Chile; Caltech Submillimeter Telescope – Mauna Kea, Hawaii; Heinrich Hertz Telescope – Mt. Graham, Arizona; South Pole Telescope - Antarctica) are essentially blind due to atmospheric absorption over much of the far-infrared. ESA/NASA's Herschel mission launched a 3.5-meter aperture into L2 orbit in 2009,

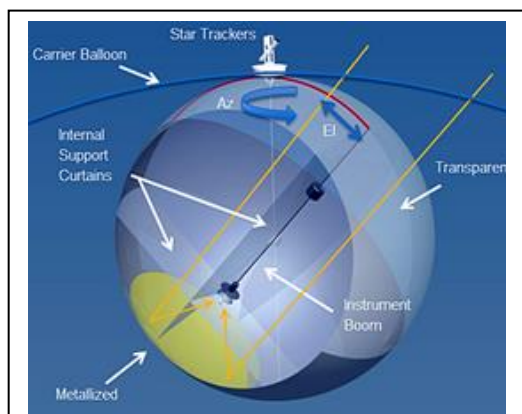


Figure 2: LBR Concept. The LBR spherical reflector resides within a transparent carrier balloon, which serves as both a launch vehicle and radome.

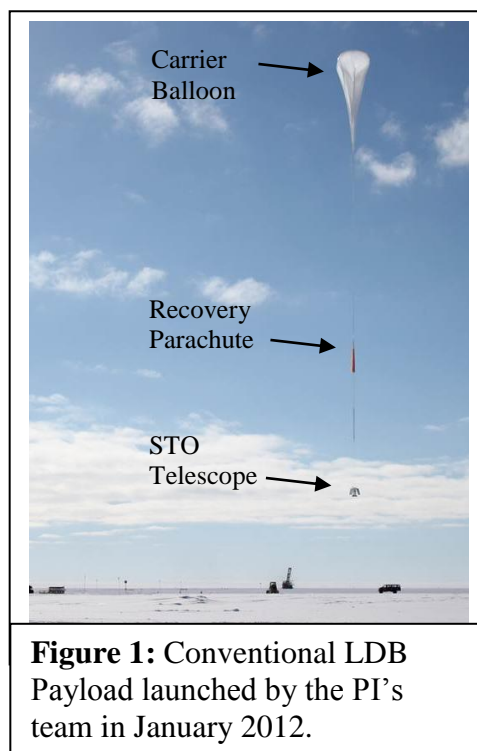


Figure 1: Conventional LDB Payload launched by the PI's team in January 2012.

which made major advances in far-infrared and THz astronomy and technology.

However,

Herschel's 3-year cryogenic mission has ended, leaving behind more questions than answers. New capabilities are urgently needed to make forward progress. The airborne Stratospheric Observatory for Far-Infrared Astronomy (SOFIA) is now available to fill the gap, but it brings a modest 2.5-meter aperture and limited sensitivity for the high angular resolution observations needed to probe distant galaxies and forming stellar and planetary systems in the Milky Way. The James Webb telescope at 6.5 meters will do an excellent job probing the thermal infrared with its dedicated suite of instruments, but it lacks far-infrared coverage and the high spectral resolution needed to

disentangle the complex velocity fields associated with much of the interstellar medium. What is required is a 10-meter-class telescope in near-space capable of conducting far-infrared wavelength (THz frequency) high spectral resolution ($R > 10^5$) observations – LBR.

NASA's zero pressure or, more recently, super pressure balloons provide a means of transporting to and maintaining payloads of 2-3 tons in near space (see Figure 1). With this lift capability it is perhaps possible to construct a 10 meter carbon-fiber telescope and launch it to near space. However, the combination of stratospheric winds over such a large dish surface and pendulation at the end of a long balloon tether will make pointing the telescope at the required arc second levels problematic or impossible.

Instead of attempting to maintain the pointing of a large telescope at the end of a tether, we propose to deploy a telescope in the benign, protected environment *within* the carrier balloon. The telescope is itself a balloon, spherical in shape, metalized on one side and anchored to the top of the carrier balloon via a rotating azimuth plate (see Figure 2). The carrier balloon serves as both a stable mount and a radome for the inner balloon reflector. Light from space (or the atmosphere or ground) first passes through the ~ 2 mil thick polyethylene skin of the carrier balloon and then through the ~ 1 mil thick Mylar side of the inner balloon. Together these layers have $\leq 8\%$ absorption at the wavelengths of interest. The incoming light then encounters the aluminized, spherical, back surface of the inner balloon and is then focused into a receiving system. To achieve the



Figure 3: Pageos 1 Satellite during tests in 1965: 30.5 m in diameter, 0.5 mil Mylar.

performance of a 10 meter parabolic reflector, a 20 meter diameter inner balloon can be used with a modest size (~ 1 meter) spherical corrector. For acceptable aperture efficiency, the inner balloon needs to hold its spherical figure to $\leq \lambda/8$ of the wavelength of interest. The surface roughness should be $\leq \lambda/30$. As an example, the ground state transition of water has a wavelength of $646 \mu\text{m}$ (557 GHz). At this wavelength the LBR surface roughness needs to be $\sim 21 \mu\text{m}$ and the spherical figure held to $40 \mu\text{m}$. The required surface roughness is achievable for Mylar under pressure (e.g Pageos I balloon, ca. 1965 in Figure 3). The spherical figure specification is more challenging and may require a combination of surface monitoring and active feed focus/positional control to achieve. Telescope pointing is accomplished by rotating the azimuth ring and the LBR sphere in elevation. Attached to the rotating azimuth plate on the outside of the balloon are star cameras to determine absolute position on the sky and gyroscopes to maintain pointing knowledge as the telescope slews. The telescope's power system and command and control unit are housed in a conventional gondola service module hanging below the carrier balloon. Low-loss power and fiber optic data cables connect the service module to the telescope and instrument. The 'Top Hat' Long Duration Balloon (LDB) experiment launched in 2001 had a similar payload configuration, but with a 1 meter aluminum telescope mounted to the

top of a rotating azimuth plate. During the launch (see Figure 4) a tow balloon is used to lift the telescope/rotating plate up while the carrier balloon is being inflated underneath.

1.2 Spherical Reflectors

At the heart of LBR is a spherical reflector. Spherical reflectors have a long history in astronomy. This is due in part because a spherical shape is a “natural” result of different types of surface grinding processes. It is also an easy form to measure since all points are at a single distance, the radius of curvature, from the center of the curvature. It has been recognized for several centuries that a spherical reflector is an imperfect focusing element. As shown in Figure 5 a spherical reflector unlike a parabola, does not bring a plane wave (parallel rays) to a point focus. Radiation



Figure 4: Top Hat Balloon Launch in 2001.

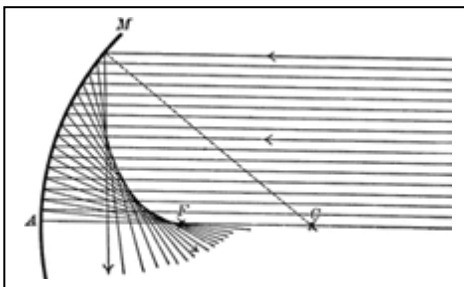


Figure 5: Schematic of spherical aberration from a spherical reflector. The rays passing close to the center of curvature (C) are brought to the paraxial focal point (F), while parallel rays incident at greater distances from C cross the C-F axis closer to the reflecting surface.

from a small section of a sphere (discussed further below) is brought to the paraxial focus denoted F, located at a distance equal to half the radius of curvature from the surface of a sphere. As one uses more and more of the sphere, the initially parallel rays are focused to a line extending away from the center of curvature (towards A).

The large field of view of a spherical reflector means that to point the beam in different directions, one need only move the feed/receiver in a circular arc centered on the center of curvature of the sphere and having a radius approximately equal to half the radius of curvature of the sphere. The reflector surface, if made larger than the portion utilized at any moment, does not need to move at all. This important advantage was one of the motivations for the design of a 1000 foot diameter radio telescope; steering such a large structure to point in different directions would be difficult (to say the least) but as conceived (Gordon and LaLonde 1961) the Arecibo telescope’s spherical primary is held above the surface of a natural bowl-shaped depression. The



Figure 6: The Arecibo radio telescope. The spherical primary reflector is 1000 ft in diameter. A line feed for 400 MHz operation can be seen hanging below the platform and track. The tip of the line feed is at the paraxial focal point of the spherical primary.

radius of curvature of the primary reflector of the Arecibo telescope is 870 ft., and the feeds thus move along an arc approximately 435 ft above the spherical surface, as seen in Figure 6.

1.3 LBR Sphere Fabrication

LBR uses the natural shape of an inflated balloon to create the shape of a spherical reflector. Three different approaches to fabricating LBR have been investigated in Phase I. The first approach uses the typical “gore” technique (Figures 7 and 8) (i.e. banana peel) employed in the fabrication of large scientific balloons. The “gore” technique makes use of flat sheets of film cut into a pattern and then sealed together to create a 3 dimensional (3D) structure. For a small number of gores under low pressure the volume looks faceted. This then requires higher pressures to stretch or deform the material into the more spherical shape. If too few, it will exceed the structural limits of the material and fail, often catastrophically. This can be remedied by increasing the number of gores but this further creates an undesirable stiffening of the structure at the apex and nadir of the sphere due to converging seam tapes. The structure thus has a variable structural stiffness along its length which has to be accounted for in the structural analysis such that the final shape will be the desired spherical shape. Whereas this is usually fine for large scientific balloons using large deformation polyethylene, it presents more difficulty for the stiffer materials and smaller volumes associated with the LBR. Another is seaming together of latitudinal bands of flat material.



Figure 7: Typical “gore” pattern sections used in most scientific balloons



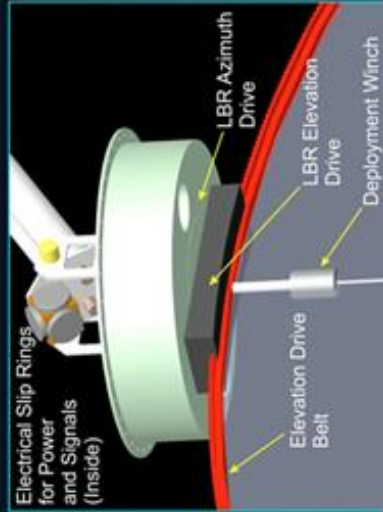
Figure 8: Example of an inflatable that uses the “gore” fabrication technique.

THz Sub-Orbital Large Balloon Reflector (LBR)

FO1

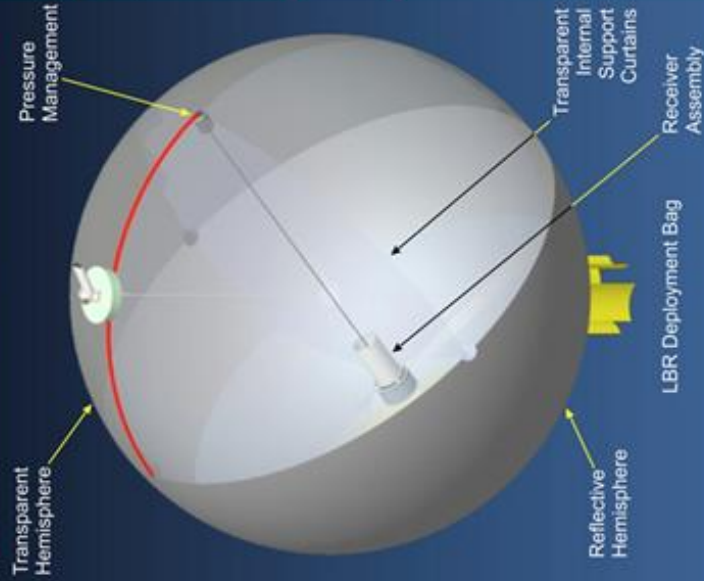
Top Plate Assembly

Mounts to the Carrier Balloon Top Ring



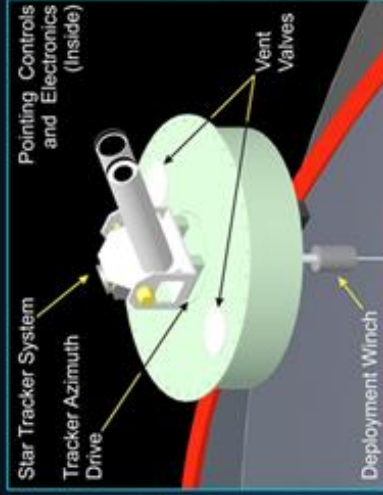
Spherical Reflector Assembly

20 Meter Diameter
Pressurized to 1 mbar with Helium
Azimuth Range : Unlimited
Elevation Range: 0° to 60°



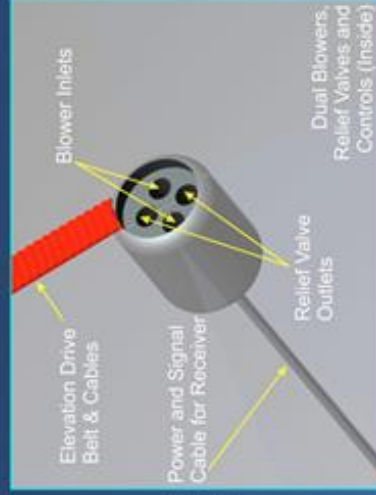
Top Plate Assembly

Diameter: 2m
Depth: 0.75m



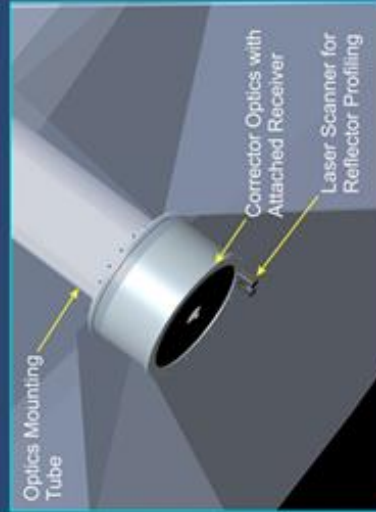
Pressure Management

Constant Differential Pressure
Redundant Blowers and Relieve Valves

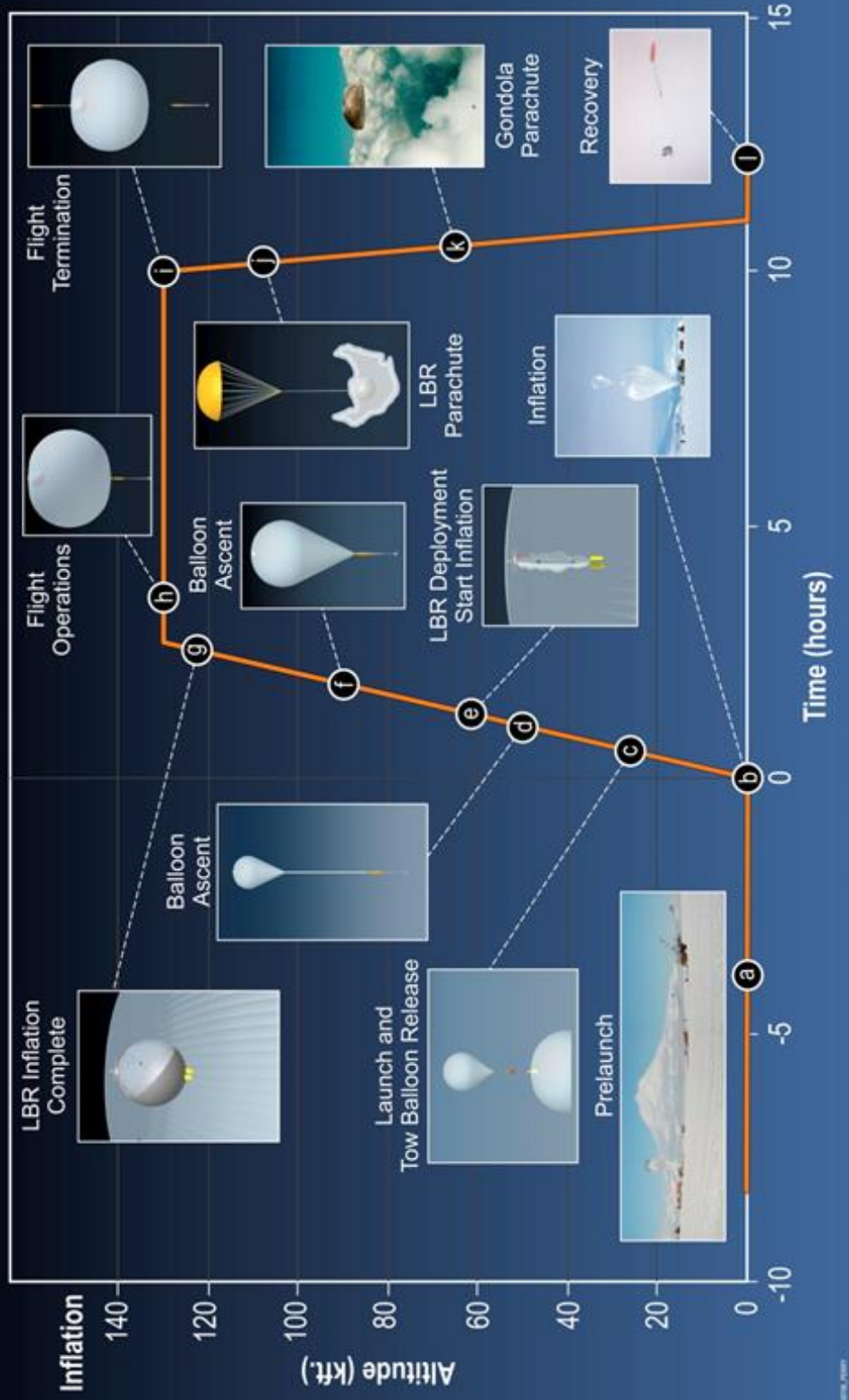


Corrector and Receiver Assembly

Adaptive Optics Axial Focus Control



Typical LBR Balloon Flight Profile



Another construction method is similar to that employed in soccer balls (and geodesic domes), where hexagonal and pentagonal sections are seamed together into a Goldberg polyhedron. This approach could provide more uniform loading over the “gore” approach, but may be more costly to fabricate. The polyhedron can be constructed from an icosahedron with the 12 vertices truncated such that one third of each edge is cut off at each of both ends. A sphere fabricated this way would offer a more uniform structural stiffness distribution. However, the fabrication of such a sphere may be more difficult from a production standpoint due to the size of the inflatable and possibly be more costly.

The ideal way of designing and fabricating the LBR would be to cast it in the correct spherical shape. Several methods were investigated, such as blown extrusion, casting, etc. None of the approaches investigated appeared very feasible for our application based on complexity, required environmental controls and equipment availability. As such, we investigated other ways of obtaining a 3D shape rather than trying to deform flat panels into a 3D shape. A leader in this field of sail making is North Sails North America located in Minden, Nevada with their 3DL® sail making process (North Sail 2014). This same process can be applied to the LBR fabrication.

The LBR sphere is an inflated structure as shown in FO1. The structure is made of two hemispherical hull sections, one that is transparent and one that is metalized to be reflective to the THz signal. Three internal orthogonal curtains will provide shape stability and serve as mount for the optical signal corrector and signal receiver. This whole structure will be folded and packaged in a container for installation in the carrier balloon. The packed LBR remains in this protective container during launch. During ascent the container will be slowly lowered using an internal winch. Once the flaccid LBR is completely extended from the container, the blowers will pump helium from the carrier balloon in to the LBR sphere. The two blower assemblies will maintain the selected differential pressure to provide the optimum shape and stability. The LBR hull and internal curtains will be made of very thin film and scrim that have been selected to be almost completely transparent to the target signal. FO2 illustrates the flight profile for a 1day LBR test flight using a standard zero pressure balloon as the carrier balloon. Flight of 100+ days will be possible using NASA’s Super Pressure Balloon (SPB).

1.4 Instrument Overview

A Block Diagram of the Instrument Unit (IU) is shown in Figure 9. LBR’s optics are designed to provide a 13" full-width-half-maximum (FWHM) diffraction limited beam at the frequency of the astrophysically important ground state water line (557 GHz). The LBR Instrument Unit (IU) includes; 1) the adaptive spherical corrector, 2) the surface measurement system, and 3) the THz receiver system. The IU is mounted inside the sphere at the intersection of three orthogonal support curtains. Rigidly fixed at the focus point of the spherical reflection surface, the IU mount will include a gross focus motion that can move the whole assembly axially, while an array of actuators will warp the secondary reflector to fine tune the focus while correcting for any distortion in the reflector surface. During flight the LBR beam quality will be routinely measured and optimized on a strong calibration source (e.g. Moon and planets).

In Phase II a detailed design of the IU required for use with a 1/4 scale LBR was performed and a prototype constructed using many of the components employed in our Phase I, 3-meter LBR prototype. A photograph of the completed unit is shown in Figure 10. The prototype IU was tested in the laboratory and found to meet functional requirements. Here a fixed-shape secondary is employed. The technology for the adaptive secondary was constructed and tested separately (see Sec. 1.6).

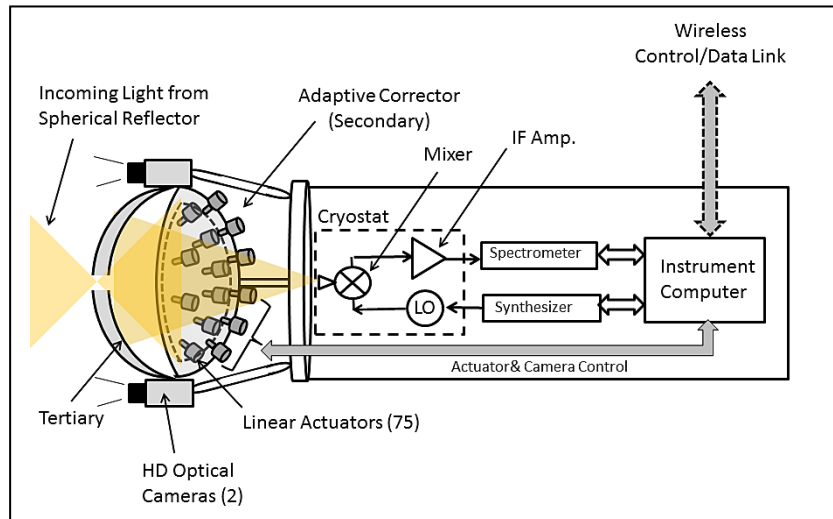


Figure 9: LBR's Instrument Unit (IU). THz light from the 10 meter reflector enters the optical system which corrects for spherical aberration and focuses it into a low-noise THz receiver system. The receiver produces a power spectrum of the THz light which is passed on to the instrument computer and wirelessly to the telecommunications system. The instrument computer also produces a real time fit to the primary reflector's surface using parallax measurements from two optical cameras. The computer reshapes the corrector using actuators to compensate for nonspherical distortions.

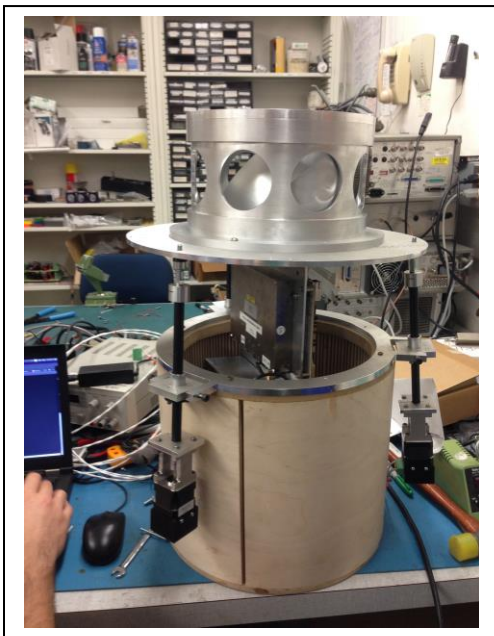


Figure 10. Instrument Unit (IU) developed in Phase II. In this orientation light from the spherical reflector enters the IU from above where it encounters a spherical corrector consisting of two mirrors. The corrector collapses the focal line produced by the spherical reflector to a focal point just within the aperture of a waveguide feedhorn. The feedhorn conveys the light to a mixer. The mixer downconverts the incoming signal to ~1.5 GHz. The spectrometer within the IU then digitizes the signal and performs a Fast Fourier Transform to yield the desired power spectrum.

1.5 Spherical Correctors

It is possible to use a spherical reflector without any corrector, provided the f/D ratio is limited to a value determined by the allowable phase error (see Phase I report). The result is that

to achieve single focus operation, the effective diameter of the spherical primary is reduced to ~25% of its physical size. It is thus appropriate to consider the use of a spherical corrector for LBR. Correctors can be divided into two general classes – those which are on-axis (e.g. used on the HET and the Armenia Telescope) and those that are off-axis (e.g. used for Arecibo). Figure 10 compares the morphology of these two approaches. To realize a corrector where the receiver system (Rx) is located behind and not in front of the corrector, two mirrors are required. The first mirror encountered by light arriving from the spherical reflector is referred to as the secondary and the subsequent mirror the tertiary. In both the On and Off axis designs the corrector blocks ~10% of the incident radiation. In the Arecibo system the receiver is small compared to the telescope and can be mounted to the side of the tertiary with no significant increase in blockage. In the case of LBR, the size of the receiver is a significant fraction of the corrector itself, so an on-axis approach, where the receiver is behind the corrector, was initially investigated.

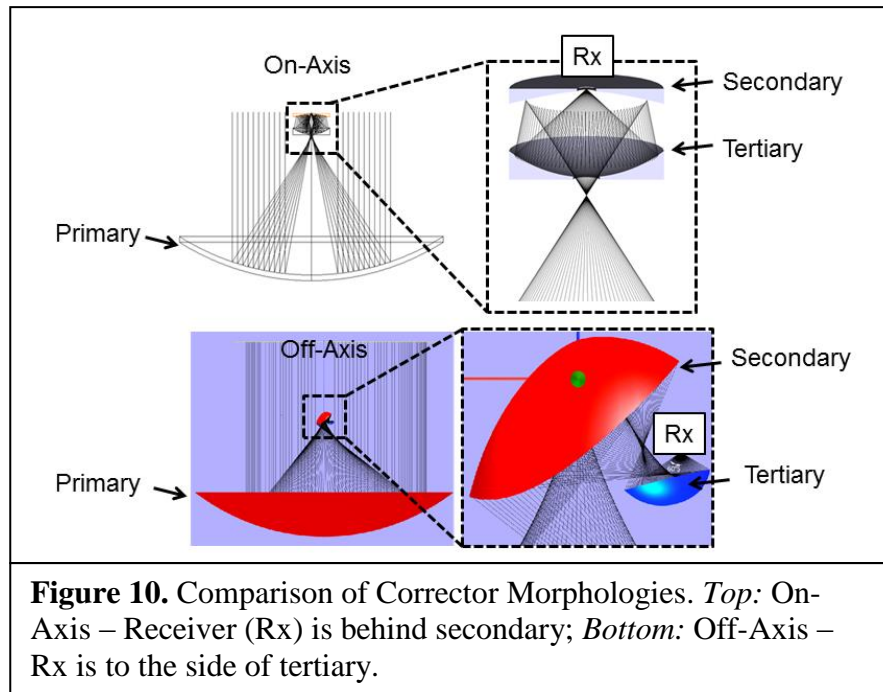


Figure 10. Comparison of Corrector Morphologies. *Top:* On-Axis – Receiver (Rx) is behind secondary; *Bottom:* Off-Axis – Rx is to the side of tertiary.

The main drawback found with the on-axis designs are limitations imposed by the through hole on the tertiary mirror. Due to Gaussian Beam constraints based on locations, the illumination of the primary spherical mirror is limited to about half of its radius with this approach. Nonetheless, the introduction of the on-axis corrector system allowed for excellent performance, minimizing the rms wavefront error of the system. A tolerance study showed that LBR would benefit greatly from having an adaptive secondary. The on-axis spherical corrector design increases the amount of the primary mirror that can be utilized by a *factor of two* over the under illuminated, no-corrector approach.

The off-axis corrector used at the Arecibo radio telescope is, like the on-axis configuration, a dual shaped mirror system. The system corrects for spherical aberration and provides an elliptically shaped aperture illumination, with nearly uniform distribution. The corrector illuminates only partially the 305m available aperture. The telescope is pointed by moving the whole corrector system on an elevation track (1° to 19.7°) centered at the center of the main reflector parent sphere. Scaling from the Arecibo design, the off-axis corrector system

for LBR should permit the realization of a 10 meter telescope aperture to be realized with a balloon diameter of ~20 meters.

1.6 Adaptive Spherical Corrector

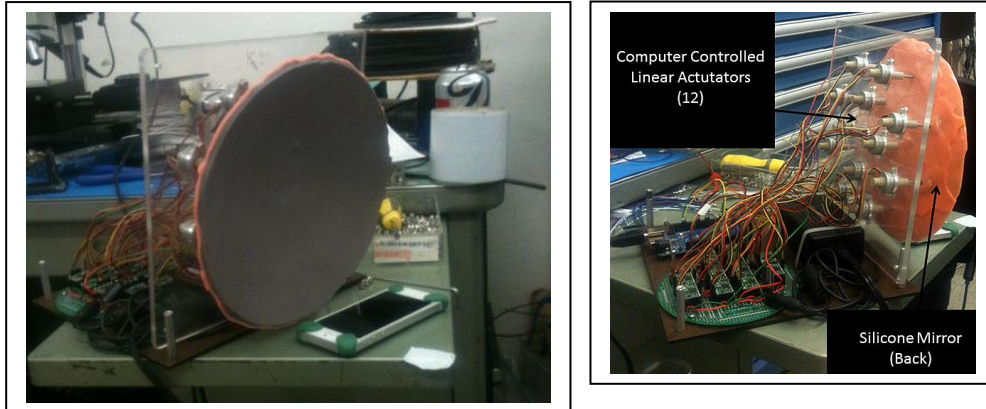


Figure 11: Phase I adaptive corrector prototype. The LBR spherical reflector requires a spherical corrector to bring converging rays to a single focus. The spherical corrector must be adaptive to compensate for nonspherical distortions in the balloon reflector surface. Pictured is an 8 inch scale model prototype of a computer controlled, flexible corrector.

On- and off-axis correctors described in the previous two sections assume incoming rays from an ideal spherical surface. However, even with the proper choice of materials and careful manufacture, nonspherical distortions due to a combination of gravity and differential pressure will inevitably lead to nonspherical distortions. The analyses of these forces over the course of a flight suggest the distortions will occur over large physical and temporal scales (>1 meter and ~ 0.5 to 12 hours) with peak amplitudes of between 25 and 50 mm. The shape of the LBR sphere will be measured optically (see Section 1.7) and deviations from an ideal sphere computed every few seconds. The shape of the spherical corrector will then be adjusted to compensate for these deviations.

The diameter of the LBR corrector will be ~ 1 meter. To provide a conjugate match to the distortions, the mirror surface must be extremely flexible and adjustable under computer control. In order to investigate the feasibility of such a structure, in Phase I we constructed a $1/6^{\text{th}}$ scale model of an adaptive corrector (see Figure 11) out of silicone with 12 linear actuators. To make the mirror, a high quality negative of the ideal corrector surface was first made out of plaster. While the silicone was still in liquid form, it was loaded with fine grain aluminum powder. The aluminum powder is used to make the final mirror reflective at the frequency of interest. The silicone/aluminum powder mixture is then poured over the plaster mold and allowed to cure. Attachment points for the linear actuators are embedded in the back of the mirror while it is still in the curing process. The mirror is indeed quite flexible, allowing displacements of at least 15 mm (the maximum displacement of the available actuators). A movie showing the actuator in action is can be viewed at <http:soral.as.arizona.edu>. To provide ~ 1 meter spatial resolution on the LBR surface, ~ 80 actuators will be required across the back of the full-size adaptive corrector. In Phase II a $1/4^{\text{th}}$ scale adaptive corrector with 45 actuators was built and tested (see Figure 12).

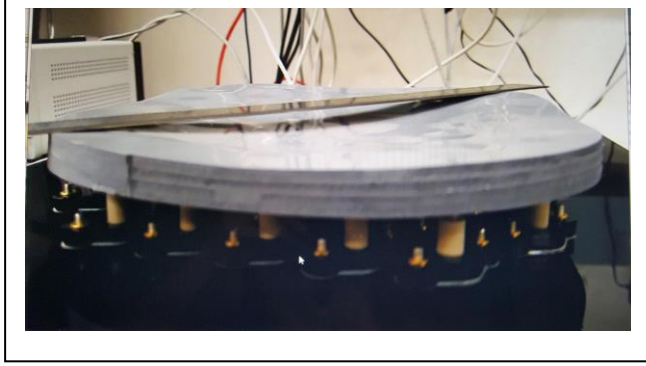


Figure 12. Phase II adaptive corrector prototype. Here, 45 actuators provide fine figure control of a ~10 inch diameter flexible mirror suitable for use in a 2.5 meter spherical corrector.

1.7 Surface Measuring System

A key to the successful operation of LBR will be the ability to measure its surface figure during flight and compensate for nonspherical distortions that may occur. The surface figure of the inflated reflector will be determined by an optical instrument mounted to the front surface of the corrector housing. The instrument will measure the surface figure by determining the location of several million positions on the reflector surface in 3 dimensional space. Each measured position will serve as a control point in a non-uniform rational basis spline (NURBS) model fit to the reflector surface. Several different types of ranging devices have been under consideration; these include a time of flight (TOF) infrared laser ranger, an infrared parallax range finder, and an optical parallax range finder. As part of our Phase I study we gained access to the FARO Focus 3D laser ranger (TOF) system. Figure 12 (left) shows the laser ranger is being operated from inside our 3 meter LBR prototype. The ranger uses a single 905 nm laser to scan across the balloon surface using two rotating mirrors. A full image of the balloon can be made to ~ 1 mm accuracy in just a few seconds. The sphere surface is formed from 0.8 mm thick thermoplastic

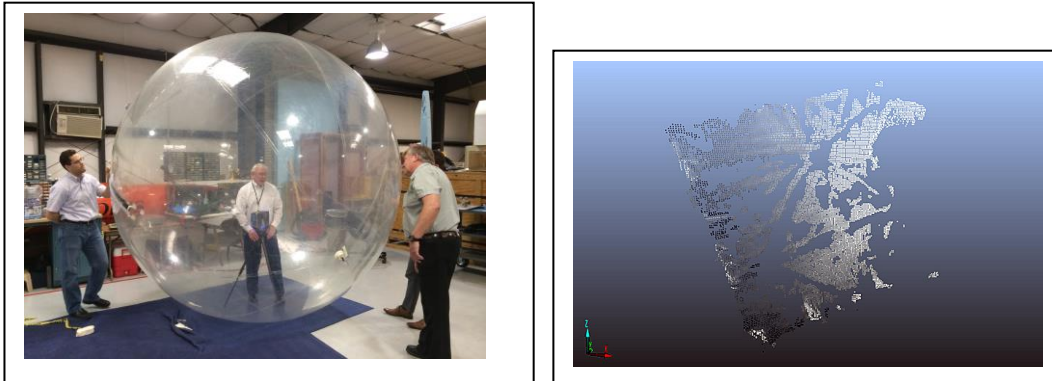


Figure 12: Left: FARO TOF ranger (and operator!) within 3 meter prototype LBR plastic sphere. Right: TOF ranger image of aluminized Mylar surface.

polyurethane (TPU) gores. The TPU material was found to be largely transparent at the laser frequency, yielding only a small percentage of returns. However, when covered with aluminized Mylar (the reflecting surface material for the flight version of LBR) strong reflections and accurate surface determinations could be made. Figure 12 (right) shows the surface fit to returns from a section of the sphere where a sheet of aluminized Mylar was loosely attached to the outside. Gaps in the coverage are due to small scale wrinkles in the sheet. The reflector surface of a flight sphere would itself be fabricated from aluminized Mylar, dramatically reducing the number and scale of wrinkles. The laser system has a ranging distance of ~25 meters, making it a

good match to the 20 meter diameter LBR required to realize a telescope with a 10 meter aperture.

The two other surface measurement approaches studied in Phase I use a parallax based approach to determine distances to targets on the sphere's surface. The first of these employed a 'Kinect' system from a Microsoft X-Box gaming console to project 1000's of infrared laser dots onto the balloon surface. The Kinect system then uses an IR camera and a stored reference image to determine the angle of parallax and subsequently the distance to each spot. This system was also able to measure distances to an accuracy of ~ 1 mm with no moving parts. The gaming system used here has a range limit of ~3.5 m. Non-gaming versions with larger range limits are available.

Testing with the rooftop version of LBR in Phase I showed that the Kinect system can be blinded by infrared radiation emitted by the aluminized Mylar surface when illuminated by the Sun. A solution to this problem is to utilize an optically based parallax ranging system. Here, instead of using infrared laser dots projected onto the reflector's surface for parallax measurements, a regularly spaced array of small (~5 mm diameter) optically reflective dots are printed on to the gore surfaces from which the LBR sphere is formed. By combining the parallax measurement with the location of the dot on each camera's CCD, it is possible to locate the dots in x, y, z and generate a 3-D image of the reflector surface. From this image the displacements on the corrector's actuators required to achieve optimum performance can be calculated. In Phase II we constructed a prototype parallax system utilizing webcams. Software was developed from which surface distortions could be derived from the stacked images (see Figure 13). Ultimately, LBR will be flown in the Antarctic summer from McMurdo, where the Sun is up 24 hours. However, for a test flight, it will likely be flown from Ft. Sumner, NM, in which case it is likely to encounter night. At such time a light will be turned on inside LBR to provide the necessary illumination of the surface.

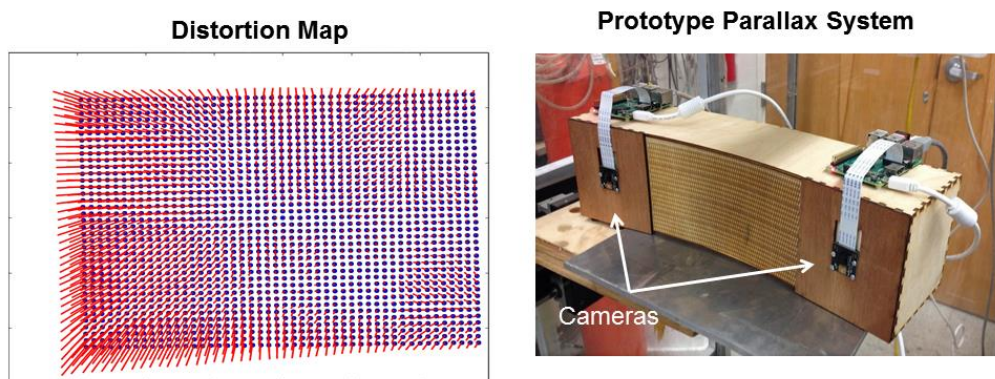


Figure 13. LBR Phase II Metrology. Right: Prototype parallax metrology system consisting of two webcams separated by ~1 meter. Left: Distortion map of test surface generated from stacked images.

1.8 Receiver System

After being transformed by the adaptive secondary and the tertiary, the incoming signal comes to a focus at the feedhorn of a mixer. The mixer down-converts the THz sky signal to microwave frequencies; multiplying the incident sky and LO signals together. The product of the multiplication contains sum and difference frequencies. Filtering permits only the difference (*i.e.*

intermediate frequency (IF)), signal to appear at the mixer output. From there coax conveys the downconverted sky signal to a series of low-noise microwave amplifiers. For optimum performance, the mixer and first stage amplifier reside in a cryostat where they are cooled to cryogenic temperatures by a closed-cycle refrigerator. The amplifiers boost signal levels to where they can be digitized without increasing the noise. A digital spectrometer is used to produce a power spectrum of the amplified signal. The instrument computer 1) reads-out the spectrometer, 2) models the shape of the spherical primary from parallactic surface measurements, and 3) adjusts the secondary's shape to produce a conjugate match to nonspherical surface distortions. In Phase II the 115 GHz receiver used in Phase I was replaced with a 345 GHz version to enable ground testing closer to our desired frequency of 557 GHz.

1.9 Steering Mechanisms

The LBR instrument is pointed by rotating the whole spherical reflector in elevation and azimuth (see F01). The azimuth rotation range is unlimited. The elevation range will be -10° to 70° . Wireless communications is used for the processed signals and instrument control. A slip ring assembly is used to provide electrical power to the LBR. The azimuth rotator is powered by a direct drive servo motor with a high resolution encoder, while the elevation change will be accomplished by driving a toothed belt that is secured to the circumference of the LBR sphere. This belt is driven by a servomotor powered anti-backlash gear arrangement. A linear high resolution encoder provides accurate elevation positioning. These drive systems are housed in the bottom of the carrier balloon's top plate assembly along with the azimuth drive for the star camera telescope that will be mount on the top of the top plate assembly. Star cameras will lock on to a reference star and provide offsets to the elevation and azimuth drives to keep the LBR reflector pointed to within $\pm 0.5^\circ$ of the target position. Fine pointing will be performed using the tip-tilt controls of the adaptive corrector. A similar approach has been used by our team members on the BRISSON gondola, where pointing accuracies of $<5''$ were achieved. This measured performance meets our pointing goal of $\sim 5''$, corresponding to $\sim 1/3^{\text{th}}$ our diffraction limited beam at our target observing frequency, 557 GHz.

A Service Gondola suspended underneath the carrier balloon (see Figure 14) will carry and protect the command and control computer, the power system, and the balloon control and telecommunication systems, which are needed to support the LBR instrument and mission. The design is based on the heritage of several gondolas built and flown by CSBF as well as subsystems built and flown by APL. The gondola and all its subsystems will be designed built and tested at APL, with the exception of the balloon control and telecommunications package which is provided by CSBF. The service gondola can be divided in four main components: the structure, the power system, the command and data handling system, and the telecommunication system.

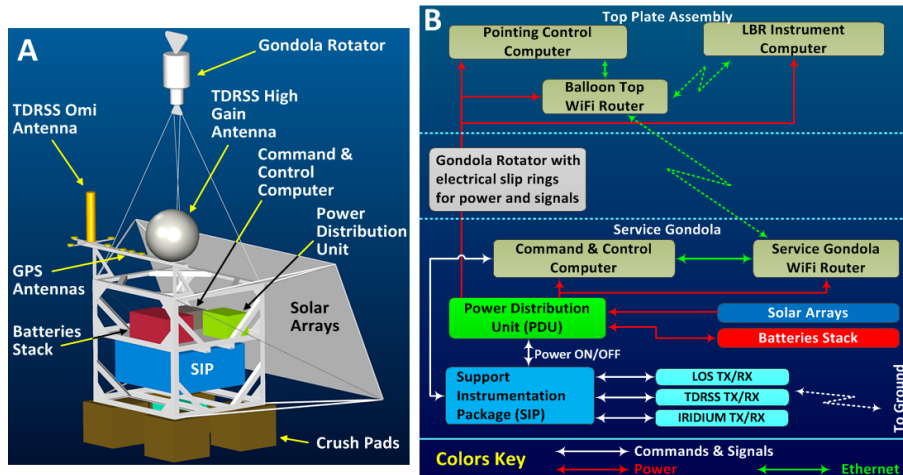


Figure 14. Conceptual design of the LBR Service Gondola (Applied Physics Laboratory design)

2 Prototypes: 3 and 5 meters

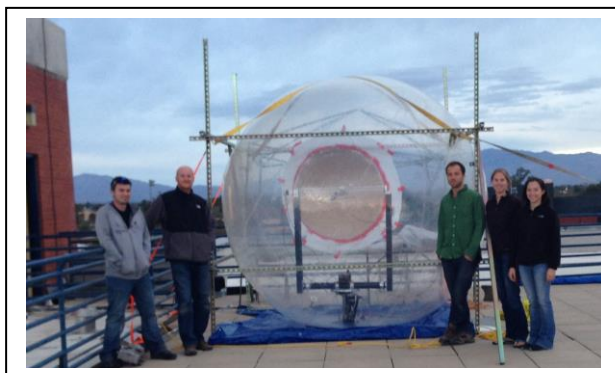


Figure 15: 3 meter LBR rooftop prototype. The rooftop prototype is a fully functional 1/6th scale model of the flight version of LBR designed to operate at 115 GHz.

Figure 15 is a photograph of the 3 meter diameter, rooftop LBR prototype developed in Phase I. The prototype was constructed to gain experience with the technological approaches needed to realize and operate a full 20 meter LBR. The prototype has all the key elements of the flight version. The sphere was purchased from a toy company and is formed from 0.8 mm thick, thermoplastic polyurethane (TPU) gores. The gores are thermally bonded together (as in the flight model) to create a spherical shape. The plastic sphere has a 1 meter long zipper through which hardware (and people!) enter and leave. As will be the case for the flight model, a blower is used to inflate the balloon with outside air. For the flight version the ‘outside’ air is the helium gas that fills the carrier balloon. A liquid water monometer is used to regulate the pressure in the balloon to just above ambient. A reflective surface was first created by spaying a 1 meter diameter section of the sphere with metallized spray paint. Later we found that aluminized Mylar sheets stretched over the outer surface can achieve the same high reflectivity. The optical performance of the rooftop LBR was characterized by performing a series of scans across the position of a test transmitter and the Sun, yielding diffraction limited performance. A number of valuable lessons were learned in the construction and operation of the LBR rooftop prototype.

We have incorporated these lessons into the proposed LBR design (see Phase I Study Report Sec. VII.A.2 for details).

In Phase II a 5 meter (1/4 scale) version of the LBR sphere was constructed in a high bay at SwRI (see Figure 16). The sphere included the dielectric support curtains described in Section 1.3 and was filled with a mixture of helium and nitrogen gas to achieve neutral buoyancy. The



Figure 16. Steerable 5 meter LBR prototype sphere. The sphere includes dielectric sheets to ensure a spherical shape and provide a stable mounting point for the instrument module.

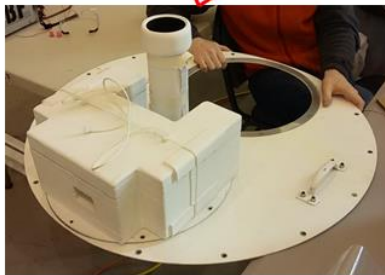
structure achieved a spherical shape to better than 1%. This result means the adaptive secondary need not be as flexible as originally thought. Indeed, instead of aluminum loaded latex, a thin flexible metal sheet (e.g. made from phosphor-bronze) can be employed.

3 LBR Sensor Package Stratospheric Flight

The Mid-Term Review for LBR Phase II was held in Washington, DC on April 27th, 2015. The consensus amongst reviewers was that, based on the work presented, LBR could indeed be built and flown as a stratospheric balloon payload. They concluded that what would ultimately limit the size of LBR is the ability to point it. Intuition suggests that, owing to a closer proximity to the center of mass and the dispersive effects of the balloon on wind gusts, having LBR suspended from the inside top-center of the balloon would be more stable than having it suspended from the gondola. However, this needed to be proven. The suggestion was made to fly an accelerometer/camera sensor package on the top of a balloon and on a gondola underneath to obtain the required empirical data. This idea was soon presented to NASA HQ and the Balloon Project Office. A “piggy-back” stratospheric flight was approved for summer 2015. The sensor packages for the flight were designed and built by our team and launched from Ft. Sumner, NM on Sept. 4th, 2015 (see Figure 17). The flight lasted for several hours during which time data was obtained from both sensor packages. A time lapse image of the Moon and sample accelerometer data taken during the flight are shown in Figure 18. A Fourier analysis of the data shows there are several oscillation modes on top of the balloon, but all with periods greater than 5 seconds. These can be readily dealt with by the LBR pointing system. However, observed oscillations on the gondola were more pronounced and had periods between 2 and 0.8 sec. The conclusion is, from a pointing control point of view, it is much better to have LBR suspended internally from the top-center of the balloon than suspended from a gondola.



Figure 17. LBR Sensor Package Launch from Ft. Sumner, NM.



LBR Sensor Package (SP) with camera and accelerometers. One SP was located on top of the balloon and another on the gondola.

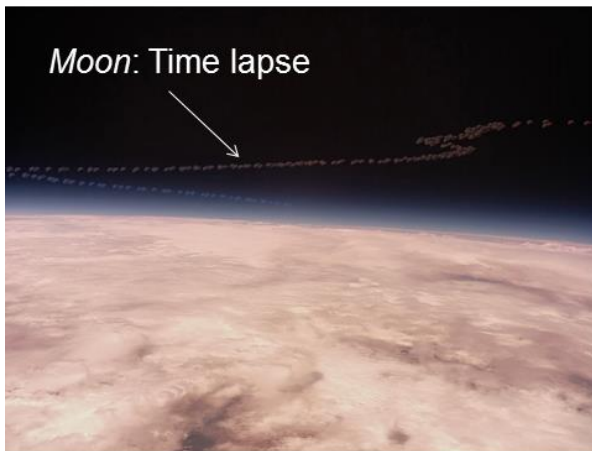
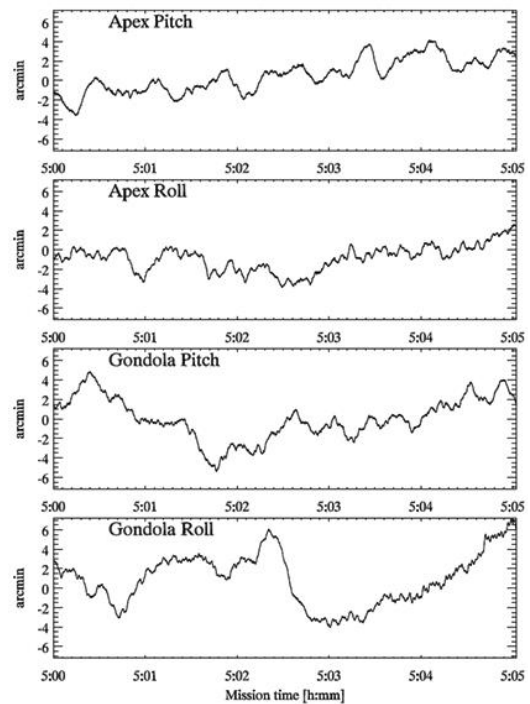


Figure 18. LBR test Data. Above: Time lapse image of the Moon. Left: Sample accelerometer data.



4. NASA Mission Concept

A 10 meter class telescope capable of performing observations in the far-infrared/THz free of atmospheric absorption has long been a goal of NASA and the astrophysics community. However, the costs of such a mission have been daunting. LBR can make this dream a reality for spectroscopic studies at THz frequencies for a fraction of the cost of other mission approaches. NASA's only two missions operating in this spectral regime are SOFIA and JWST (see Figure 17). SOFIA is an airborne observatory flying at ~45,000 ft that hosts a 2.5 meter, uncooled telescope in a modified Boeing 747SP. JWST is a 6.5 meter, radiatively cooled telescope that will perform observations from L2, ~ 1 million miles from Earth. The costs of both missions are staggering, over \$1B for SOFIA and over \$5B for JWST. Of the two missions, SOFIA is closest to LBR in capability and science goals. However, **LBR has 16x the collecting area and flies ~3x higher than SOFIA, making it a superior platform from which to conduct high spectral resolution THz observations, at a cost < 1% of what has been spent on SOFIA to date.** Table 1 is the projected cost breakdown for building and flying a 10 meter sub-orbital LBR. The program includes both a test flight from Ft. Sumner, NM and an Antarctic science flight. The estimates are based on ROMs from balloon manufacturers and the actual cost of similar hardware built for the PI's ongoing Stratospheric TeraHertz Observatory (STO) program.

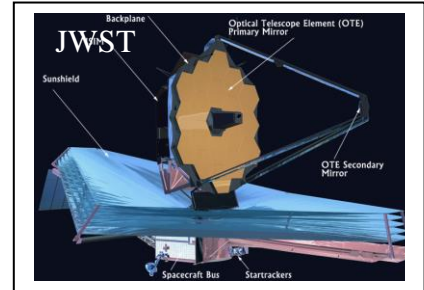


Figure 17: *Top:* JWST is the NASA flagship IR/FIR mission with a 6.5 m telescope for >\$5B. *Middle:* SOFIA is a 2.5 m airborne IR/FIR telescope for >\$1B. LBR is a 10 m FIR/THz sub-orbital telescope for <\$0.01B.

Table 1: LBR Mission Budget

Phase	Cost (\$M)	Duration
Test Flight	LBR Balloon	1.0
	Service Gondola	1.5
	Pointing System	1.0
	Instrument	1.5
Science Flight	LBR Balloon (+ spare)	1.5
	Service Gondola (refurb)	0.5
	Pointing System	0.5
	Instrument	1.5
Total	9.0	4 years

5. DISSEMINATION OF RESULTS

At the Phase II mid-term review in April 2015 we presented preliminary results and findings of this NIAC Phase II effort. We also gave a briefing at the NIAC Symposium in Seattle on October 27, 2015. In addition, LBR presentations have been given at the IEEE Aerospace Conference in 2014 and the IRMMW-THz conferences in 2014 and 2015. In each instance the

NASA NIAC program was acknowledged. We have also had discussions with organizations and companies about potential DoD and intelligence applications of LBR related technology. We have submitted a proposal under the NASA TPCOR program, “**TeraHertz Space Telescope (TST): A Far-Infrared Probe Class Concept**”, to help realize a 20 meter, space-based version of LBR.

6. FUTURE PLANS

Our team plans on submitting additional proposals to NASA, DoD, and intelligence communities to further advance LBR related technology. In particular, we plan to propose to NASA for a stratospheric LBR engineering flight in 2017. A stratospheric LBR flight would yield exciting science results and serve as a stepping stone to the 20 meter, TeraHertz Space Telescope. The Flight Profile for the envisioned stratospheric mission is shown in FO2. The proposed flight would pave the way to a new era of scientific ballooning.

7. ACKNOWLEDGEMENTS

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