Optical Design for the Large Balloon Reflector

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ABSTRACT

We present the details of the optical design, corrector system, mechanical layout, tolerances, pointing requirements, and overall performance of the sub-millimeter wavelength Large Balloon Reflector telescope (LBR).

Keywords: Sub-mm, Stratospheric Balloon Telescope, THz Optical Design

1. INTRODUCTION

Balloon-borne telescopes have enabled terahertz observations of astrophysical objects which would otherwise be blocked or severely attenuated by the Earth's atmosphere. At balloon altitudes, a large portion of the submillimeter spectrum becomes accessible. Spectral lines that can be observed from airplane (12–14 km) altitudes with difficulty, and for which certain velocities are completely "blocked" by atmospheric absorption, become readily observable with nearly perfect transmission from balloon (37–40 km) altitude. One important example is the 63 μm fine structure transition of neutral oxygen ([OI]). This line is an important coolant of the relatively hot layers of molecular clouds close to young, massive stars—in Photon Dominated Regions (PDRs). In addition to its biological importance, water is a key molecule for astronomy, in that it is a major coolant of dense, gravitationally bound condensations, allowing them to contract and form new stars, starting from modest temperatures of 50–100 K. Water has been found in a wide variety of objects including such cloud cores, protostellar disks in which planetary systems are forming, as well as primitive objects in our solar system such as comets. Systematic observations of all of these will be necessary to trace the "water trail" connecting water in interstellar clouds to the Earth's water. However, objects in our solar system and most of the Milky Way cannot be observed in water lines even from the SOFIA airborne observatory because the atmosphere is completely opaque. From a balloon, however, almost the entire galaxy can be observed in a wide range of water lines, which together can yield critical information about the molecule's excitation, and thus on its abundance and cooling. For the solar system, observations of the most common isotopologue, H_2^{16}O , are challenging due to the small Doppler shifts, but taking advantage of the Earth's motion, many objects will be observable at the right time of the year. The rare variants, H_2^{18}O and HDO are of particular interest for cometary studies as they may well be able to answer whether cometary impacts early in the history of the solar system were the origin of the Earth's water. The 557 GHz ground state transition of ortho- H_2O is a key objective for LBR. The unequaled angular resolution and sensitivity at the frequency of this important astronomical tracer will certainly yield spectacular new results for a wide range of objects of great astronomical interest.

Balloon borne missions such as STO (Stratospheric THz Observatory),¹ BLAST (Balloon-borne Large Aperture Sub-millimeter Telescope),^{2,3} and BLAST-Pol^{4,5} have proven that hanging a telescope from a balloon is a very economical approach for terahertz astronomy compared to the cost of flying space-borne instruments. Nevertheless, one of the drawbacks is the ultimate pointing accuracy of the hanging telescope, which restricts the use of large apertures at very high frequencies.

Figure 1. *Left*: Large Balloon Reflector Sub-mm wave telescope concept mounted inside a large stratospheric balloon. *Right*: Spherical cap of a 5 m diameter LBR balloon telescope (all dimensions in mm).

A new concept, the Large Balloon Reflector (LBR) has been proposed and funded through the NASA Innovative Advanced Concepts (NIAC) program. In this approach the main reflector of the telescope is a metallized hemisphere of a smaller spherical balloon, 5 to 20 m in diameter, inflated inside the much larger (100 m) carrier stratospheric balloon. Light from space first passes through the $\sim 50 \mu\text{m}$ thick polyethylene skin of the carrier balloon and then through the $\sim 25 \mu\text{m}$ thick Mylar side of the inner balloon. Together these layers have $< 8\%$ 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 spherical corrector optics and terahertz receiver sit in the interior of the sphere (See Fig. 1-*Left*). This location effectively shields the spherical telescope from external atmospheric effects that normally would influence the instrument hanging from a gondola about 30 m under the main balloon.

We present here the details of the optical design, corrector system, mechanical layout, tolerances, pointing requirements, and overall expected performance of a 5 m prototype LBR.

2. LARGE BALLOON REFLECTOR OPTICS

2.1 Spherical Corrector for a 5m Sub-mm Spherical Telescope

Since LBR's main reflector (M1) is a spherical surface an spherical corrector system is needed to compensate. The corrector system is based on a scaled version of the 300 m Arecibo radio telescope Gregorian system.⁶ The corrector system is an off-set double Gregorian reflector that refocuses the incoming field at the foci of the optics eliminating the spherical aberration. Fig. 1-*(Right)* shows the dimensions of a 5 m diameter LBR telescope concept with spherical corrector in place. The spherical cap is part of a spherical sector with a vertex angle of 70° . This vertex angle yields an aperture of 2868 mm in diameter for a 5 m spheric reflector. This is larger than the actual effective aperture of the corrector optics in order to control spillover. The Gregorian corrector system sits at a distance of half radius from the center of the sphere. The spherical corrector system for LBR telescope consist of two highly shaped surfaces, M2 and M3, needed to correct the incoming spherical wavefront aberration as evidenced by the caustic lines in the ray tracing shown in Fig. 2-*(Left)*. The secondary reflector (M2) is 130 mm in height, by 178 mm $\times$ 218 mm wide. The tertiary reflector (M3) is smaller: 29 mm in height by 72 mm $\times$ 65 mm wide. Fig. 2-*(Right)* shows an oblique view of the Gregorian corrector system showing the larger wide dimensions of M2 and M3 reflectors. The incoming wavefront forms a half full angle of 60° at the foci of the telescope optics.

2.2 Performance at 557 GHz

Fig. 3-*(Left)* shows the aperture field power distribution of the 5m LBR telescope with the dual Gregorian reflector corrector system at a frequency of 557 GHz. The illumination in the aperture is nearly uniform and elliptical

Figure 2. *Left*: Side view of the spherical corrector system consisting of two surfaces M2 and M3. *Right*: Oblique view of the corrector system. The dimensions correspond to a 5m diameter LBR balloon telescope.

in shape with major and minor diameter dimensions of 2263 mm $\times$ 1980 mm respectively. The figure shows the blockage produced by the corrector structure at the center. Fig. 3-(*Right*) shows the corresponding aperture phase distribution of the LBR telescope with corrected optics at 557 GHz indicating a residual phase error rms of $1.2 \times 10^{-4} \lambda$ across the aperture, equivalent to a Strehl ratio of $\sim 100\%$.

Figure 3. *Left*: Aperture field power distribution of the LBR telescope with the spherical corrector system at 557 GHz. The aperture is elliptical in shape with major and minor diameter dimensions of 2263 mm and 1980 mm respectively. *Right*: Corresponding aperture phase distribution at a frequency of 557 GHz. The residual phase errors of the corrected optics are less than $1.2 \times 10^{-4} \lambda$.

Fig. 4-(*Left*) shows the corresponding (linear polarization) co-polar far field radiation pattern of the 5m LBR telescope with corrected optics at a frequency of 557 GHz. The panels depict a Field of View area in the sky of 13.35 arcmin^2 . The main beam is elliptical in shape with a FWHM of $59.5 \text{ arcsec} \times 52.4 \text{ arcsec}$. The nearly uniform aperture power distribution produces a sidelobe level of -16.2 dB. Fig. 4-(*Right*) shows the far field cross-

Figure 4. *Left*: Far field Co-polar antenna pattern of the 5 m LBR telescope with the spherical corrector system at 557 GHz. The main beam HPBW is elliptical in shape with a size of 59.5 arcsec $\times$ 52.4 arcsec. *Right*: Corresponding cross-polar far field antenna pattern of the 5 m at 557 GHz, with peak cross-pol level of -39 dB.

polar radiation pattern at 557 GHz, indicating excellent cross-polarization performance, with a peak cross-pol value of -39 dB across the field.

In Fig. 5 we show a series of ϕ -cuts near the main beam of the far field radiation pattern at $\phi = 0^\circ$, 45° and 90° respectively. As it is evident from the cuts, the first sidelobe level presents some azimuthal variation, between -16 dB to -18 dB. The cross-polarization performance determined by the 45° diagonal pattern cut indicate a peak value of cross-polarization of -39 dB.

Table 1 summarizes the LBR telescope performance at 557 GHz, with a gain of 81.5 dB, beam efficiency of 99.9 %, and an overall aperture efficiency of 92.4 %.

Table 1. Overall Telescope Performance for a 5 m LBR

Parameter	Value	Units
Wavelength	538	μm
Frequency	557	GHz
Gain	81.5	dB
Cross-Pol	-39.1	dB
FWHM	59.2×52.4	arcsec
Image Plate Scale x-axis	3.6	arcmin/mm
Image Plate Scale y-axis	2.8	arcmin/mm
Effective Aperture	3.23	m^2
Aper. Phase rms	1.2×10^{-4}	λ
Aper Illum. Efficiency	96.9	%
Aper Phase Efficiency	99.9	%
Spillover and Blocking Efficiency	99.9	%
Beam Efficiency	99.9	%
Total Antenna Efficiency	91.8	%

Figure 5. Cuts in the principal planes of the calculated far field radiation pattern, near the main beam, at 557 GHz of the 5-m diameter LBR's. The cuts are at $\phi = 0^\circ$, 45° and 90° respectively. The figure indicates a cross-polar peak value of -39 dB.

2.3 Field of View

Fig. 6 shows the calculated characteristics of the field of view (FoV) of the 5m LBR telescope with spherical correction optics. The correction optics is off-set, therefore there is a small asymmetry between the x-axis and y-axis. (See Fig. 1-Right and Fig. 2). Assuming a typical value of tolerable optical performance degradation of -1.0 dB (or approximately 80% efficiency), the FoV can accommodate up to 6x6 beams, separated by one FWHM, (i.e., 59 arcsec at 557 GHz) with a power scan loss better than -1dB. The image plate scale is:

$$\begin{aligned} \text{IMS}_X &= 3.6 \text{ arcmin/mm} \\ \text{IMS}_Y &= 2.8 \text{ arcmin/mm.} \end{aligned} \quad (1)$$

This indicates relatively small field distortion: i.e., compression along the y-axis and stretching along the x-axis

3. CORRECTOR SYSTEM POSITION SENSITIVITIES

One of the more challenging aspects of balloon born telescopes is the pointing, and the problem aggravates with aperture size in terms of wavelength.

3.1 Feed Positioning Sensitivities

Fig. 7 shows the calculated scanning loss with respect to feed position in the focal plane, i.e., lateral displacements, along the x-axis and y-axis, as well as defocusing in a direction perpendicular to the focal plane (along the local z-axis) for a 5 m class LBR telescope at frequency of 557 GHz. Lateral feed displacements along the y-axis in the focal plane up to ± 1 mm produce scanning losses of -0.8 dB. Along the x-axis, lateral feed displacements are somewhat more restrictive, as scanning losses of -1.0 dB are produced by lateral errors of -0.8 mm to +1 mm along the x-axis. Nevertheless, focusing errors, along the focal plane normal (z-axis), is what dominate the sensitivity error budget, i.e., in order to maintain gain variations smaller than 10%, the focusing error should be less than ± 0.3 mm. This implies that the feed position should be maintained within $\pm 300 \mu\text{m}$, while scanning the focal plane.

Based on the optical design a point cloud data set was generated for M2 and M3 to create a solid model shown in Fig. 8 in solid Autodesk Inventor for high precision machining. The surface precision requirements

Figure 6. Field of View and plate-scale at the focus of the spherical corrector optics..

Figure 7. Calculated scanning loss as a function of Feed position in the focal plane of 5 m class LBR telescope with spherical corrector system at 557 GHz.

are of the order of $\pm 30 \mu\text{m}$ for the overall surface rms, for good optical performance, but what dominates is the pointing requirement of $1/10^{th}$ of the beam, which at 557 GHz is 6 arc sec.

3.2 Corrector Assembly Sensitivities

In the previous section we answered the question of how precisely we have to position the feed at the foci of the optics in order to maintain good optical performance. In this section we answer the question of how precisely we have to position the whole corrector assembly (corrector reflector optics and feed) in order to maintain good optical performance. Fig. 9 shows the calculated gain losses as a function of positioning errors of the whole corrector assembly: lateral along the x-axis and y-axis, and along the z-axis. We see that the optics is very

Figure 8. Details of the corrector assembly solid model (Arizona State University).

Figure 9. Calculated scanning loss as a function of corrector assembly positioning at 557 GHz.

insensitive to lateral displacements of the corrector assembly as a whole beyond ± 1 mm. Nevertheless, in order to ensure good optical performance (i.e., scanning loss better than -1.0 dB within the FoV) z-axis positioning errors should be kept within $\pm 400 \mu\text{m}$.

3.3 Corrector Assembly Sensitivities and Pointing

Pointing requirements are normally $1/10^{\text{th}}$ of the beam or 6 arcsec. The image plate scale presented in Equation 1 refers to the feed at the focal plane. For the whole corrector assembly the Beam Deviation Factors (BDF) are smaller:

$$\begin{aligned} \text{Assembly BDF}_X &= 2.4 \text{ arcmin/mm} \\ \text{Assembly BDF}_Y &= 2.3 \text{ arcmin/mm.} \end{aligned} \quad (2)$$

Positioning errors have the largest impact on pointing rather than on optical performance: i.e., in order to maintain pointing within $1/10^{th}$ of the beam, we have to maintain the lateral positioning of the corrector assembly within $\pm 41 \mu\text{m}$. Since this is 10 times more stringent than the positioning requirement for good optical performance, therefore, if we maintain the corrector assembly within the *pointing positioning requirements*, it will also result in very good optical performance. The pointing of the telescope will be implemented in several stages: the first stage will be at the elevation/azimuth control of the spherical balloon attached to the apex platform of the carrier balloon, a second stage will be at an active fine positioning control of the corrector assembly, and finally by using an active secondary reflector (M_2) that will make corrections to the aperture phase distribution, including the "saddle" gravitational effect.

4. BALLOON DEFORMATION UNDER GRAVITY

Figure 10. *Left*: Balloon deformation under gravity changes in first order the eccentricity. *Right*: Foci separation f_e as a function of eccentricity.

We also assessed the impact in the optics of balloon deformation under gravity. We expect that the balloon will deform axially along the gravity vector into an ellipsoid (See Fig. 10-*Left*). At first order, gravity will increase the eccentricity of the main reflector, this will produce the separation between foci a distance f_e , i.e.,

$$e^2 = 1 - \left(\frac{a}{b}\right)^2 \quad (3)$$

$$f_e = \frac{2e\mathcal{R}_{c_e}}{[1 - e^2]}, \quad (4)$$

where a and b are the major and minor semi-axis, $\mathcal{R}_{c_e}$ is the radius of curvature at the vertex of the deformed balloon. We assumed that the vertex radius of curvature remains constant under this type of deformation and characterized the phase error in the aperture for different values of eccentricity. Fig. 10-*(Right)* shows the distance between the ellipsoid foci as a function of eccentricity.

Using a fixed value of radius of curvature of the balloon vertex $\mathcal{R}_{c_e} = 2500 \text{ mm}$, we varied the eccentricity of the main reflector from 0.01 to 0.2, and evaluated the optical performance paying special attention to the aperture phase distribution. Fig. 11-*(Left)* shows the aperture phase distribution for an eccentricity value of $e = 0.03$, which is equivalent to a foci separation of 0.15 m, and at a wavelength of $540 \mu\text{m}$ produces a Strehl ratio value of 99.1%. Fig. 11-*(Right)* shows the aperture phase distribution for a value of eccentricity $e = 0.2$, or a foci separation of 1.05 m. (at $\lambda = 50 \text{ mm}$). We found that the shape of the aperture phase distribution remains invariant (saddle) for all the values of eccentricity (independent of the wavelength used to assess it). This means that it could be easily corrected by calibration.

Figure 11. Aperture phase error distribution in wavelengths for different values of eccentricity for a 5 m balloon. *Left*: for an eccentricity $e = 0.03$ and Strehl ratio of 99.1% at $540 \mu\text{m}$, which corresponds to a foci separation of 0.15 m. *Right*: eccentricity $e = 0.2$, which corresponds to a foci separation of 1.05 m.

5. CONCLUSIONS

LBR is a game-changing approach to realizing large aperture telescopes at THz frequencies (aka "the far-infrared"). In this paper we provide an optical prescription for LBR and examine its performance and tolerancing. We find that the design is capable of providing diffraction limited operation throughout the THz regime.

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