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Optical design concept of the CMB-S4 large-aperture telescopes and cameras

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ABSTRACT

CMB-S4 – the next-generation ground-based cosmic microwave background (CMB) experiment - will significantly advance the sensitivity of CMB measurements and improve our understanding of the origin and evolution of the universe. CMB-S4 will deploy large-aperture telescopes fielding hundreds of thousands of detectors at millimeter wavelengths. We present the baseline optical design concept of the large-aperture CMB-S4 telescopes, which consists of two optical configurations: (i) a new off-axis, three-mirror, free-form anastigmatic design and (ii) the existing coma-corrected crossed-Dragone design. We also present an overview of the optical configuration of the array of silicon optics cameras that will populate the focal plane with 85 diffraction-limited optics tubes covering up to 9 degrees of field of view, up to 1.1 mm in wavelength. We describe the computational optimization methods that were put in place to implement the families of designs described here and give a brief update on the current status of the design effort.

Keywords: CMB Telescopes, CMB Instrumentation, CMB Camera Optics, Millimeter-wave telescopes.

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1. INTRODUCTION

CMB-S4, the next-generation cosmic microwave background (CMB) experiment, will deliver detailed maps of the microwave sky to advance our understanding of the history of our universe from the high energies at the dawn of time to the growth of structure we observe today. The science case of CMB-S4 is broad and it includes:^{1,2} the search for gravitational waves predicted from inflation, constraints on dark energy, determining the role of light relic particles in the structure and evolution of the universe, tests of gravity at very large scales, measuring the emergence of clusters of galaxies, new observations of transients at millimeter-wavelengths and the exploration of the outer Solar System. To achieve its ambitious scientific goals, CMB-S4 will require a great increase in sensitivity from current generation experiments.³ This drastic increase in sensitivity and mapping speed will be achieved by increasing the number of high-sensitivity detectors on the sky and the number of telescopes that observe at the same time. CMB-S4 will make use of two of the best equipped sites in the world for millimeter-wave observations of the CMB: the high Atacama Plateau of Chile and the Geographical South Pole. The CMB-S4 concept will exploit features of the two sites, using the stable atmosphere of the South Pole to map a deep patch of sky and using the ability to observe up to 80% of the sky from the dry Atacama site.⁴

In the last decade, large-aperture (six-meter class) CMB telescopes have deployed an increasing number of background limited detectors in order to provide faster mapping speeds at arcminute resolutions.^{8,9} This sustained increase in detector count has occurred concurrently with advances in superconducting detector technologies and cold multiplexing. Optical designs of large-aperture telescopes (LATs) have also evolved to accommodate an increasing number of detectors. Currently observing telescopes, which make use of Gregorian designs, can accommodate thousands of transition edge detectors.^{10,11} Planned and under-construction CMB observatories, like the Simons Observatory and CCAT-prime, have proposed larger throughput LAT designs, using the crossed-Dragone (CD) optical configuration.⁷ These observatories are planned to accommodate tens of thousands of detectors. Next-generation telescopes will accommodate hundreds of thousands of high sensitivity detectors to provide a unique view into the early universe.¹²

The science goals of CMB-S4 will be met with two surveys: 1) One ultra-deep survey covering 3% of the sky, observed from the South Pole. This survey will make use of small-aperture telescopes (not discussed in this document). These small-aperture telescopes will be complemented with one five-meter diameter three-mirror anastimatic telescope (TMA). Maps made with observations of the TMA will be used to remove contamination of the degree-scale B-modes caused by gravitational lensing, in a process called delensing. 2) A deep-wide survey covering approximately 60% of the sky using two six-meter crossed-Dragone LATs located in Chile. The deep-wide survey requires modestly higher angular resolution and its optical design was selected based on the CCAT-prime and Simons Observatory optical designs that are now undergoing construction. The smaller patch observed by the ultra-deep survey requires a uniform distribution of bands across the field of view, so the survey deepth is sufficiently uniform. The ultra-deep survey does not require as high angular resolution as the deep-wide survey, and the delensing required to achieve the inflation science goal motivates the pursuit of additional features like the higher and more uniform Strehl ratios provided by the introduction of a third optical surface, the mitigation of systematics provided by gap-less mirrors and boresight rotation.

In this work we present an overview of the baseline optical design concept of the large-aperture telescopes of CMB-S4 and their arrays of 85 imaging cameras. The baseline optical design presented here combines the tested technologies of heritage CMB experiments that are under fabrication with an innovative concept that will deliver higher fields of view and mapping speeds at high frequencies (up to 286 GHz, or 1.1 mm). We describe the optical concept and the methods used to find optical solutions. The methods presented here are capable of generating the specific lens prescriptions for a given set of mechanical constraints. The detailed design prescriptions will be presented in a future publication as the opto-mechanical design and the optical design converge. Throughout this document the term diffraction-limited performance is used to refer to Strehl ratios better than 0.8 at a specified wavelength.¹³

2. DESIGN CONCEPT

The baseline design concept of the large-aperture telescopes for CMB-S4 consists of two types of telescopes: the Chilean Large Aperture Telescope (CHLAT) and the South Pole Large Aperture Telescope (SPLAT). The



Figure 1: Top: Rendering of the baseline design concept of CMB-S4. Telescopes are not to scale. Top Left: The South Pole LAT, a five-meter three-mirror anastigmatic telescope. Top Right: The Chilean LAT concept, which is composed of the six-meter paneled crossed-Dragone design.⁵ Bottom: Optical layout of the two telescope concepts. Bottom Left: Three Mirror Anastigmat optical layout to be used in the SPLAT; this design is an optimized version of the concept presented in Padin 2018.⁶ Bottom Right: coma-corrected crossed-Dragone optical layout to be used in the CHLAT. This design is identical to the Simons Observatory LAT and the CCAT-prime Fred Young Submillimeter Telescope.⁷



Figure 2: Strehl ratio in angular coordinates at 2 mm (top) and 1 mm (bottom) wavelengths for the SPLAT TMA (left) and CHLAT CD (right) optical designs. Note that because of the different dynamic ranges in Strehl ratios among the TMA and the CD designs (left vs right), the ranges in the color bars are different (left panel covers 0.5 - 1.0, while right panel covers 0.0 - 1.0). The angular extent of the field is wider in the left panels (± 6 degrees vs ± 5 degrees) due to the larger field of view provided by the TMA.



Figure 3: Camera band distribution for the SPLAT (left) and CHLAT (right). Cameras operating in four dichroic bands are shown. HF: 286, 227 GHz (1.1, 1.3 mm, purple), MF: 149, 92 GHz (2.0, 3.3 mm, green), LF: 39, 26 GHz (7.7, 11.5 mm, orange) and ULF: 20 GHz (15.0 mm, red).

Chilean site will use a six-meter crossed-Dragone optical design, a two-mirror system that allows a field of view of 6.4 degrees in diameter at 150 GHz (2 mm in wavelength).^{7*} The SPLAT optical design is a five-meter aperture three-mirror telescope, an innovative optical concept that cancels out astigmatism, and therefore offers a wide field of view of 9 degrees in diameter at 286 GHz (1.1 mm in wavelength), at the expense of increased complexity.^{6,14} Figure 2 shows a comparison of the Strehl ratios across the field of view for these two designs. The reflectors in this three-mirror telescope are gap-less, thus providing low sidelobes when compared to the paneled six-meter crossed-Dragone configuration.⁵ Figure 1 (top) shows renderings of these two concepts, while Figure 1 (bottom) shows their optical layout.

2.1 CHLAT: crossed-Dragone Design

The telescopes to be deployed in Chile are arranged in a coma-corrected crossed-Dragone optical configuration. A first physical demonstration of such system is currently under construction for the Simons Observatory and CCAT-prime.⁷ This optical design is a f/2.6 system, which illuminates a focal plane of 2 meters in diameter, a field of view of 7.8 degrees and can accommodate $\sim 100,000$ detectors with diffraction-limited performance at 3 mm wavelength.⁷ The telescope mirrors are made out of rectangular panels, which are machined to shape and are individually adjusted to achieve phase wavefront coherence. A detailed description of this design concept development and implementation can be found in the literature.^{15–18}

The CD can be used at very high frequencies with a limited the field of view, as will be demonstrated by CCAT-prime. This optical design is optimal for minimal cross polarization. The gaps between the panels that form the six-meter reflectors produce sidelobes at about 60 dB below the main beam at degree angular scales.⁵ The diffraction-limited field of view of the crossed-Dragone design (at 1 mm and 2 mm in wavelength) is limited by astigmatism, which appears at the highest frequencies in fields far from the boresight. This optical feature

^{*}The crossed-Dragone is capable of 1 mm (300 GHz), or even shorter wavelength, observations albeit with a reduced field of view due to astigmatism on the outer fields.⁷

can be corrected in the camera system by the inclusion of one biconic lens, as will be discussed later in this document.

2.2 SPLAT: Three Mirror Telescope

Three-mirror anastigmatic telescope designs are appealing for millimeter-wave large-aperture systems because they can deliver a wide field of view that is free of astigmatism down to 1 mm in wavelength. This lack of astigmatism is the result of the additional degree of freedom given by the three surfaces. These three surfaces are able to cancel all three first-order optical aberrations, as opposed to the only two aberrations that can be cancelled using two reflecting surfaces like in a crossed-Dragone or a Gregorian telescope. An extensive discussion on three-mirror telescope configurations was presented by Korsch (1991).¹⁹

The first proposed three-mirror anastigmat for large-aperture millimeter-wave observations of the CMB was presented in Padin 2018.⁶ This optical design was adapted for CMB-S4 by reducing the f-number to make it similar to the crossed-Dragone's f/2.6.¹⁴ This allows the TMA to have more throughput and share the camera concept with the crossed-Dragone, which has benefits from the opto-mechanical perspective. This redesign also improved image quality at 1 mm to excellent values across the whole focal plane. The TMA design consists of a five-meter aperture primary, with a tertiary of a similar size. A detailed description of the TMA for CMB-S4 will be presented in a separate publication (Gallardo et al, in prep¹⁴).

The five-meter TMA can be manufactured with gap-less mirrors. These mirrors can be machined in halves and bolted together to form reflectors which present a continuous and smooth surface to incoming light. This smooth surface avoids diffraction sidelobes that originate from the gaps in the paneled surface, which has been historically used in the manufacture of large-aperture telescopes for CMB studies (and are present in the CHLAT design). The telescope structure is being designed to meet the stability requirements determined from optical tolerancing analysis, as well as from the expected environmental and operational loads. Optomechanical performance will be discussed in a future publication.

3. CAMERA ARRAYS

The concept for the CMB-S4 array of cameras consists of 85 cameras arranged in a hexagonal pattern covering different bands. Each camera is composed of a tube that holds silicon lenses ("optics tubes" for short), and filters. These optics tubes are housed in a single cryostat that cools the system. The optical prescription for these optics tubes can be different among cameras, depending on the optical properties of the LAT. Because the LATs were



Figure 4: Camera optical layout for the TMA LAT showing: the three silicon lenses, the Lyot stop and the alumina prism. From left to right: Focal plane, L3, Lyot stop, L2, L1, Alumina wedge and filter stack. Rays are traced in the time reverse sense, ie: from left to right. Colors indicate different detector positions in the detector focal plane. The focal plane has 130 mm in diameter, L1 measures 200 mm, while L2 and L3 measure 170 mm in diameter. The crossed-Dragone camera results in a very similar layout.

Algorithm 1 Merit function pseudo-code to be used in the optimization of the TMA and CD camera designs. Steps in this list are performed sequentially and updated in each evaluation during the optimization. Each line represents one term in the sum shown in Equation 3. Each term is composed of multiple ray evaluations in Zemax. In practice, the merit function to be optimized is composed of hundreds of terms.

- 1. Illuminate Lyot stop evenly
- 2. Limits on lens thickness and camera total length
 - 3. Constrain wedge slope sign
 - 4. Constrain ellipticity on a screen past L3
 - 5. All rays within L1
 - 6. All rays within L2
 - 7. All rays within L3
 - 8. f/# constraint
 - 9. f/# ellipticity constraint
 - 10. Chief ray focal plane angle constraint
 - 11. Prism wedge tilt and clocking
 - 12. Minimize RMS spot size

$\operatorname{component}$	$R^{-1} [\mathrm{mm}^{-1}]$	c	$t_{j,j+1} [\mathrm{mm}]$
L1	-9.68×10^{-4}	-1	271
L2	$1.99 imes 10^{-3}$	-1	78.5
stop	—	_	152
L3	-2.29×10^{-3}	-1	120

Table 1: Initial values to be used with the merit function described by Algorithm 1 to optimize for a suitable optical solution for the camera lenses. Rows indicate an optical component, R is the radius of curvature, k is the conic constant and $t_{j,j+1}$ is the physical distance that separates the current surface from the next. The coordinate system is defined in the time reverse sense as shown in Figure 4, such that the radii of curvature for L1 and L3 are negative, while L2 curves in the opposite direction. In the TMA system, a camera solution is defined by 10 variables, while in the biconic CD camera, the optimization solves for 16 variables. The wedge tilt and clocking angle are also left as variables but they are optimized again after the lens solution has been reached with a more detailed merit function.

designed to have a similar f-number and focal plane size, the footprint of the camera array is arranged to be identical in both telescope concepts (SPLAT and CHLAT); therefore they can use the same camera to camera separation and diameter. This simplifies the design greatly and it enables shared features among mechanical designs. Figure 3 shows the distribution of cameras and bands in this hexagonal pattern. Figure 4 shows the layout of one camera system and Figure 5 (top) shows the 85 camera system layout as intended to work with the LAT optics.

Each camera is composed of three plano-convex lenses. These lenses are labeled L1, L2 and L3 in the direction of propagation of light. The TMA has minimal astigmatism, which allows the three lenses to be radially symmetric and their curved surface is described by

$$z(r) = \frac{(r/R)^2}{1 + \sqrt{1 - (1+k)(r/R)^2}},$$
(1)

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Figure 5: Top: Ray trace for the two telescope concepts with their arrays of cameras. Upper Left: TMA with 85 cameras using only two types of lens prescriptions. Upper Right: crossed-Dragone design with 85 cameras optimized (biconic L2) individually. Bottom: Diffraction-limited (Strehl ratio > 0.8) focal plane fraction (percent units) for all 85 cameras. The footprint of this hexagonal array covers the same area in both telescopes. Bottom Left: Strehl ratio coverage for the TMA array of 85 cameras using two groups of optical prescriptions and individual alumina wedges. Plot shows diffraction-limited performance (Strehl ratio > 0.8) at 1 mm in 81 of the 85 cameras. Diffraction-limited performance for all cameras is achieved at 2 mm of wavelength. Bottom Right: Image quality coverage for the crossed-Dragone optical design with individual lens prescriptions for the 85 cameras. Map shows the existence of solutions at 2 mm with diffraction-limited performance using a biconic lens L2 to correct astigmatism. This solution set is being evaluated in order to select a minimal set of groups that show acceptable image quality while minimizing fabrication complexity.

where R is the radius of curvature, k is the conic constant (k < -1 for hyperbolas, k = 0 for parabolas, 0 < k < -1 for ellipses, k = 0 for spheres and k > 0 for oblate ellipsoids) and r is the radial distance from the axis of symmetry of the lens. Astigmatism in the crossed-Dragone telescope can be corrected with the use of one biconic surface in the lens that is closest to the Lyot stop (L2). A biconic lens has two radii of curvature in two orthogonal directions and has a shape given by

$$z(x,y) = \frac{(x/R_x)^2 + (y/R_y)^2}{1 + \sqrt{1 - (1 + k_x)(x/R_x)^2 - (1 + k_y)(y/R_y)^2}},$$
(2)

where x and y are two coordinates perpendicular to the axis of the lens, the sub-index denotes parameters in the x or y direction. The three lenses in the camera are made of silicon (n = 3.38), and before L1 there is a alumina (n = 3.14) wedge that corrects for the curvature of the telescope focal surface. The tilt in the surface of this prism and the clocking angle are optimized jointly while finding the shapes of the lenses.

The design of the three-lens camera system is best performed in the time-reverse sense (focal plane \rightarrow L3 \rightarrow Lyot \rightarrow L2 \rightarrow L1 \rightarrow Telescope), as it is numerically easier to set the pupil-defining aperture close to the start of the ray trace than at the end. This time-reverse design requires time-reversing the large-aperture telescope.¹³ We start the optimization with lens parameter values that roughly focus light into a 6 inch focal plane (see Table 1 for initial values), while re-imaging the primary in an intermediate surface (Lyot stop) between L2 and L3.

We define a merit function as the weighted quadratic sum of the differences between the current design and target values given by

$$MF = \frac{\sum W_j (V_j - T_j)^2}{\sum W_j},\tag{3}$$

where W_j are weights that are used to set the importance of each term, V_j are the values obtained by evaluating the current design and T_j a target value. The list of values that are evaluated sequentially is shown schematically as pseudo-code in Algorithm 1 (the actual merit function has hundreds of terms). The optimization consists of minimizing the quantity MF using numerical techniques to obtain the best lens shapes and distances considering these constraints. As shown in Algorithm 1, we use numerical constraints to keep all rays within the limits of their apertures (diameters of 200 mm for L1 and 170 mm for L2 and L3); we also use constraints that limit the telecentricity (angle between the normal and the chief ray) at the focal plane to be lower than 2.5 deg, and a constraint for the maximum f-number asymmetry of 12% evaluated in an imaginary screen beyond L3. Finally we use the R.M.S. spot size (see Zemax manual¹³) to optimize for optical quality. The optimization was performed in Zemax Optics Studio using the damped least squares method, which is accessed via the Python API. We optimized sequentially all 85 cameras to demonstrate that suitable solutions exist for each camera. After we found suitable solutions for all the cameras, we used these individual solutions to evaluate the system with identical lens prescriptions. We make exhaustive evaluations of camera performance using these 85 solutions copied to all cameras to assess how many cameras can have the same optical prescription.

Using the methods described in this section we found that a satisfactory solution (which gives diffractionlimited performance in all but four cameras at 1 mm) can be found for the TMA if we define two groups of cameras (details of this solution will be presented in Gallardo 2022 in prep.¹⁴). For the crossed-Dragone design, we have shown that astigmatism can be cancelled out at 2 mm by the use of a biconic lens L2 optimizing all cameras individually, which demonstrates the existence of solutions. We are currently searching for grouped solutions for this design. Figure 5 (bottom) shows the fraction of the focal plane covered with diffraction-limited performance (Strehl > 0.8) for the TMA (two groups of optical prescriptions) and CD (individual camera prescriptions) design at 1 mm and 2 mm in wavelength, respectively. The iterative process of replicating camera prescriptions and finding suitable groups is being carried out for the crossed-Dragone telescope design cameras to find a grouped solution that minimizes fabrication complexity with a biconic prescription. Opto-mechanical checks are being carried out to define manufacturability constraints that will inform the optical prescription as the design converges. Table 2 shows a summary of the current status of the optical design.

4. CONCLUSION

We presented the optical design concept and current status for the conceptual design of CMB-S4. This optical concept is composed of two types of large-aperture telescopes, a CD and a TMA, with their respective arrays

Concept	Individual Camera Solution Found	Grouped Lenses Solution Found	Opto-Mechanical
SPLAT	Yes	Yes	In progress
CHLAT	Yes	In progress	In progress

Table 2: Current progress in the design of the 85-camera system. Second column (Individual Camera Solution Found) describes the status of the search of a solution for all three lenses and Lyot stop that is unique for each one of the 85 cameras. This step in the design is used to prove the existence of solutions and to gather information about the parameter space. Third column (Grouped Lenses Solution Found) shows if the solution found in the first step has been replaced with fewer groups of identical lenses. This step is done to minimize fabrication complexity. The fourth column (Opto-mechanical) shows progress on the integration between the optical and mechanical design.

of 85 cameras. We have identified two groups of optical prescriptions that fully populate the 85 cameras in the TMA design, and we are working on identifying groups of optical solutions for the biconic CD cameras. A prototype primary mirror of the TMA is complete, demonstrating the joining technology. We have discussed the computational methods used to generate families of solutions given mechanical constraints for the 85 camera arrays. Opto-mechanical iterations are being carried out to converge on an optical solution of this design using the tools that we have presented here. Diffraction properties in the point spread function will be evaluated when the optical design prescription converges. The optical concept we have presented will allow to populate the focal planes of these large-aperture telescopes with 85 cameras to achieve an unprecedented increase in mapping speed in large-aperture CMB experiments.

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