Restoring an Eighteenth Century Sea Telescope

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Abstract. This report looks at characterising an eighteenth century telescope which is missing at least two lenses with a particular focus on the lens missing from the achromatic doublet objective. Three potential candidates for the missing objective lens are given and the resulting aberration characteristics of the objective are investigated with a focus on chromatic aberration. The results are similar to the 2010 report by Duane Jaecks [1] which suggested that eighteenth century telescope achromatic doublets tended to over correct for the effects of chromatic aberration. Suggestions are made for a potential method to determine the focal length of the missing eyepiece lens as well as which of the three potential objective lenses is closest to what was originally in the telescope.

1. Introduction

Since the telescope was invented in 1608 it has been continually developed and improved [2]. One such improvement was the development of the achromatic doublet which is regarded as "the first radical improvement in optics since the discovery of spectacles"(quoted by Eugene et al. [3]. Achromatic doublets are used to reduce optical aberrations, in particular chromatic aberration. Sir Isaac Newton dismissed the achromatic doublet as impossible due to perceived material limitations[4]. Chester Hall created the first achromatic doublet to reduced chromatic aberration in 1733 [5] [1]. Despite this it was John Dollond who obtained the patent for the use of achromatic doublets in telescopes and he attempted to limit their use by all other eighteenth century opticians [5].

The achromatic doublet uses two lenses of differing dispersions and opposite powers to counteract the spreading of colours due to chromatic aberration. A low dispersion convex lens, typically crown-glass, is used with a higher dispersion, typically flint-glass, concave lens of lower optical power. This leads to a convergent system of lenses where two different wavelengths of light can be brought into focus at the same plane as shown in figure 1 [1]. This effectively eliminates chromatic aberration for two wavelengths of light and reduces the total effect of chromatic aberration.

Chromic aberration is the result of dispersion which occurs because the refractive index of materials is wavelength dependent [6]. Polychromatic light is not focused onto

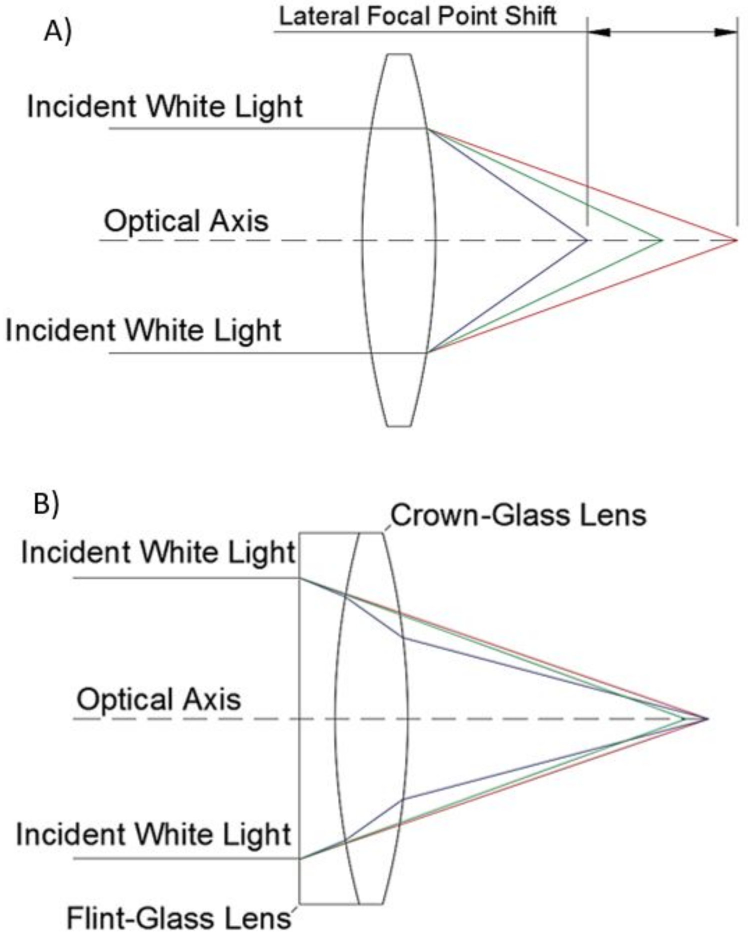

Figure 1: A) shows a ray diagram of the effect of chromatic aberration. Note how the focal length of the lens depends on the colour of the light, this gives rise to lateral focal point shift. B) shows how this can be corrected with a achromatic doublet, shown here in the flint-glass first arrangement.

a single plane, instead it is spread out along the optical axis of a lens as shown in figure 1. This means that any image as seen through a telescope would be blurred and have colour fringing reducing the optical quality. Another aberration effect which severely limited the optical quality of 18th century telescopes is spherical aberration.

Any light focused by a spherical object (lens or mirror) will be focussed to different points depending on the radial distance of the light incident on the object. This is due to the geometry of spheres. As the incident light gets closer to the optical axis, the focal length increases as shown in figure 2. The simplest method to reduce spherical aberration is to use a small aperture. This ensures all incident light is located on approximately the same point on the lens and so is focused at the same location. This reduces the total light entering the lens and so reducing the brightness of any image formed. A different approach is to use lenses which are not spherical however this has only been possible in more recent times and so was not a reasonable solution in the eighteenth century. Another method of spherical aberration correction is to optimise the radius of curvature of each lens surface to minimise spherical aberration in any given lens [7].

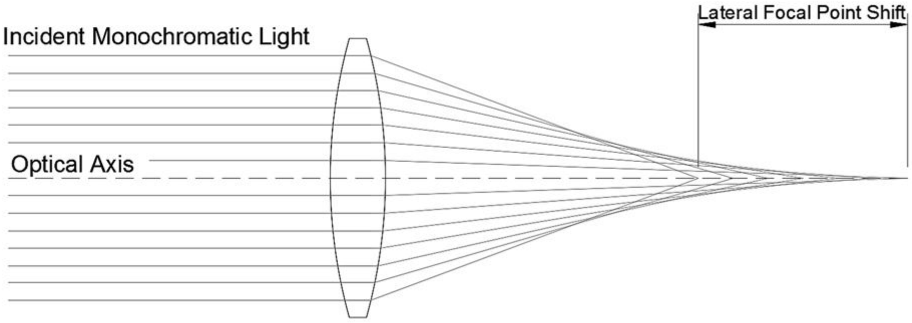

Figure 2: A ray diagram depicting spherical aberration and its effect on the focal length of a lens.

A full mathematical description completely in agreement with modern theorems of achromatic doublets were known in the time of the creation of this telescope [1]. Despite the relative abundance of eighteenth century achromatic telescopes, it is still not clear exactly how successful this theory was applied in the creation of achromatic doublets. It is known that this theoretical description was largely ignored by many opticians, at least initially [1] [8]. Previous studies [1] [8] have also shown that the achromatic doublets found in other eighteenth century telescope objectives generally over corrected for chromatic aberration. It has been suggested that this was done intentionally to compensate for the under corrected eye piece lens arrangements [1].

In this report an antique 18th century sea telescope which is missing at least two lenses is investigated. The telescope was made by George Ribright and his son Thomas Ribright and so must have been created in the mid to late 18th century [5], and prior to George Ribright's death in 1783. The objective of the telescope will be the main focus of the report as it appears to have been an achromatic doublet, however it is currently missing the converging lens. By determining the optical properties of the telescope's achromatic doublet, it is possible to gain an insight into how well such models were applied and increase our understanding of eighteenth century telescope design. It is also hoped that this telescope will be able to be restored to its original condition if desired.

2. Ribright's Telescope

Figure 3 shows a diagram of the telescope in its current state with the missing lenses marked by a broken line. One lens from the objective, a convex lens, is missing. This would make the objective a doublet lens arrangement. Given the age of the telescope this suggests it is likely to be some form of achromatic doublet. The missing eyepiece element is possibly a second doublet making a 5 lens eye piece commonly found in achromatic telescopes of this age [1] although it could simply be a single lens as depicted.

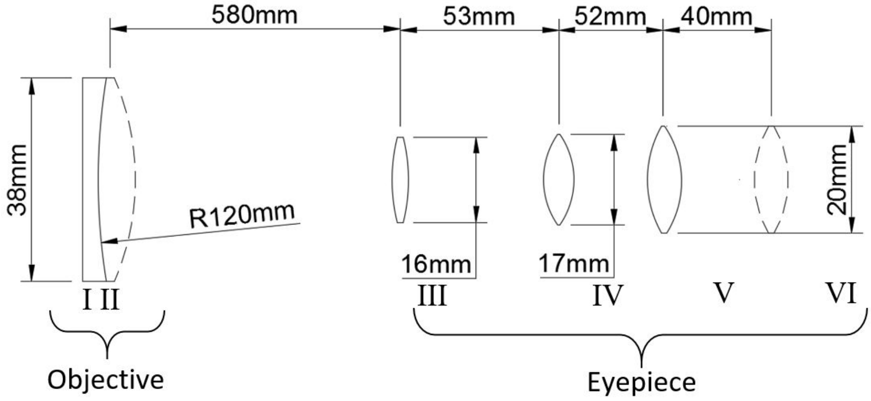

Figure 3: Diagram of Ribright's telescope in its current state with proposed missing lenses drawn in with a dotted line. Note the roman numeral lens labeling system used throughout the report

3. Methods and Results

The focal lengths of the lenses which are currently present were determined first and then what material the concave lens is made from. The experimental set-up used to find the focal lengths of the lenses is shown in figure 4. The image formed from the reflection of the object was observed through the convex lens, the distance between the object and the lens was adjusted until the image was located at the same point as the object. This occurs when the object and image appear to move together when the viewing angle is changed. The focal length of the lens can then simply be read off as the distance between the object and the lens.

To determine the focal length of the concave lens initially a method was used which involves determining how the image location for a converging system changes when the concave lens was inserted into optical system. This method was found to have unacceptably high uncertainty and so was not used. Instead the method used for the convex lenses above was employed except now the convex lens was replaced with a system of a concave lens and the convex lens. The focal length of the system was found and from this, and given that the focal length of the convex lens can be found, the focal length of the concave lens was then determined using equation 1 where F is the focal length of the entire system and f_1 and f_2 are the focal lengths of the individual components. Table 1 shows the measured focal lengths of all four remaining lenses as well as the extra convex lens used to find the objective lens' focal length.

$$1/F = 1/f_1 + 1/f_2 \tag{1}$$

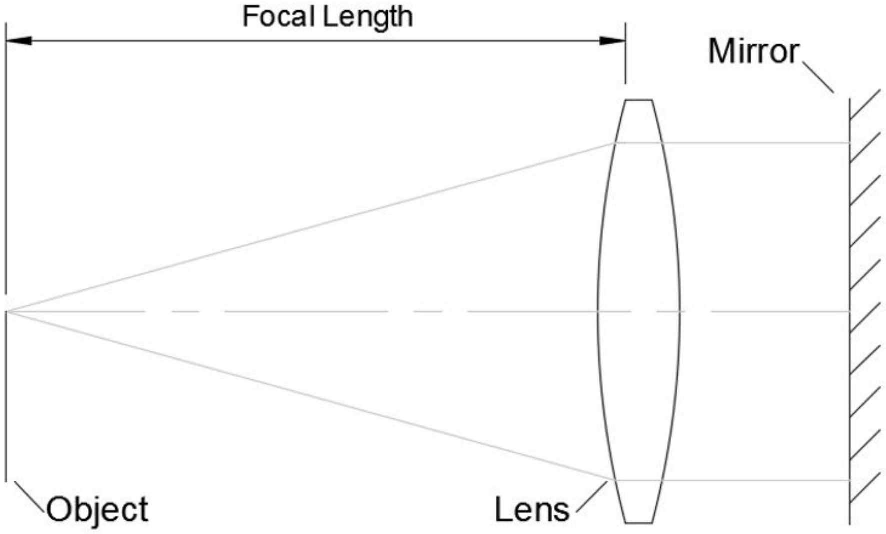

Figure 4: Diagram of experimental set up used to find focal lengths.

Table 1: Lens Focal Lengths

Lens	Focal length (mm)
I	41.1 ± 0.3
III	51.7 ± 0.3
IV	28.0 ± 0.4
V	-213.4 ± 0.4
Extra Convex Lens	133.8 ± 0.5

The uncertainty in the focal length measurements was determined by remeasuring the focal length many times and using the spread of values as the uncertainty.

The next task was to determine the refractive index of the concave lens. Initially we explored whether an Abbe-Refractometer could be used to determine the refractive index as it is the standard method of determining the refractive index with high precision. An Abbe-Refractometer uses a high refractive index prism to determine the refractive index of materials by determining the critical angle for the material in question. This allows an accuracy of ± 0.0002 in the refractive index and it is primarily used to characterise liquids [9]. It can be used to characterise solids however it requires a polished flat surface and some monobromonaphthalene which we did not have. It can also potentially cause damage to the lens surface due to small crystals in the liquid required for its operation [9]. Therefore so it was decided that this would not be used to avoid damaging the antique lens.

Instead the radius of curvature of the lens was measured and from this the refractive index was found. A spherometer was used which has three legs of equal, fixed length

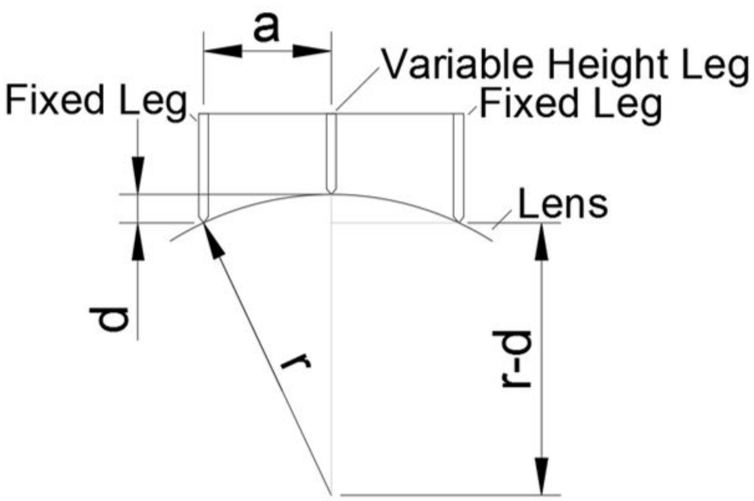

Figure 5: Diagram of a three legged spherometer

Table 2: Radius of curvature of Lenses

Lens	Radius of Curvature (front side)(mm)	Radius of Curvature (back side)(mm)
V	∞	-126.1 ± 0.4
Extra Convex Lens	114.1 ± 0.3	199.4 ± 0.9

spread evenly around the edge of a disk of radius, a, of 15mm and fourth leg in the centre which has a variable height. The spherometer measures the height difference between the three outer legs and the centre legs, d which can then be used to find the radius of curvature, r using equation 2. Figure 5 shows a diagram for a three legged spherometer. The radius of curvature of the extra convex lens which was used to find the focal length of the concave doublet lens was also measured with the results shown in table 2.

$$r = a^2 + d^2/2d \tag{2}$$

To increase the accuracy of the result, rather than using the standard lens maker's formula which relies on the thin lens approximation the lens was modelled in Optics Software for Layout and Optimization (OSLO), which is a ray tracing software. The optical set-up used to find the focal length was modelled in OSLO to find the refractive index of the extra convex lens and then the concave lens. The results are shown in table 3. Given that the refractive index is 1.596 ± 0.002 it was concluded that the doublet was indeed some form of achromatic doublet given the refractive index of flint-glass is generally taken to be anything in the range $1.58 - 1.89$ while the refractive index of crown-glass is typically taken to be 1.52 [10] which suggests the concave lens is flint-glass.

To estimate what the missing lens from the doublet objective was three potential focal lengths for the entire objective were determined. Figure 6 shows example ray

Table 3: Refractive index of lenses

Lens	Refractive index
V	1.596 ± 0.002
Extra Convex Lens	1.544 ± 0.003

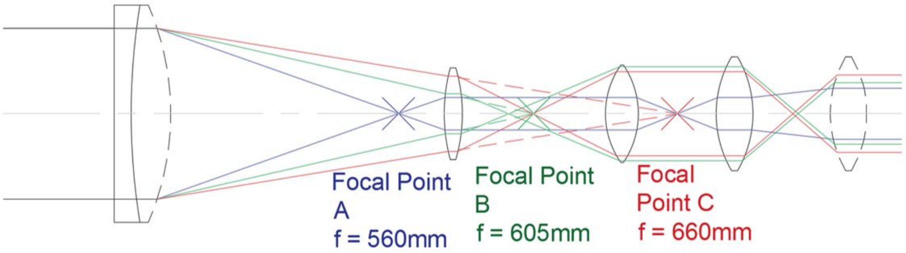

Figure 6: Ray diagram for the three potential focal lengths of the objective system (not to scale)

Table 4: Characteristics of the three potential objective systems, an optimised achromatic doublet and a single lens

Lens Arrangement	Objective Focal Length (mm)	Convex Lens Focal Length (mm)	Radius of Curvature (mm)
A	560.0	154.5	214.55
B	605.0	157.7	227.05
C	660.0	161.1	241.65
Optimised	309.1	126.4	134
Single Lens	600.3	600.3	620 (both sides)

diagrams for the three potential objective arrangements. OSLO was then used to model the objective in these three systems to determine the focal length of the missing lens as well as the chromatic aberration at the focal point. For comparison the objective was also modelled with the optimal focal length for the missing lens which would result in minimal chromatic aberration as well as a single lens. The models were all built assuming that the missing lens was made from crown-glass with ’typical’ characteristics, that the concave lens had the standard dispersion relation for flint glass, both as according to OSLO. It was assumed that the radius of curvature of side of the missing lens facing the concave surface of the remaining lens matched that for the remaining lens and so the two sit flush against one another. This meant that we eliminated all degrees of freedom except for the radius of curvature of the side of the missing lens not resting on the concave lens.

The longitudinal chromatic aberration of each objective system modelled are shown in figures 7, 8, 9, 10 and 11. These show that all three potential objective arrangements

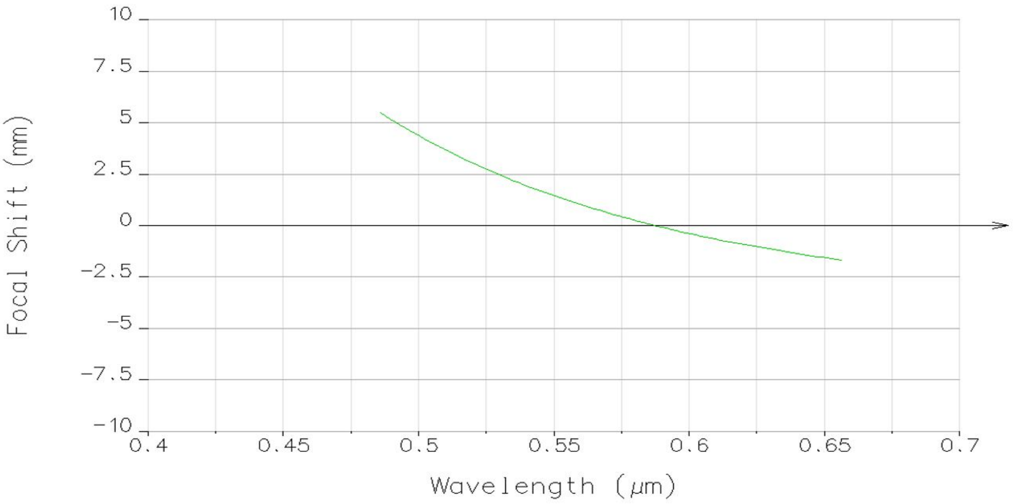

Figure 7: Longitudinal chromatic shift of lens arrangement A

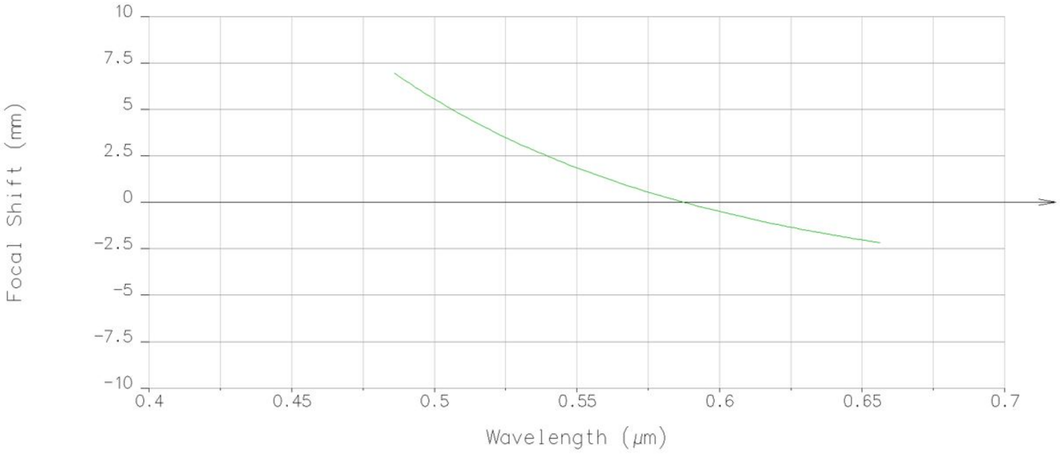

Figure 8: Longitudinal chromatic shift of lens arrangement B

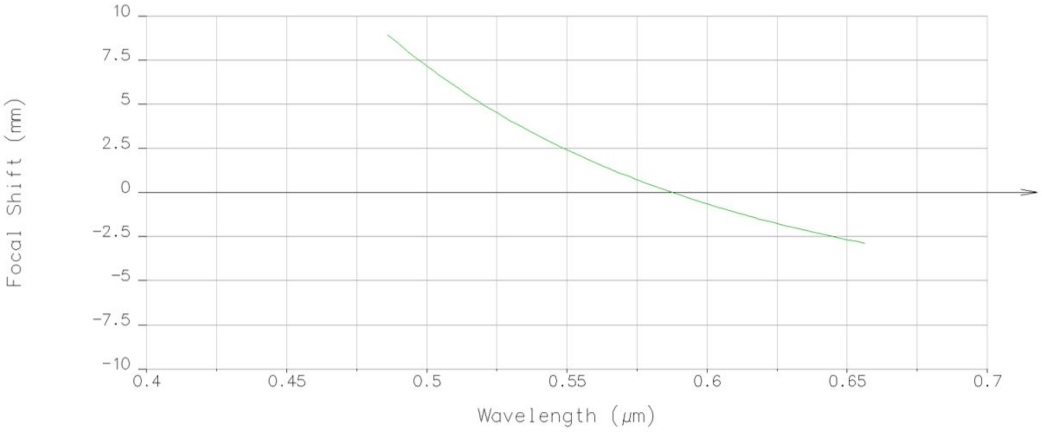

Figure 9: Longitudinal chromatic shift of lens arrangement C

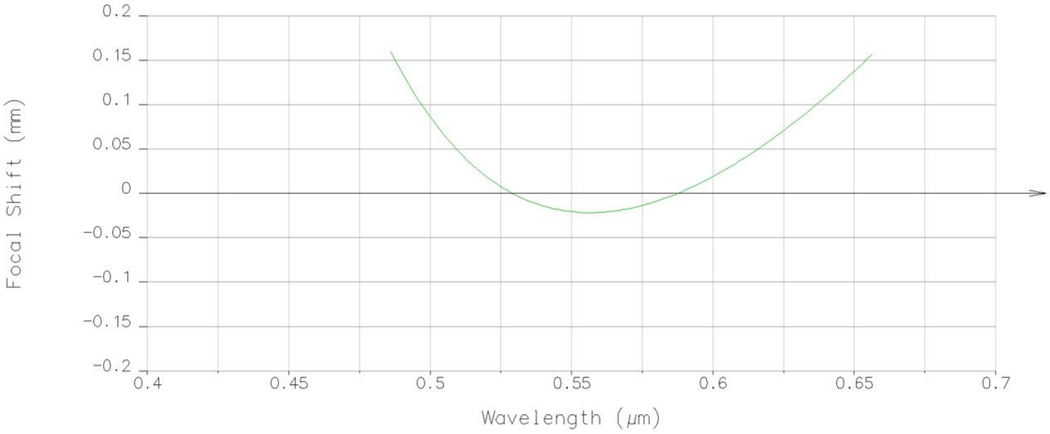

Figure 10: Longitudinal chromatic shift of the optimised achromatic doublet

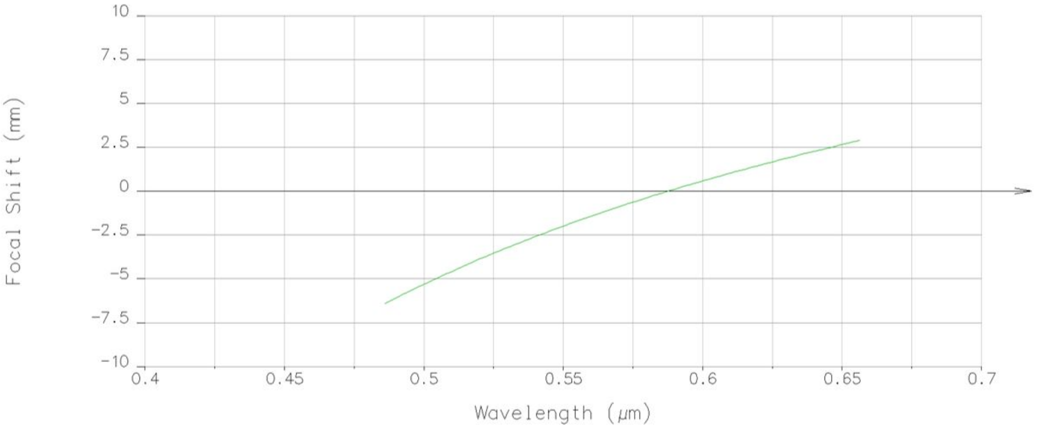

Figure 11: Longitudinal chromatic shift of the single lens objective

result in a significant overcorrection of chromatic aberration, roughly comparable to the total under correction present in a single lens arrangement of similar focal length. The longer the focal length the greater the size of the over correction. The optimised achromatic doublet, while almost eliminating chromatic aberration, would be completely unsuitable in the telescope as its focal length is far too short. Judging by the chromatic aberration only suggests that the 'A' arrangement lens with a focal length of 154.5mm is the most likely candidate for the missing lens. This over correction appears to be what was seen in Jaecks' study [1]. If this is to compensate for the eyepiece then this could allow the missing eyepiece lens to be determined from the total eyepiece chromatic aberration characteristics. This is left to a future investigation.

The spherical aberration characteristics are shown in figure 12 which shows that the 'C' lens arrangement has the least spherical aberration of all possibilities, and the 'A' doublet introduces the most spherical aberration. Interestingly the optimised achromatic doublet introduces the most spherical aberration of all the systems modelled.

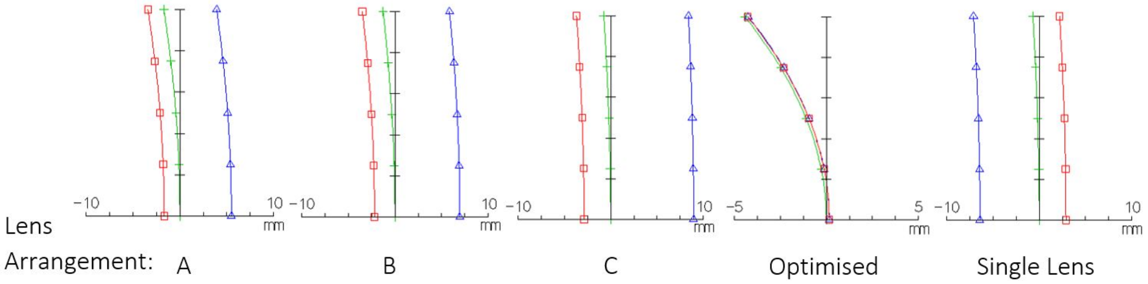

Figure 12: Longitudinal spherical aberration of the five objective systems modelled in OSLO. Each coloured line corresponds to the spherical aberration for that colour and so also gives an indication of the chromatica aberration.

These results are dependent on the assumption that the two lenses in the objective have radii which allow them to sit flush against each other. This may not have been true and so there is significant uncertainty in these results.

4. Conclusion

The aim of this project was to determine which lenses are missing for an eighteenth century sea telescope, and to characterise the achromatic doublet objective if it did indeed have one. Three potential candidates for the missing objective lens were found, with focal lengths 154.5mm, 157.7mm and 161.1mm. The first provides the best correction to chromatic aberration and the last causing the least spherical aberration. The aberration characteristics of these three potential objectives were analysed and compared against an optimised achromatic doublet and a single lens of comparable focal length. This showed that all three potential systems dramatically over corrected for chromatic aberration however they did not introduce much spherical aberration.

The missing eyepiece lens was not investigated as the available version of OSLO did not allow it. By modelling the entire telescope in OSLO with all three potential objective lenses it is suggested that the correct object and eyepiece lens could be determined by minimising the total chromatic aberration. Once this is done the entire telescope could be restored to its original condition.

5. Self Assessment

This project was largely limited by time and the version of OSLO used. The radii of curvature of all lens surfaces was not measured initially which limited the ability to investigate the eyepiece. Time limitations did not allow me to take these measurements. The entire telescope could also not be simulated in OSLO as only the education version could be obtained. This limited models to eight surfaces and so at most the objective and half of the eyepiece was all that could be modelled. This meant the missing eyepiece lens could not be determined.

Overall I believe I thoroughly explored the potential variations of the achromatic doublet as it likely occurred in this telescope originally. This was one of the primary purposes of this report. I believe I have comprehensively discussed the relevant background information and the aims of this project, I have presented what amounts to a reasonable project report and have attempted to thoroughly discuss the methods and results, taking care to explain all assumptions, uncertainty and conclusions. I would award myself an overall grade of 6.

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