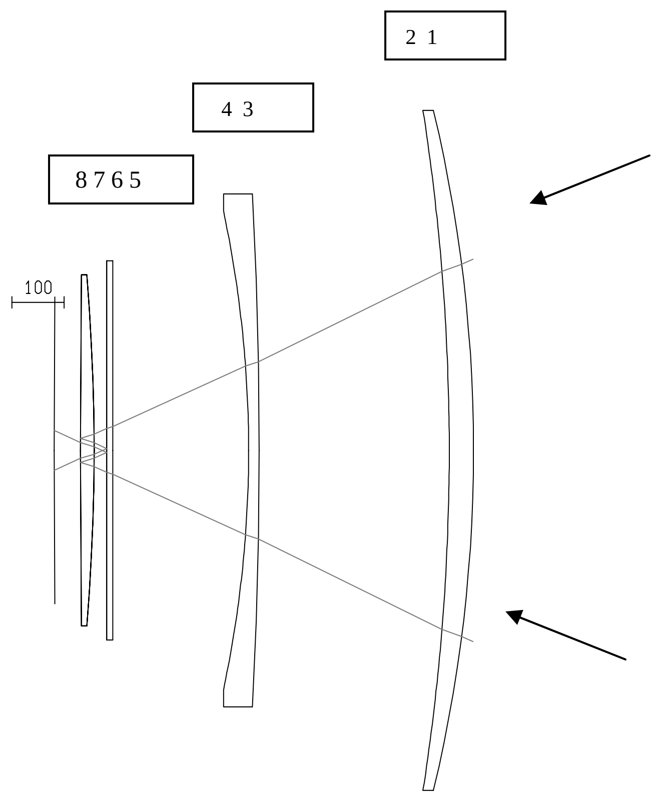
Ghost analysis, for the case 4b design: Lynn G. Seppala December 17,2001

There are four refractive elements, three lenses and a plano filter, which contribute ghost images. All even-numbered reflections ghosts are superimposed on the primary image and will contribute spurious signals. Double-reflection ghosts will potentially contribute the largest signals. Higher order ghosts, [such as 4^{th} order ghosts from the refractive elements], have not considered yet, but are extremely unlikely to present a problem. The figure below shows these four elements for the case 4b design, along with a numbering scheme for each of the surfaces.



The double-reflection ghost path shown above is labeled as " 8 – 6 ", a reflection first from surface 8 and then from surface 6. Note that there are a total of 7 + 6 + … +1 or 28 possible double-reflection ghosts from the eight surfaces.

The ghost fluence, relative to the primary focused star image, can be calculated. Let D_g = diameter of the ghost and R_i = surface reflectivities. If one assumes that the star image has a diameter S, then the relative intensity of the ghost image is[See appendix]:

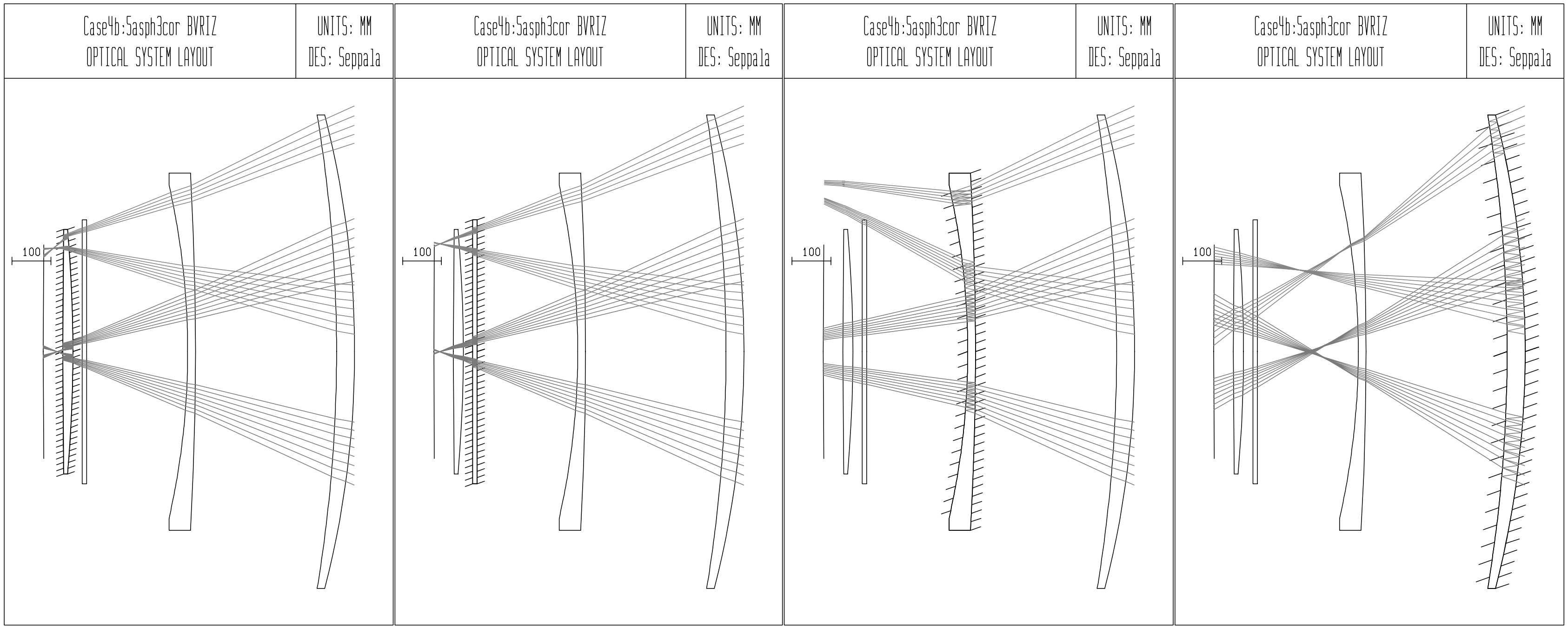
$$I_{i\text{-}j} = [\, S / D_{i\text{-}j} \,]^2 R_i \, R_j$$

This particular ghost, 8 – 6, has a diameter of 67 mm on the detector. For S = 0.02 mm (0.4 arc-sec image for a 10.5 m EFL telescope), $D_{8\text{-}6}$ = 67 mm and R = 2.0%, the relative fluence decrease is I = 3.6 $\times 10^{-11}$ or a difference of over 26 visual magnitudes.

Pages 3 to 10 show ray traces for ghost images, for on-axis and full-field object points (+/- 1.5 degrees). Note that a particular ghost can appear on the detector for field angles greater than 3 degrees (most ghosts) or less than 3.0 degrees (ghost 4 – 3). Page 3 shows the double reflection ghosts generated by surface reflections in each element, which are most of the brightest ghosts of the case 4b design. Pages 4 to 10 show sequentially almost every double reflection ghost. Since the filter is so thin, I have not included all ghosts [but I do include the most significant ghosts] for each of the two possible reflections involving the filter. Some ghost images exceed the diameter of the detector, and are totally negligible.

Page 11 gives a summary table showing eight of the most significant ghost images. A star image of 0.02 mm is the source of the ghost, probably the smallest achievable image point for the best seeing conditions. Reflectivities of 2% for lens surfaces and 1% for filter surfaces are assumed, reasonable values that may be achieved. In every case, the attenuation is at least $2.7x10^{10}$.

Page 12 is an appendix of miscellaneous calculations estimating if ghosts will be a problem. These calculations indicate that ghosting will rarely present a detectable signal since there are so few bright stars.

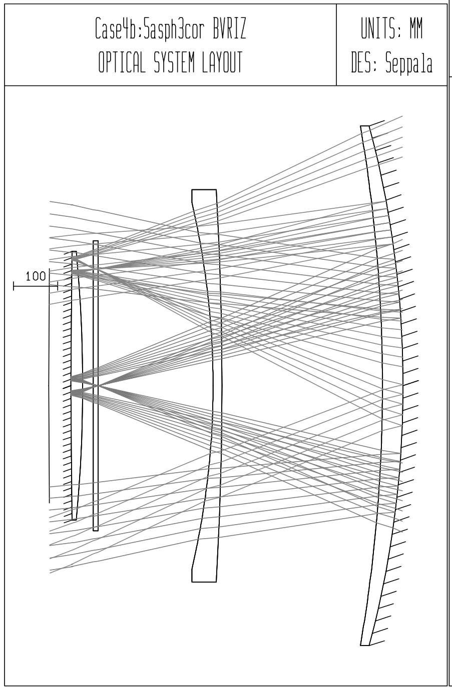


Double-reflection internal ghost of:

8 – 7	6 – 5	4 – 3	2 - 1
Last lens	Filter	Middle lens	First lens

Ghost diameter:

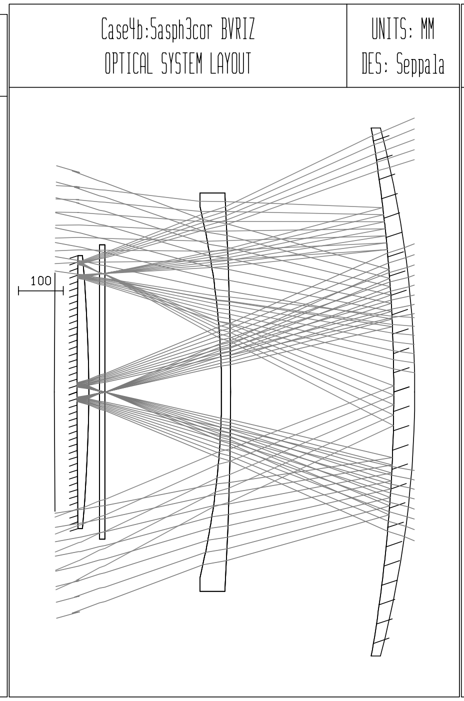
30.3 mm	12.2 mm	102.2	226.3



8 – 1

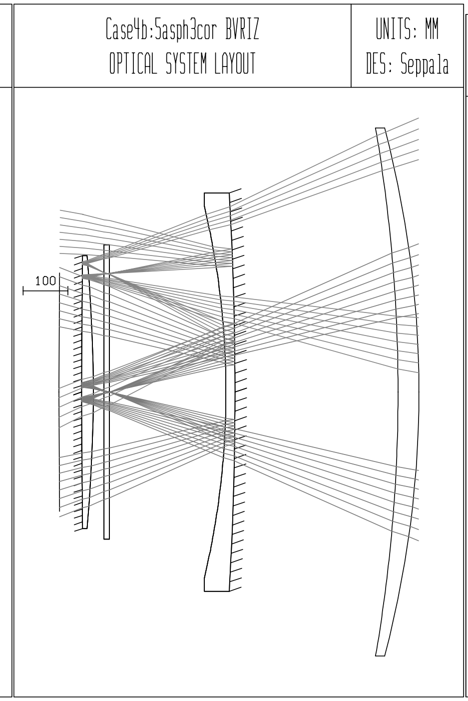
Ghost diameter:

832 mm



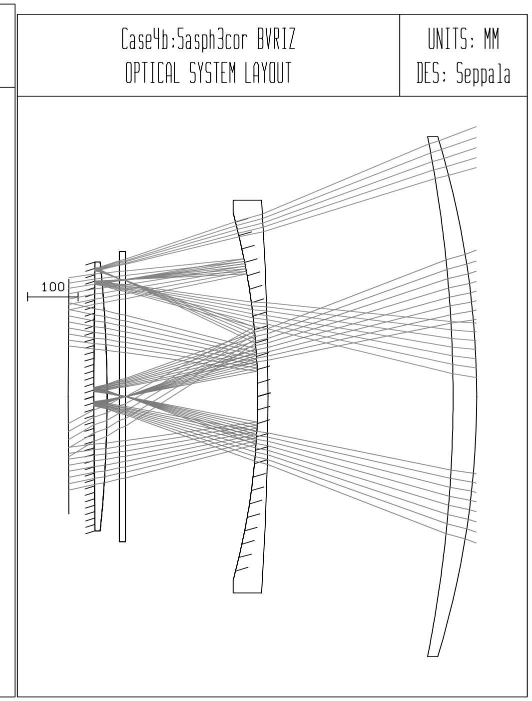
8 – 2

976 mm



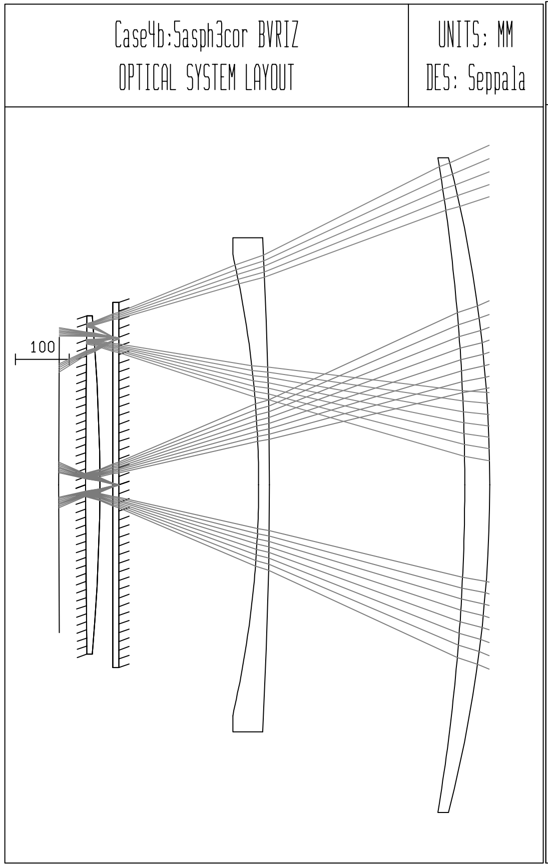
8 – 3

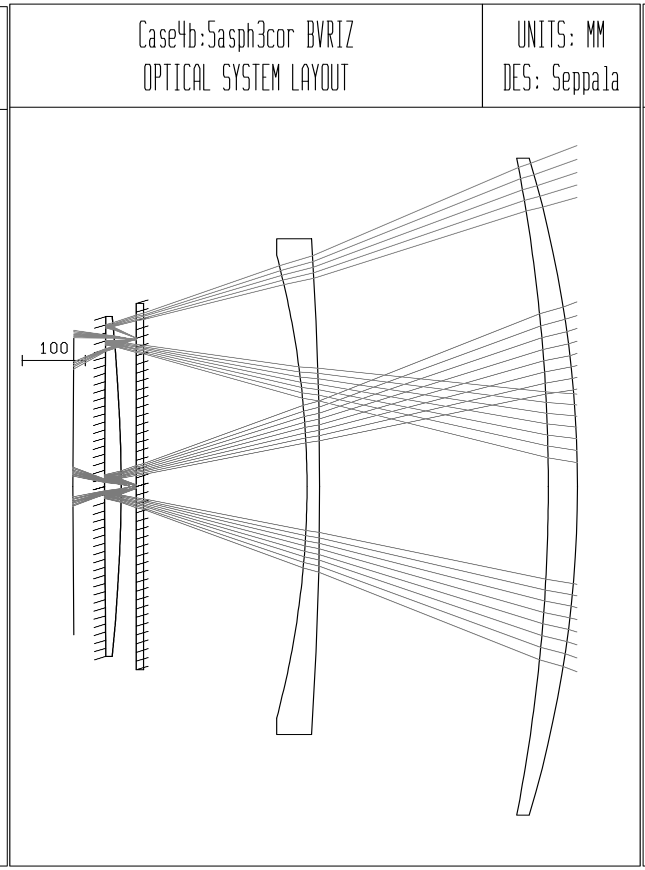
524 mm

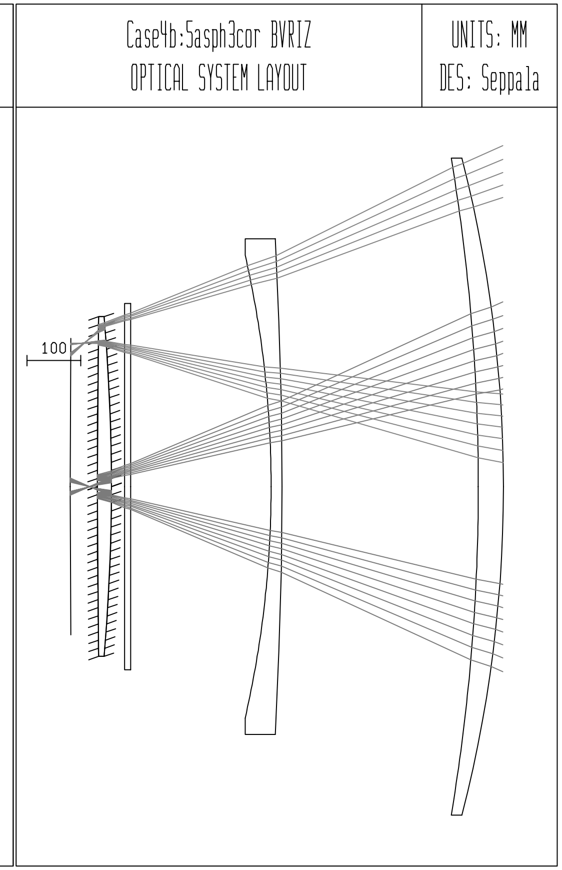


8 - 4

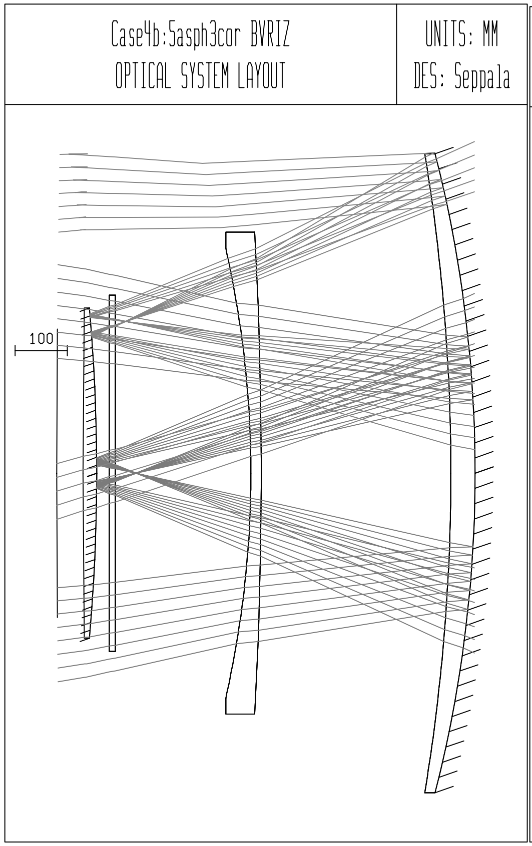
416 mm

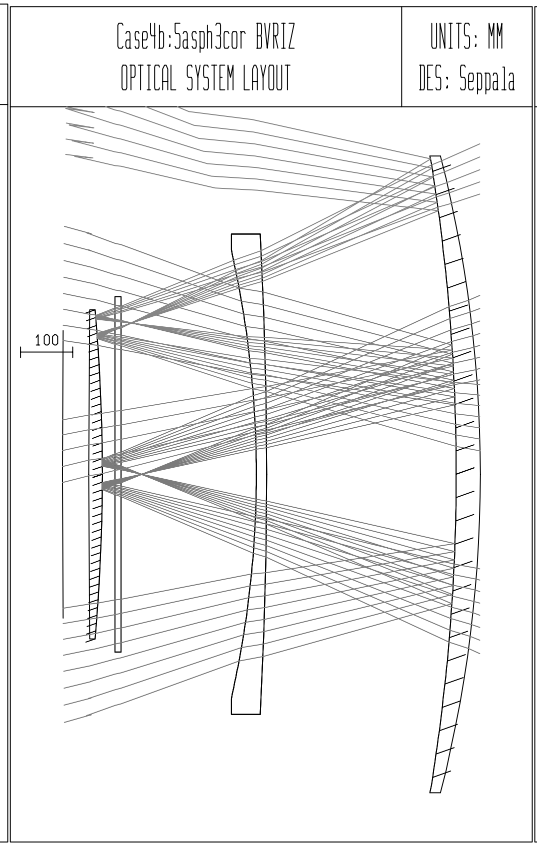


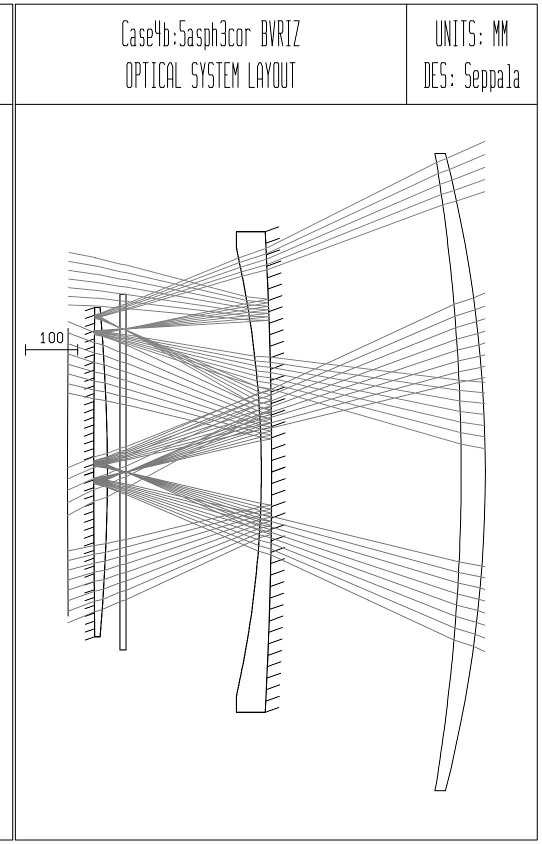




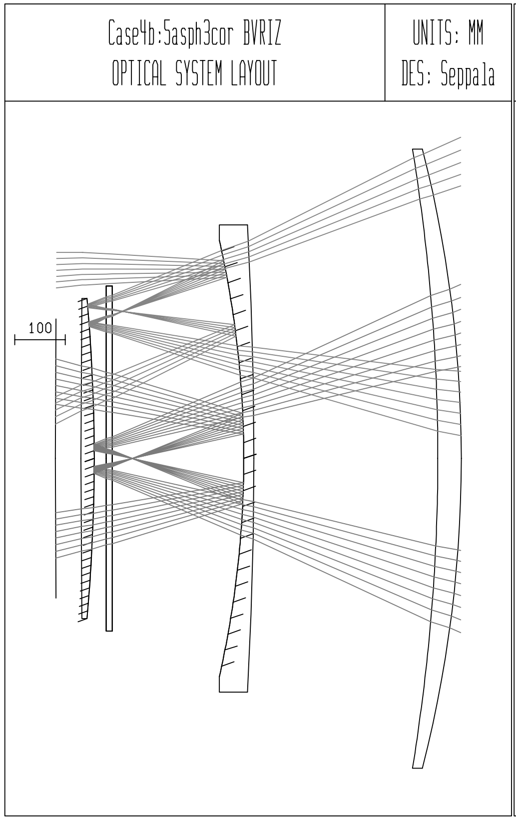
	8 – 5	8 – 6	8 – 7
Ghost diameter:	80 mm	67 mm	30.3 mm

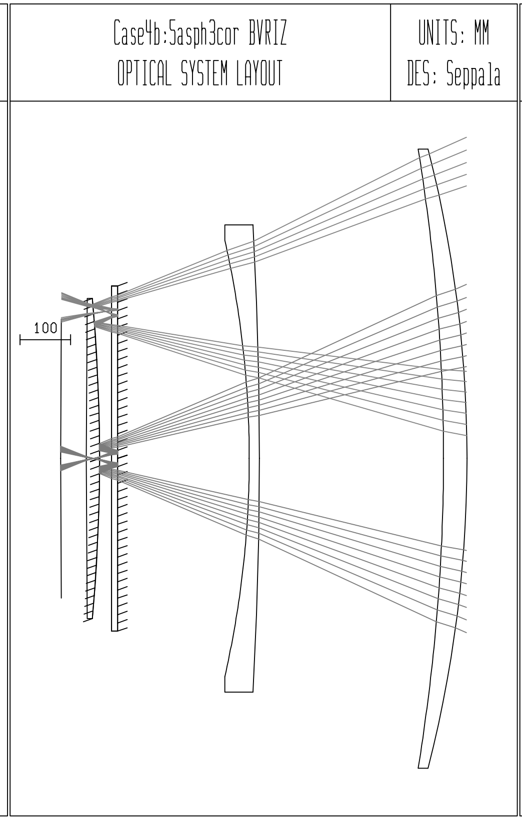


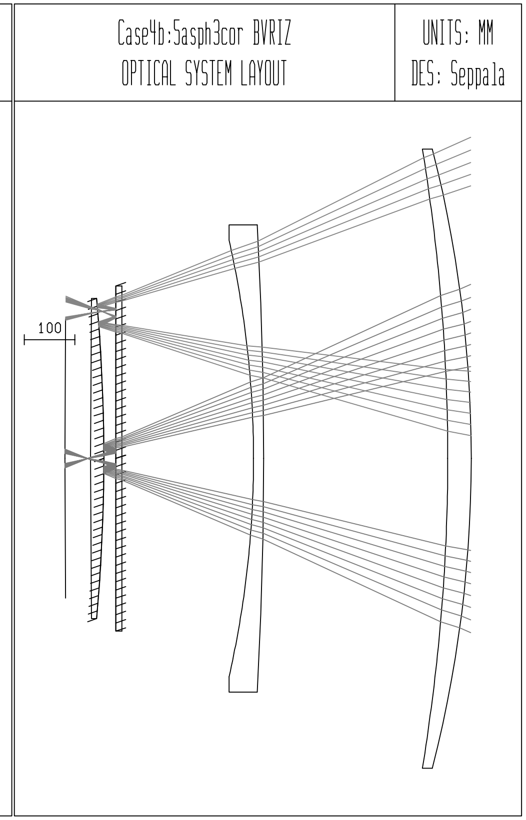




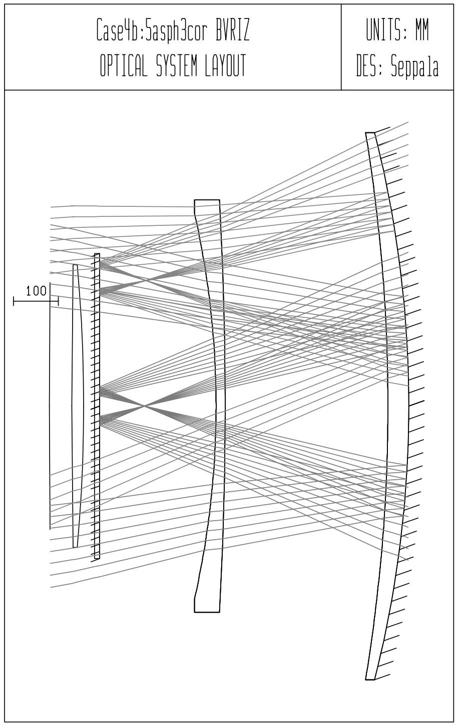
	7 – 1	7 – 2	7 – 3
Ghost diameter:	770 mm	894 mm	524 mm

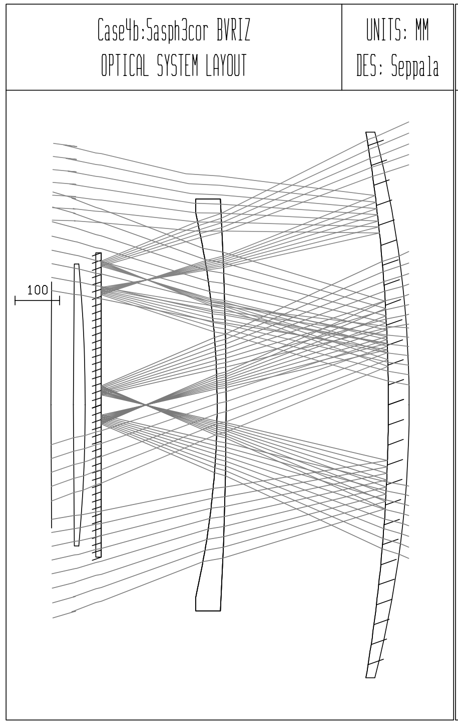


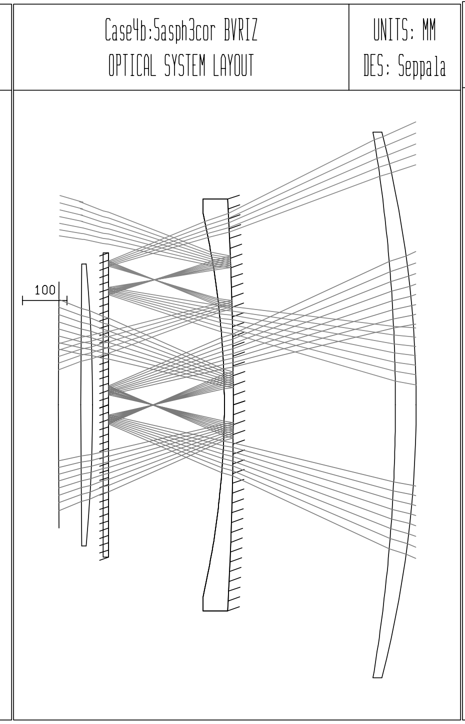


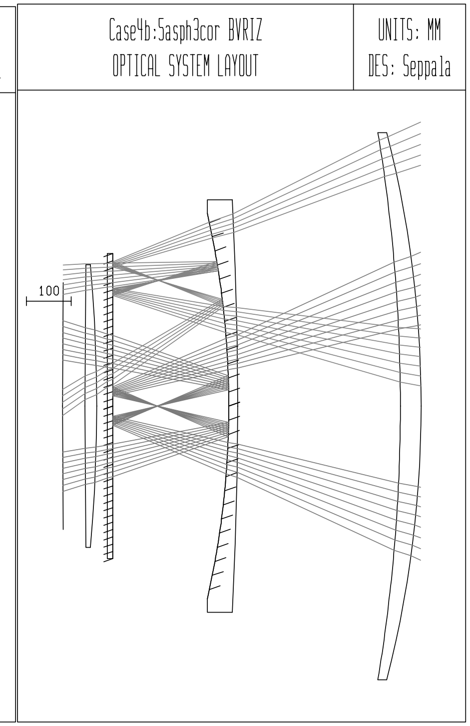


	7 – 4	7 – 5	7 – 6
Diameter:			
	375 mm	46 mm	34 mm

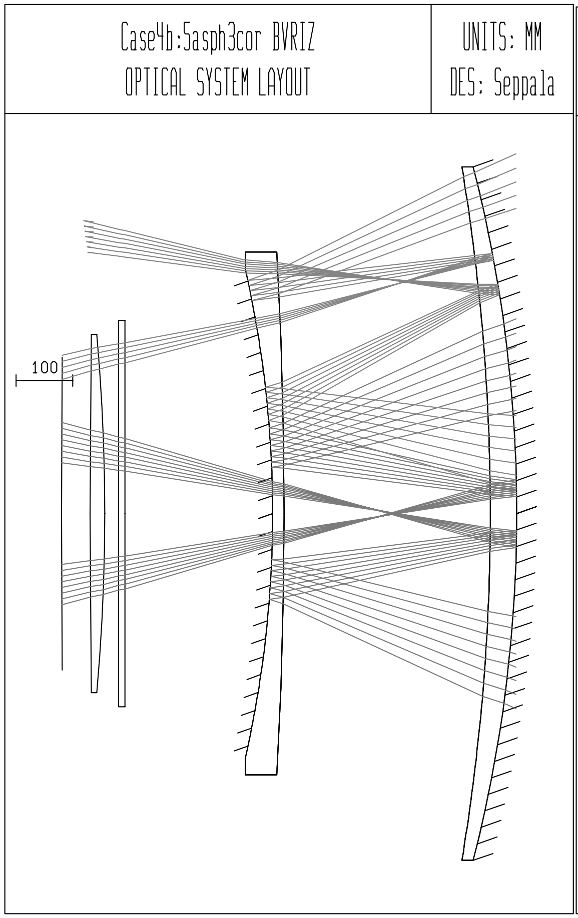


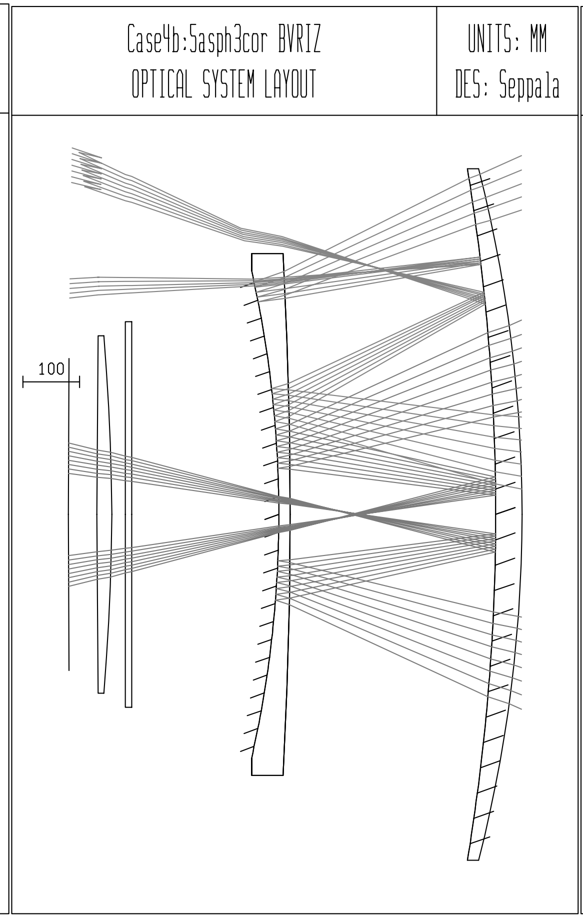


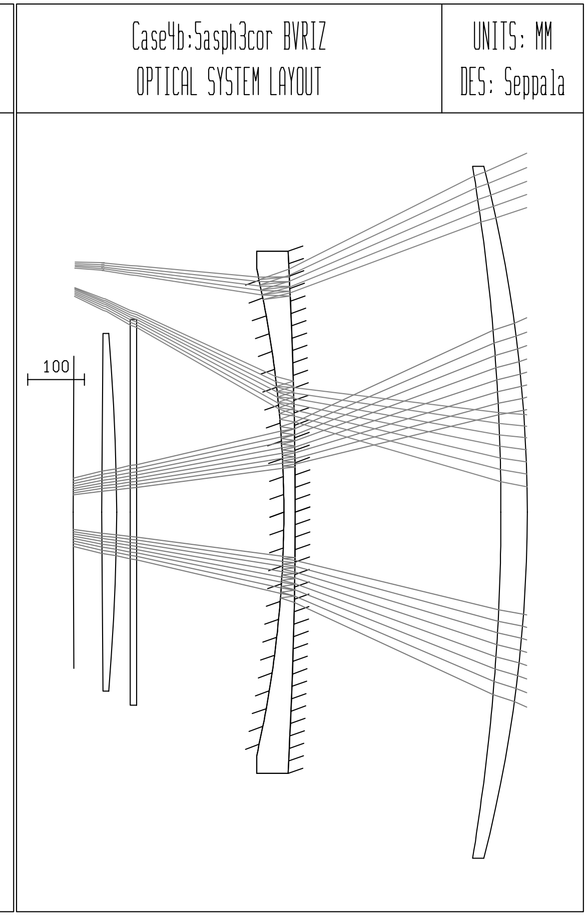




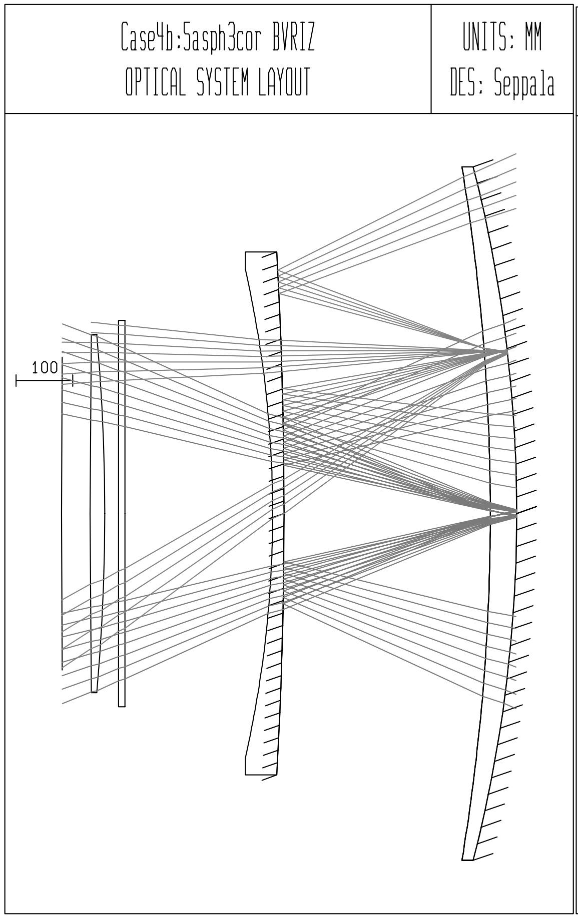
	5 – 1	5 – 2	5 – 3	5 – 4
Diameter:				
	780 mm	890 mm	430 mm	360 mm

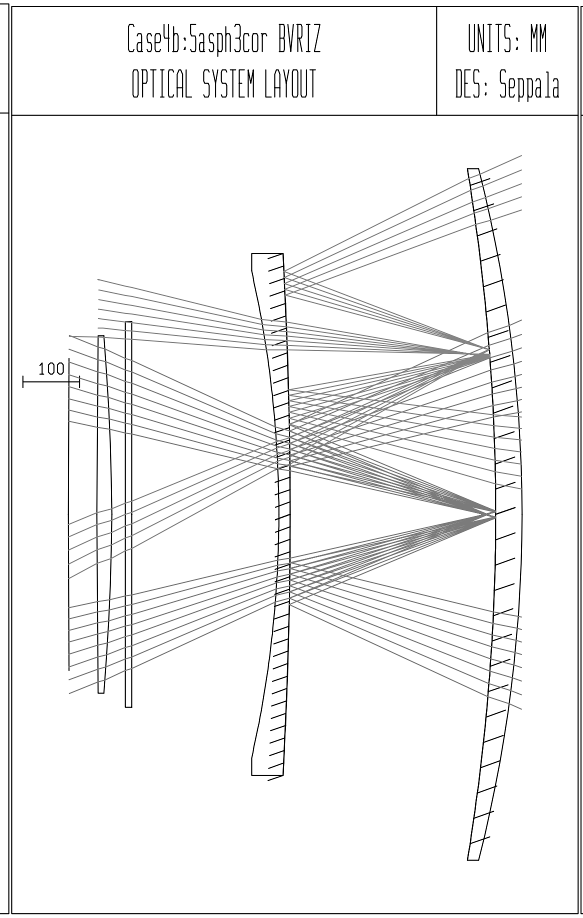


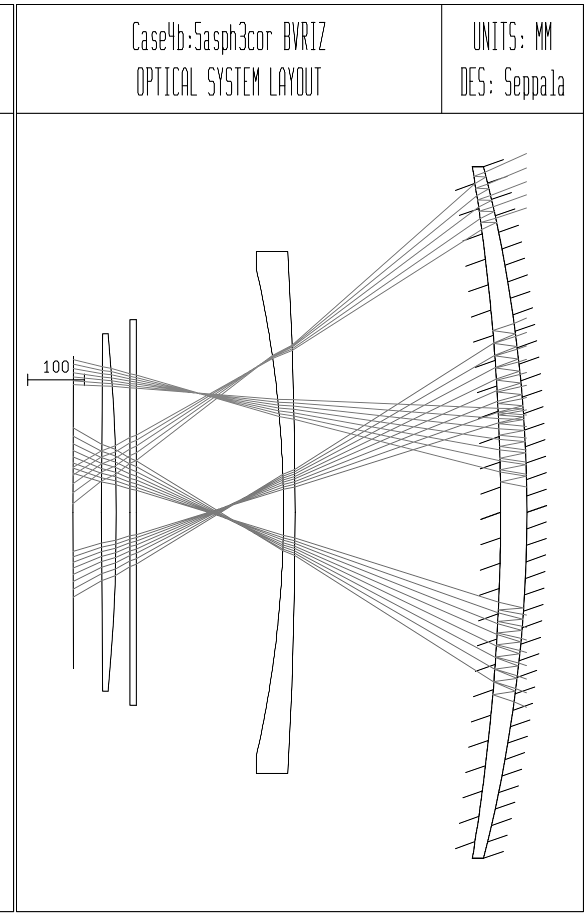




	4 – 1	4 – 2	4 – 3
Diameter:	320 mm	260 mm	102 mm







	3 – 1	3 – 2	2 – 1
Diameter:	606 mm	567 mm	226 mm

Table 1 shows the relative intensity of a ghost image, in terms of decreasing values of relative intensity. This table assumes that the source of the ghost is a uniform star image of 0.02 mm [0.4 arc-sec, EFL = 10.5 m telescope]. Note that all of the listed ghosts involve surfaces that are very close to each other. For this calculation, I assume that each lens surface has a 2% reflectivity, across the entire bandwidth. Since each filter covers on a small portion of the bandwidth, I assume that a 1% reflectivity can readily be achieved.

Relative ghost intensity, assuming a 20 μm star image, as the source

Ghost designation	Description	Diameter of ghost [mm]	First Reflectivity	Second reflectivity	Relative intensity
6 - 5	internal filter ghosts	12.2	0.01	0.01	2.7E-10
8 - 7	internal last lens	30.2	0.02	0.02	1.8E-10
7 - 6	last lens-filter	34	0.02	0.01	6.9E-11
7 - 5	last lens-filter	46	0.02	0.01	3.8E-11
8 - 6	last lens-filter	67	0.02	0.01	1.8E-11
8 - 5	last lens-filter	80	0.02	0.01	1.3E-11
4 - 3	internal middle lens	102	0.02	0.02	1.5E-11
2 - 1	internal first lens	226	0.02	0.02	3.1E-12

Table 1. Relative intensities of ghosts

No ghost, even the brightest, should be detected unless a very bright object is involved. If the source were VM of –1, then the first ghost would yield a signal of only 3% of a VM 24 star.

Optical coating reflectivities:

Table 2 lists the maximum angle of incidence on each surface, for the vignetted beam. The maximum angle of incidence of each surface varies from 26.4 to 20 degrees. Preliminary coating design studies indicate that it is possible to achieve less than 1% reflection over a 0 to 28 degree angle of incidence, for a 400-1000 nm bandwidth. Therefore, the reflectivities assumed in the table 1 are conservative. In fact, throughput considerations imply that one desires better reflectivities. Six surfaces with 98% transmission and two surfaces with 99% transmission give a throughput of 87%. A 1% coating for 8 surfaces gives a throughput of 92.3%.

Surface	Maximum angle of incidence	Surface	Maximum angle of incidence
S1	**18.2**	S5	**23.2**
S2	**20**	S6	**23.2**
S3	**24.3**	S7	**23.6**
S4	**24.1**	S8	**26.4**

Appendix: Visual Magnitude: [Whitney's Star Finder, pp64-68]

Each VM unit increase = 2.512x decrease in brightness
Five VM unit increase = 100x decrease in brightness
Count of stars brighter than given magnitude

Magnitude	# brighter than	Magnitude	# brighter than
-2	0	5	1,700
-1	1	6	4,900
0	4	7	14,000
1	16	10	350,000
2	45		
3	150	15	$3.7x10^{7}$
4	540	20	$1.2x10^{9}$

Field of view of LSST telescope = +/- 1.5 degrees
Solid angle of LSST telescope ~ = $2 \pi[\ \sin(1.5deg)]^2 = 0.00430$
Ratio of LSST telescope solid angle to full sky 4π steradians = 0.000342 = 1 / 2,924

Therefore, there is less than a 5% chance that a star with a VM of 3.0 will appear in a particular frame, 1.6% for a VM of 2, and 0.5% for a VM of 1.

The telescope is expected to detect a VM 24.0 star during a 20 second exposure. The difference between a VM of 4 and 24 is 10^{-8}, and the difference between a VM of -1 and 24 is 10^{-10}.

Ghosts will be a negligible problem provided that the ghost intensity from any bright star is reduced by 10^{10} or so.

Double-reflection ghost:

- area of image = $[\ \pi / 4\ ]\ [\ 0.020 \text{ mm }]^2$
- area of ghost = $[\ \pi / 4\ ]\ [\ D \text{ mm }]^2$
- reduction in fluence = $[\ R \times (0.02 \text{ mm} / D)\ ]^2$ where R = single surface reflectivity
  $10^{-4} = R \times (0.02\text{mm} / D)$ or
  D = 200R mm ; D = 2.0 mm for a single reflection of 1.0%
  D = 8.0 mm for a single reflection of 4.0%

Ghost problems are primarily avoided by ensuring that each ghost is sufficiently out-of-focus; reduced reflectivity can offer only minor improvements.