Summary of telescope designs considered by the optics group for the COrE+ M4 proposal in 2015

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1 Introduction

The purpose of this document is to summarise the findings and discussions within the optics group from last year when assembling the COrE+ proposal. This should allow a good starting point for the work on the new COrE++ proposal. The documents acts as a summary of the presentation given by Neil Trappe at the meeting in Paris on September 28$^{\text{th}}$ 2015, detailing work carried out by everyone involved in the optics part of the project.

2 Review of Telescope Types+Advantages/Disadvantages

For CMB polarisation missions, typically off-axis Gregorian or front/side-fed crossed-Dragonian designs are used. For missions such as COrE++, several challenges exist;

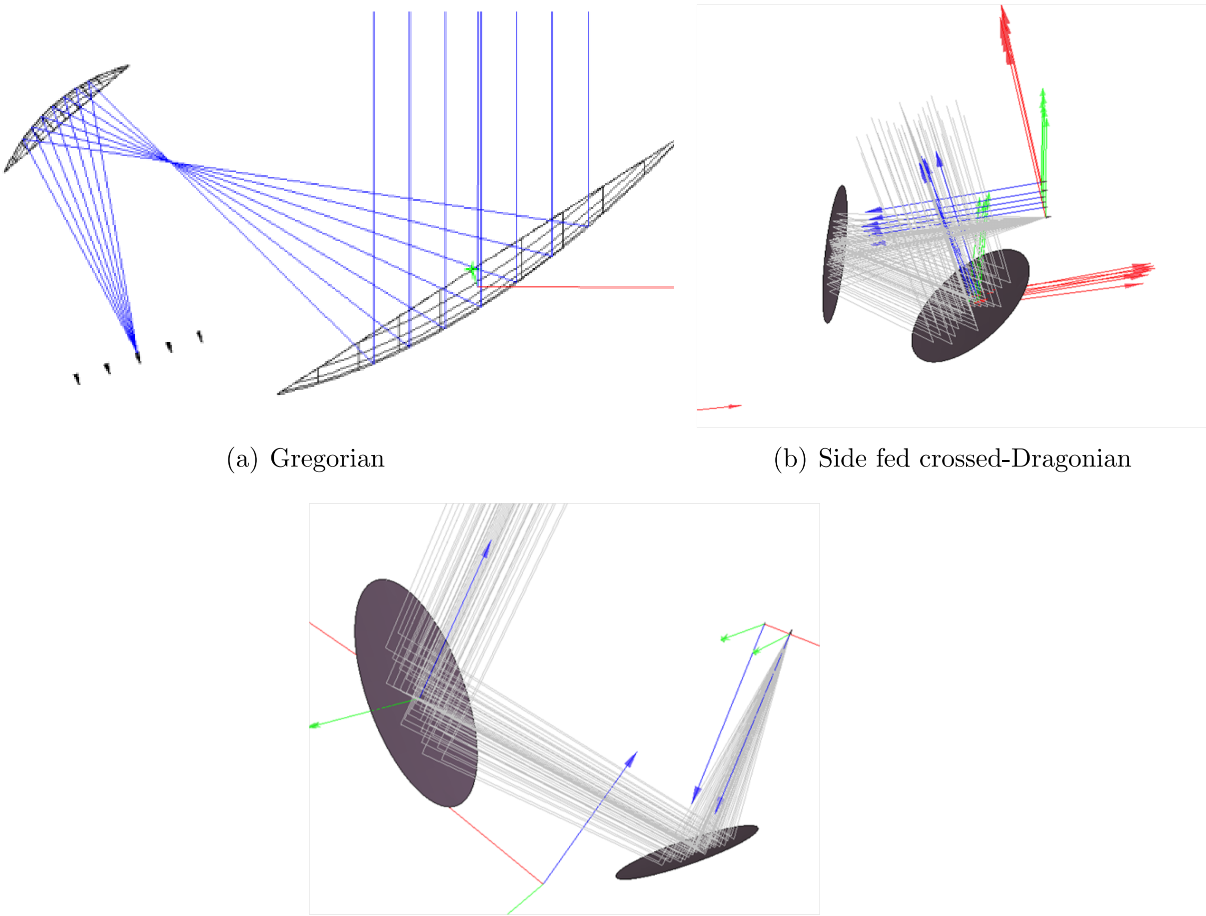
- Maximise optical resolution - large primary mirror
- Maximise sensitivity - large focal plane array
- High beam directionality and symmetry with low sidelobe/cross-polar levels
- Telecentric focal plane and possibly cold stop/re-imaging optics - determined by detector regime
- Meet stringent mass/volume requirements - determined by launcher
- $\approx$ F/2 to match to pixel f-number

Table 1 compares Gregorian and crossed-Dragonian telescopes in terms of parameters that are relevant for selecting a geometry for COrE++, and so the performance requirements listed above should be compared with the properties of the different geometries in order to assist in selecting the best geometry.

Parameter	**Gregorian**	**Crossed-Dragonian**
Focal Plane Area	Good	Better
Telecentric Focal Plane	More difficult	Reasonable
Cold Stop	Inter-mirror focus	Tertiary optics
Secondary Mirror	Small	Large
Mechanical Volume	Reasonable	Larger than Gregorian

Table 1: Comparison of Gregorian and crossed-Dragonian telescopes

A Dragonian design would appear to perform well. It offers a larger focal plane area than a Gregorian design, in addition to the focal plane being highly telecentric. This is advantageous in



(a) Gregorian

(b) Side fed crossed-Dragonian

(c) Frond fed crossed-Dragonian

Figure 1: Gregorian and side/front fed crossed-Dragonian configurations

terms of offering flexibility when determining the detector regime (planar antennas etc.). This is not possible for the Gregorian design without significant modifications, including tertiary optics such as lenses.

A significant disadvantage that is encountered when using crossed-Dragonian designs is the size of the secondary mirror. Typically it is comparable in size to the primary mirror which results in increased complexity, mass and cost. An additional disadvantage is that there is no natural cold stop in the system. If horns are used on the focal plane then this is not a significant issue, however if technology such as planar antennas is used (which could save mass and reduce the complexity associated with cooling the horns) then a cold stop would likely be required that would need tertiary optics. The required lenses would introduce significant additional mass and would also be of detriment to the optical quality of the system.

With the above advantages and disadvantages in mind, side and front fed Dragonian designs were examined. The side fed configuration has the lowest aberration in general (highest beam symmetry), but ultimately the configuration is such that it fits poorly in the launcher. Of the two, the front fed configuration is therefore preferable and so was selected for investigation ahead of the side fed option. A front fed configuration is shown in figure 2. For such configu-

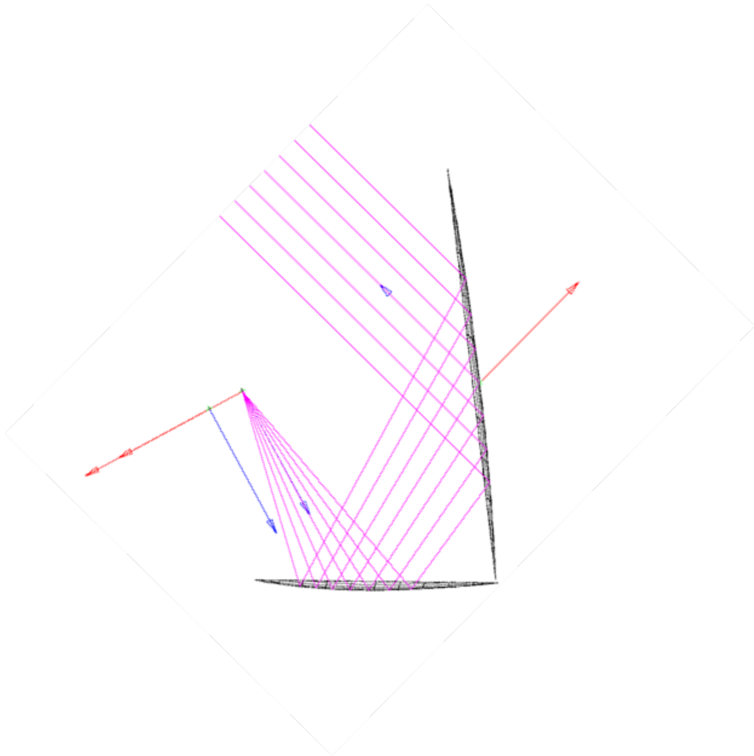


Figure 2: Front fed Dragonian configuration

rations (based on F/2 and 1.5m primary mirror), optical performance is maintained across the focal plane, only deteriorating by approximately 5% across a 400 mm focal plane. The design would appear suitable, however the disadvantages listed above still apply. The secondary mirror is similar in size to the primary mirror, and the requirement to use tertiary optics to form a cold stop (if required) would add further mass to the system. Additionally, the location of the focal plane in this configuration is an issue. Although it fits within the volume of the launcher, it is away from the base of the telescope where the electronics and cooling equipment (service unit) is located. Interfacing with this unit would therefore introduce significant additional mass and complexity. These disadvantages are significant enough to warrant the consideration of a Gregorian design, despite the smaller non-telecentric focal plane.

The equivalent Gregorian design (F/2 and 1.5 M aperture)offers a naturally smaller diffraction limited focal plane, out to approximately 150 mm versus the 400 mm offered by the crossed-Dragonian designs. In terms of ellipticity, the performance is equivalent to the side-fed Dragonian out to this distance, quickly deteriorating beyond this.

Despite this, a Gregorian telescope is a very viable candidate for COrE++. The secondary mirror is significantly smaller than the primary, offering a saving in mass and cost. The overall volume occupied by this design is smaller than the equivalent Dragonian designs. It is also possible to increase the size of the focal plane by means of optimising the mirror surfaces, separations, offset angles and focal plane geometry. Although this naturally increases cost and manufacturing complexity, it is worth it in terms of the increase in performance. The natural formation of an image between the mirrors provides a location for a cold stop, which provides flexibility when determining detector type, however with this in mind it should be noted that if the detectors require a flat focal plane then the ability to optimise the focal plane geometry is removed and re-imaging optics will be required to form a telecentric beam on the focal plane. This means that the size to which the focal plane can be increased (by means of optimisation) will be decreased and the re-imaging optics will introduce additional mass, whilst also requiring more volume to be available in the launcher. An example of such a system, with re-imaging optics, is shown in figure 2.

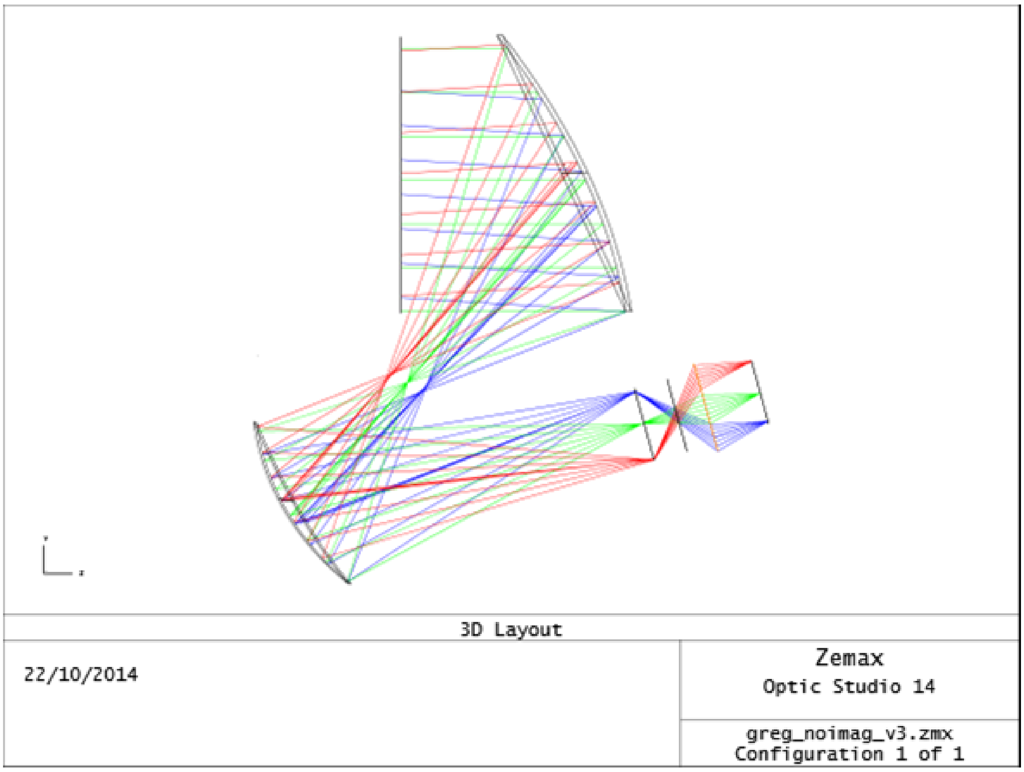


Figure 3: Gregorian design with re-imaging optics

With the above arguments considered, a Gregorian design was taken as the baseline design for the M4 proposal (with no re-imaging optics). For ease of reference, we now briefly describe the baseline design from the previous M4 proposal.

3 M4 Proposal (2015)

The specific optical considerations used were as follows.

- Primary mirror projected aperture of 1.1-1.65 m (from the diffraction limit), which yields an angular resolution of between 6 and 4 arcminutes at 200 GHz. The projected diameter for the baseline design was therefore chosen to be 1.5 m

- Reflector surface accuracy of 500 microns
- Design should allow a diffraction limited focal plane that is large enough to house the required number of detectors to meet sensitivity requirements
- Low sidelobe levels to maximise rejection of radiation from the Sun, Earth, Moon and Galaxy
- At least -20 dB edge taper on the telescope reflectors

The design chosen, as stated previously, was an off-axis Gregorian. The diffraction limited focal plane of a standard Gregorian is not necessarily large enough to host the required number of detectors, and so the basic design was optimised to increase the size of the focal plane. As a telecentric focal plane was not required by the detector regime (thus no re-imaging optics were required, reducing instrumental polarisation), it was possible to increase the size of the focal plane by varying the focal plane geometry. This was carried out at Maynooth using Zemax. Using this optimised focal plane geometry, the performance was further increased by representing the mirror surfaces as 12^{th} order aspherical surfaces and optimising them, and also by varying the angle between the primary and secondary mirror axes and the mirror separation. This optimisation was carried out in CodeV at the University of Minnesota. Figure 4 shows the optimised values and a schematic of the optimised design. It also shows the Strehl ratio contours (0.8) for each frequency, mapped onto the focal plane. This shows the 'usable' focal plane area for each frequency.

With the optimised design in place, GRASP was used to propagate representative beams through the the telescope to check the optical quality of the beam on the sky. The design was found to provide good performance in terms of focal plane size, sidelobe and cross-polarisation levels, and beam ellipticity. This design places the focal plane unit near the service module, reducing mechanical complexity and the moment of inertia of the satellite.

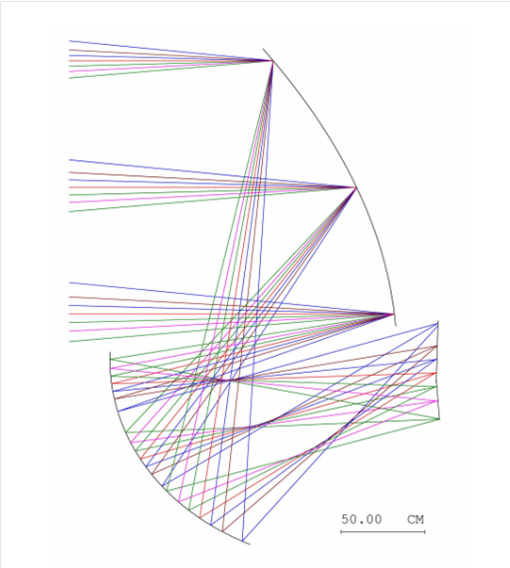
A smaller telescope (1 m Dragone) was also proposed as a descoped option, however no detailed description is given here. This design would not compromise the diffraction limited field of view relative to the Gregorian design and would maintain the total number of detectors, but would have degraded angular resolution. A telecentric focal plane would also be present, resulting in a less complex focal plane unit, with the possibility to also include a third reflective surface. Disadvantages include larger mass and volume of the optical system. An upgrade option was also considered, a 1.5 m open-Dragone system that would give a diffraction limited field of view that is approximately 20% larger in area, albeit with larger mass, mirrors, and the necessity to use deployable shields.

Parameter	Value
Off-axis Gregorian (baseline for *COrE+*)	
Primary mirror projected diameter	1.50 m
Primary mirror actual diameter	1.82 m × 1.64 m
Secondary mirror size	1.40 m × 1.31 m
Telescope focal ratio (f#)	2.07
Estimate of total mass	53 kg

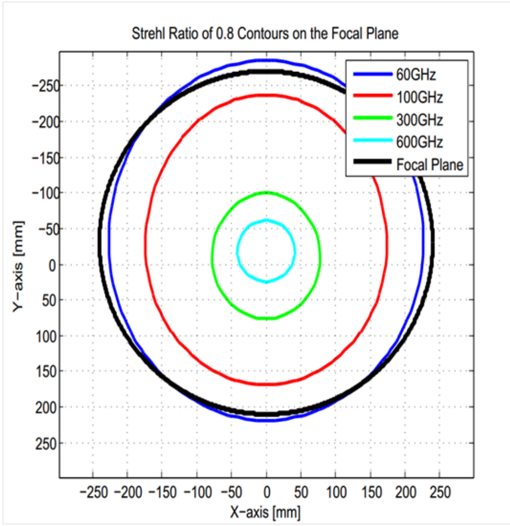
(a) M4 baseline optical specifications

Parameter	Value
Primary mirror projected diameter	1.500
Primary mirror actual diameter	1.700
Primary mirror focal length	0.890
Offset between mirror axes	5.600°
Interfocal distance	1.300
Secondary eccentricity	0.554686
Focal plane diameter	0.480
Working f#	2.05

(b) M4 baseline optimised parameters



(c) M4 baseline schematic (optimised Gregorian)



(d) M4 baseline Strehl=0.8 contours on the focal plane

Figure 4: Gregorian and side/front fed crossed-Dragonian configurations

4 Conclusion

It is clear when comparing the telescope options, what advantages and disadvantages each type brings. We must decide what features are of priority, and in that way we can perform a trade-pff analysis to determine the ideal design to use. Questions to be considered include:

- Launcher volume constraints
- Mechanical requirements e.g. focal plane placement relative to the service unit, this will determine what telescope design/orientation we can use
- Choice of focal plane technology - horn array, planar antennas etc. This will determine if the focal plane must be telecentric or not, and if we need a cold stop. → Re-imaging optics? Does adding re-imaging optics introduce issues in terms of performance, mass and volume? Does a design that does not need re-imaging optics meet the other requirements?
- Do we need a halfwave plate, and if so where in the optical train will it go?