1 Telescope

In this section, the choice of telescope design will be considered. The optical performance of two configurations will be examined, a Gregorian design and a cross-Dragone design. These two designs will now be examined, highlighting the advantages and disadvantages of each, as applicable to the *COrE+*mission, whose requirements are high polarization purity, 6 arcminute resolution at 145 GHz, mirrors less than 1.5×1.6 m, minimising weight and a large focal plane to accommodate several thousand detectors from 60-600 GHz. Darragh: That sentence is a bit of a placeholder. The figures I took for resolution and detector numbers come from last year's proposal submitted to ESA In each case a primary mirror of effective diameter 1.2 m was assumed, satisfying the science requirements.

1.1 Gregorian Design

The Gregorian design, with unoptimised reflector surfaces, is an off-axis dual reflector telescope with a parabolic primary reflector and an ellipsoidal secondary [1]. This mission calls for a large diffraction limited field of view (DLFOV) over the frequency range 60-600 GHz. Considering this, and the limitations imposed by the volume available in which to house the telescope and associated optics and focal plane architecture, various Gregorian configurations were examined. Figure 1 shows a particular design that was considered in some detail. In order to realise optimal performance, the mirrors were optimised using aspheric surfaces.

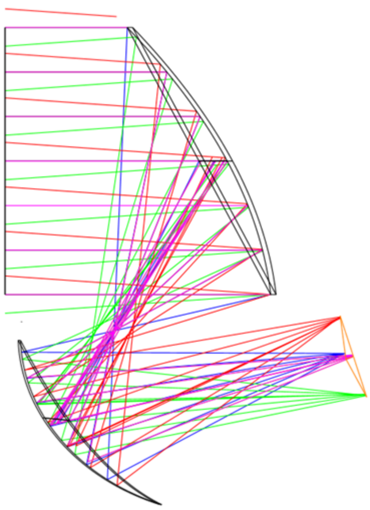

Figure 1: 1.2 m Gregorian design

The primary mirror has dimensions 1.36 m × 1.20 m (length × width), and the secondary mirror is 0.97 m × 0.67 m. These mirrors fit within the mechanical limits which allow them to be manufactured as one section, which has significant benefit in terms of cost and mechanical complexity.

This design has an 8 deg field of view and realises a usable focal plane that is approximately 40 cm in diameter (with F/#1.6 at the centre) at 60 GHz, which is determined by examining the Strehl ratio on the focal plane. 0.8 is taken to be the value below which the system is no longer diffraction limited, so plotting this contour reveals the diffraction limited focal plane available at a given frequency.

The focal plane provides a usable detector area across the band, however in order to achieve this it was necessary to use a curved focal plane surface, which is a limitation of this design. The advantages and disadvantages of Gregorian designs, in the context of this mission, are shown below. Darragh: I tried to save some space by cutting out the Strehl ratio plot of the design that we only really use as a lead in to the lens design. I will put the Strehls for the lens design later in the doc. I am not sure taking it out is the best idea, but is it okay if we're pushing to save space?

Advantages:

- Compact design
- Reflectors are small, compared to other telescope configurations
- Easier to effectively baffle for stray light than other telescope configurations

- Focal plane is located close to the base of the payload module. This is advantageous in terms of cryogenic and mechanical complexity

Disadvantages:

- Gregorian design has inherently smaller focal plane than other telescope types
- Focal plane surface is not flat, which is complex for planar coupling schemes
- Although easier to effectively baffle, the required baffling configuration is demanding and is a tight fit within the available volume

The most significant disadvantage outlined above is that of the focal plane shape. This would not pose such a large problem if horns were an option for the detector technology. As described earlier, with approximately 3000 detectors required, horn arrays are mechanically heavy and difficult to cool. Therefore, arrays of lens-coupled Kinetic Inductance Detectors (KIDs) are proposed. These must be carefully aligned according to the profile and depth of the focal plane in order to be normal to the incoming beams and to avoid defocussing effects. Owing to the dimensions of the wafers on which the KIDs are manufactured, it is not possible to satisfactorily achieve this on such a curved focal plane. If the Gregorian is to be used, it is therefore necessary to use additional tertiary optics to obtain a flat focal plane architecture.

In order to investigate this, a design with primary and secondary mirrors of dimensions 1.50 m × 1.30 m and 1.00 m × 0.70 m was used. An alumina lens was also included between the secondary mirror and the focal plane as a way to flatten the focal plane, as shown in figure 2.

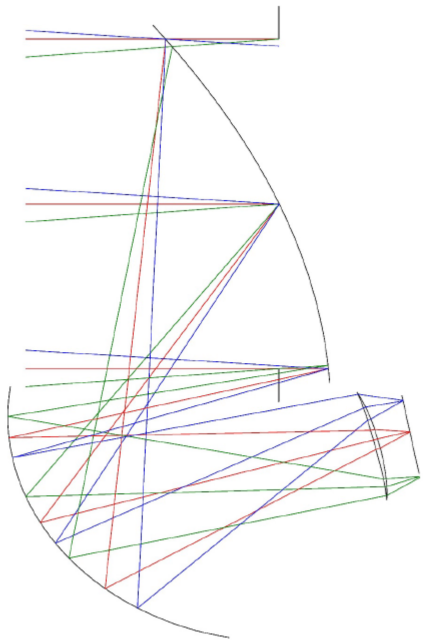

Figure 2: 1.2 m Gregorian design with alumina lens

This design provides an approximately 8 deg field of view. The lens is 44 cm in diameter (optically it is 42 cm in diameter, but a mounting flange of 1 cm is required), and is estimated to have a mass of approximately 6 kg. The diffraction limited focal plane is 1.1 m, and so a focal plane unit with a diameter of approximately 40 cm can now be realised, including the effects of the lens. The contours representing the DLFOV for various frequencies across the band are shown in figure 3. It can be clearly seen in figure 2 that the focal plane surface is now flat, and so the issue regarding the placement of the focal plane pixels has been resolved. Although the lens addresses the main issue of the Gregorian with the non-telecentric focal plane, it presents a number of additional complications. The most significant of these is the potential for the lens to introduce significant instrumental wavelength dependent polarization effects, in addition to the necessity for a broadband anti-reflection coating.

As a flat focal plane is a firm requirement that is driven by the detector technology that is to be used, a cross-Dragone design is now examined as this provides a naturally flat focal plane without the need for tertiary optics.

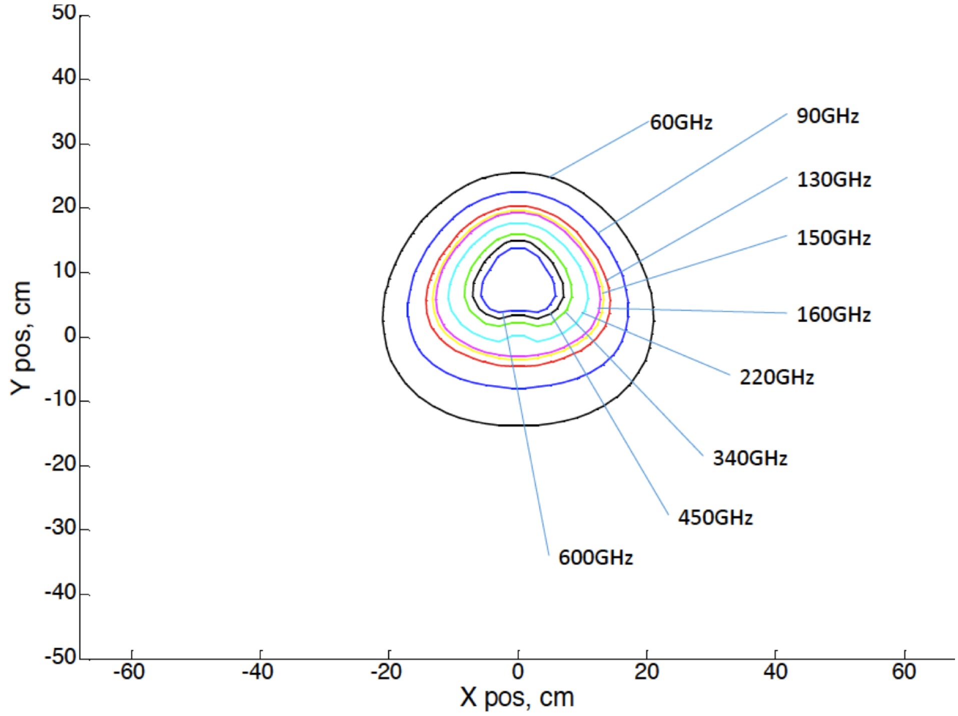

Figure 3: PLACEHOLDER FOR STREHL RATIO WITH LENS

1.2 Crossed Dragone

The Crossed Dragone configuration [2, 3] naturally has a large field of view and a flat, telecentric focal plane making it a promising CMB telescope design.

The *COrE+*optical design is a modified Crossed Dragone using mirrors defined by an anamorphic aspheric surface rather than conic sections. The anamorphic asphere is a surface with different radii of curvature in x and y, z is parallel to the chief ray, as well as higher order deformation terms. The CodeV definition is

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

where R_x and R_y are the radii of curvature, k_x and k_y are the conic coefficients, and $A_{n,r}$, $A_{n,p}$ define the higher order deformation of the surface. In our design $2 \leq n \leq 5$. When the higher order terms are zero this type of surface is often referred to as a biconic.

The basis of our system came from the LiteBIRD telescope design, a 40 cm crossed dragone using anamorphic aspheres [?] what do we cite for this? Karl will ask Tomo, who gave us the files, which we scaled up to 1.2 m. This base design has a long focal length, f/2.5, to allow for baffling the focal plane. After scaling to a 1.2 m aperture the mirror shapes and offsets were optimized in CodeV to maximize the DLFOV Darragh: I updated my section to define the abbreviation in the introduction for the full *COrE+*bandwidth, 60-600 GHz. Figure 4 shows the raytrace of this design. The f/# was appoximately maintained, with a final value of f/2.54 at the center of the focal plane. The focal plane is flat and telecentric with a DLFOV greater than 10 degrees across at 150 GHz, significantly larger than the Gregorian case. DLFOV as deffined by Strehl = 0.8 contours are shown in Figure 5.

With only two mirrors the system is too long to fit within the satellite envelope, so we added a flat tertiary mirror to fold the light path and make the system more compact. This flat mirror could be replaced by a reflective polarization modulator.

Advantages

- Large, flat, telecentric focal plane.
- All mirrors are placed near the main satellite body simplifying the mounting structure.

Disadvantages

- Large telescope is difficult to fit within payload volume.

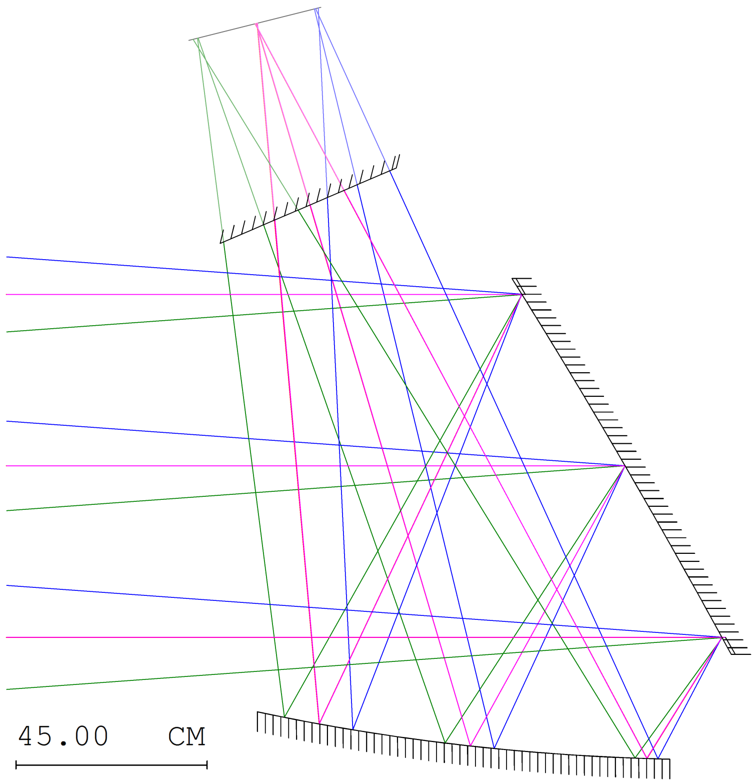

Figure 4: Ray trace of the *COrE+*design. Fields are at +4.1, 0, and -4.1 degrees. Rays are shown extending beyond the tertiary to clearly show the focal plane. In reality the tertiary folds these rays out of the page and toward the entrance aperture.

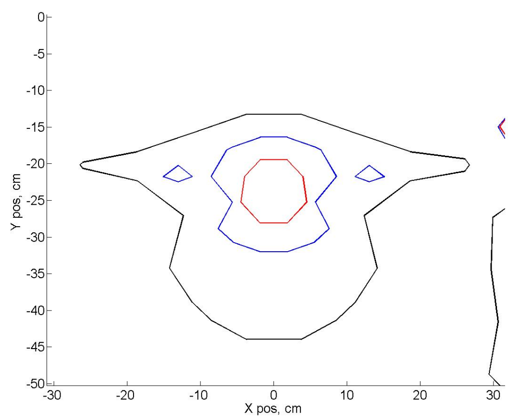

Figure 5: Strehl= 0.8 contours defining the diffraction limited field of view of *COrE+*at 600, 450, 250, and 150 GHz. The usable field of view, limited by the ability to baffle the focal plane, is shown as a dashed blue circle. Figure needs editing to include 150 GHz and the dashed blue circle. Karl is on this.

- Large heavy mirrors are required.

- Has direct views of the focal plane to the sky and strong sidelobes.

- No convenient place for baffling or for an aperture stop to control sidelobes.

The largest difficulty with this crossed dragone system is baffling the focal plane to reject stray light from the sky. In Figure 4 the gray dashed line shows there is a direct path for objects about 70 degrees off boresight to directly illuminate the focal plane. The fold mirror moves the focal plane closer to the entrance aperture, making baffling more complicated. We added a 'bucket' baffle around the focal plane (at ?? K) and a collar (at ?? K) around the entrance aperture of the system. Additionally, we limit the focal plane to 4.1 degrees in radius. Between the baffles and smaller focal plane there is no direct view of the focal plane from the sky. The final focal plane size is shown by the blue dashed line in Figure 5 and is constrained by the baffling requirement rather than by Strehl ratios, which is the limit for the Gregorian design.

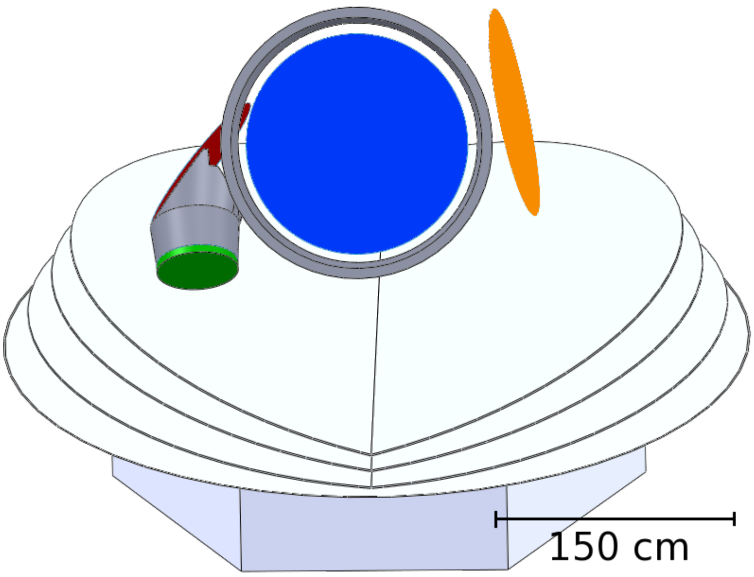

Figure 6: CAD model of the Crossed Dragone system. The view is looking down the boresight of the telescope. The primary is blue, the secondary orange, and the tertiary is red. The focal plane is green and baffles are grey. Below the telescope the white sunshields and the satellite service module are shown. ky: This caption feels confusing to me. Suggestions? Also picture maybe isn't very clear. Suggestions there?Darragh: I think the caption reads fine. At first glance it is a bit difficult to figure out the positioning of the secondary relative to the primary - would a different projection clear that up?

The final optical system with tertiary mirrors and baffles is shown in Figure 6 and fits within the satellite envelope if $\alpha = 30$ and $\beta = 65$ will these have been defined somewhere else? or do we need to define them hereDarragh: Based on the template, I think we may need to define them here. Additionally the system is rotated about the bore-sight to lay roughly on its side. This puts the mirrors and focal plane close to the main satellite body, reducing the need for heavy supports, and is the only orientation where the telescope fits within the baseline sun-shields.

The major advantage of this system is a large, flat, telecentric focal plane which greatly simplifies the required detector architecture. The main disadvantages are the three large, and therefore heavy, mirrors and the stringent baffling requirements which limit the usable focal plane area. The benefit of a flat focal plane is sufficient that the Crossed Dragone is the current baseline for *COrE+*. true?

Sidelobes other than direct views of the focal plane from the sky are currently being studied.

Primary mirror	131 cm $\times$ 152 cm
Secondary mirror	125 cm $\times$ 146 cm
Tertiary mirror	104 cm $\times$ 74 cm
Focal ratio (F/#)	2.54
FOV, Focal plane diameter at Strehl = 0.8 @ 150 GHz	4.1 deg $\times$ 4.1 deg, 87 F$\lambda \times$ 87 Fλ

Table 1: Parameters for the *COrE+*Crossed Dragone design. Mirror dimensions are the largest physical sizes. Focal plane dimensions are given at 150 GHz in degrees and in units of Fλ (λ = 2 mm) to faciliate comparison between designs with different F/#'s. Darragh: I will produce a similar table for the system with alumina lens (don't think it is necessary for the system without the lens, as that is an intermediate step in the Gregorian design process?)

References

[1] Granet C., Designing classical offset Cassegrain or Gregorian dual-reflector antennas from combinations of prescribed geometric parameters, in IEEE Antennas and Propagation Magazine, vol. 44, no. 3, pp. 114-123, Jun 2002. doi: 10.1109/MAP.2002.1028736, URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=1028736

[2] Tran H., et al., Comparison of the crossed and the Gregorian MizuguchiDragone for wide-field millimeter-wave astronomy, Applied Optics Vol. 47, Issue 2, pp. 103-109 (2008) doi: 10.1364/AO.47.000103

[3] Granet C., Designing classical Dragonian offset dual-reflector antennas from combinations of prescribed geometric parameters, in IEEE Antennas and Propagation Magazine, vol. 43, no. 6, pp. 100-107, Dec 2001. doi: 10.1109/74.979502, URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=979502&isnumber=21102