14. TELESCOPES

This last chapter is about real telescopes, as much as available information allows,and raytracing can show. They are divided in four groups: (1) early telescopes, from the time of Galileo up to the 19th century, (2) ATM telescopes, interesting designs built by amateurs, (3) commercial telescopes, those with a complete (rare), or partial specs, but sufficient to come up with a design substantially close to the real unit's, and (4) professional telescopes, those used on observatories and have their specs pulished.

14.1. EARLY TELESCOPES

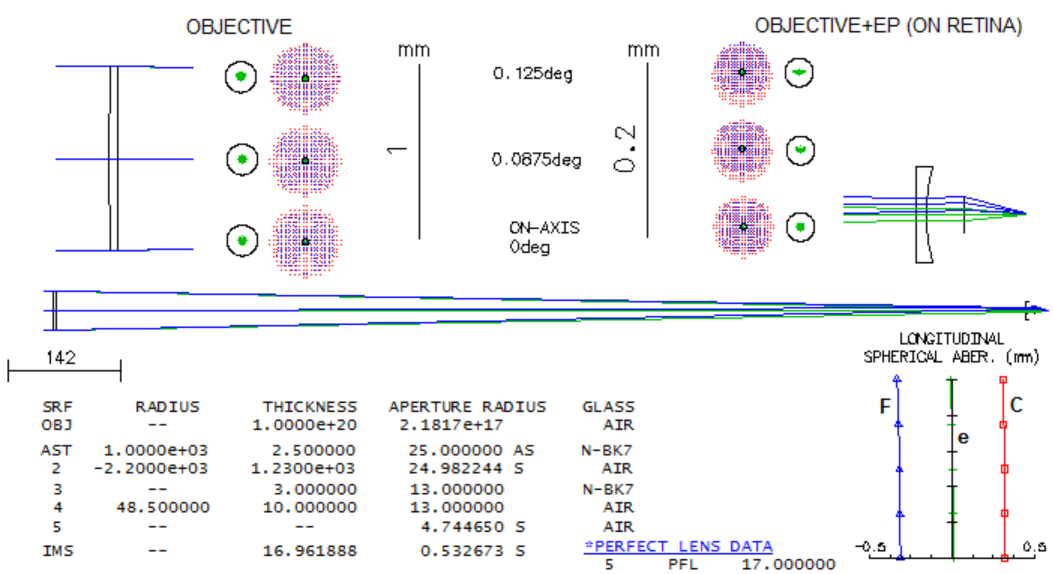
How would the earliest telescopes do in raytracing? Sure, we don't know the exact specs, but what we do know allows a reconstruction of their overall level of optical performance. How good was Galileo's big little refractor? Or Isaac Newton's reflector, Hevelius' 150-foot long singlet monster, Hershel's 40-foot big gun? Let's start from the beginning. Or, for that matter, "Elizabethan telescope"?

GALILEO'S REFRACTOR

According to the *Museo Galileo*, in possession of the original Galileo's telescope from ~1610 (Padua, Italy), it consists of a biconvex lens objective, 51mm in diameter and 2.5mm thick, with 1330mm focal length, and a plano-concave eyepiece lens, 26mm in diameter, 3mm thick, with -94mm focal length (concave side toward eye). The objective lens has unequal radii, but no specifics on which side is stronger (it makes little difference, since spherical aberrations of this small f/26 lens remains very low).

The numbers imply ~14x magnification, and the field of view is said to be about 15 arc minutes in diameter. It gathers about 50 times more light than the average eye. With this little instrument looking more like a long stick than a telescope - and a few others similar to it - Galileo revolutionized our view of the outer space: he found that the Milky Way is made of stars, that the Moon is a planet-like body, four heavenly bodies revolving around Jupiter, sunspots, phases of Venus, intriguing three-bodied aspect of Saturn...

Here's how it raytraces:



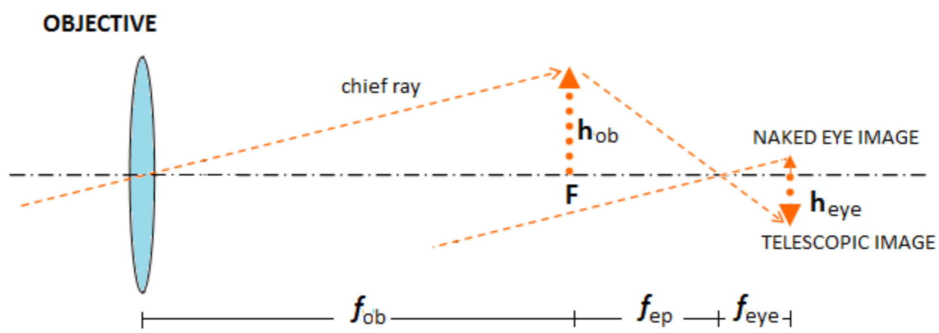
The only significant aberration of the objective is longitudinal chromatism, specifically, primary spectrum. With 3.2 waves P-V wavefront error of defocus in the blue F line (486nm), and 2.8 waves in the red C line (656nm), it is nearly twice as bad as an achromat having this much of an error in these two lines, or roughly 100mm f/2.5 at best (because secondary spectrum changes nearly quadratically, and the primary closer to linear, as illustrated on **FIG.**

68). However, due to much smaller aperture, it was less noticeable.

There is no mention of the objective being stopped down, as it is with another, smaller Galileo's scope in the possession of the museum (37mm objective diameter this time plano-convex - stopped down to 15mm, 930mm focal length, original eyepiece lost). But another source ("*The world's oldest surviving telescopes*", Bolt and Korey) states that the objective "stops down to 26mm". In fact, most telescopes from this era that still exist have their objectives significantly stopped down. Self-evident reason is the commonly poor polish on the outer lens area, but at least in some cases it could be to reduce chromatism as well. If stopped down to 26mm, this objective would have its chromatism cut in half, bringing it to the level of a 100mm f/5 achromat, or nearly so.

The "perfect lens" used to focus light exiting the eyepiece has focal length of 17mm, the approximate effective f.l. of the eye. It doesn't have significance other than it means that the Airy disc and the blurs size are equal to those actually forming on the retina. The lens radius of 4.7mm needed to fully absorb diverging light pencils for the 0.125° field radius at 10mm lens-to-eye distance means that even this narrow field was significantly vignetted toward the edge.

Note that the scale indicates the physical image over five times larger in the focal plane of objective, than on the retina. How is it that the final image appears 14x larger? The answer is that the image on the retina would have been 14x smaller without the telescope. Since eye effectively observes image by the objective from distance equaling the eyepiece focal length, it can be illustrated schematically omitting the eyepiece (shown is the standard, Keplerian scheme, but the same principle applies to the Galilean). From similar triangles, retinal



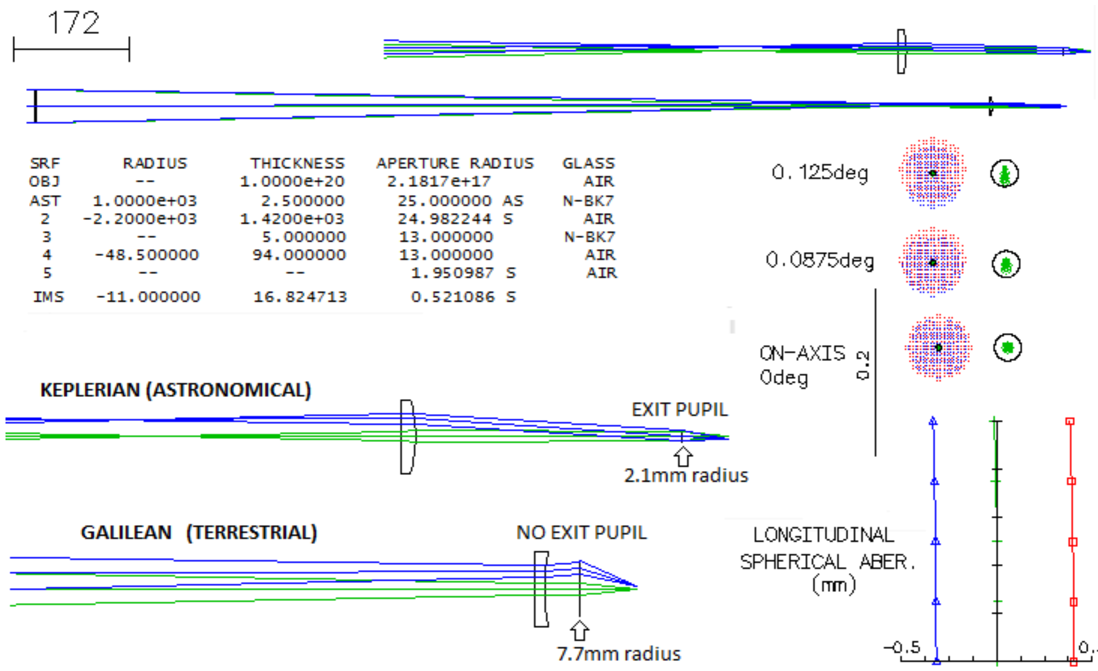
(telescopic) vs. objective's image physical size equals the proportion eyepiece's vs. eye's focal length. It is smaller, physically, than image in the focal plane of the objective when the eye's focal length is smaller than that of the eyepiece, but it is larger than the naked-eye image, by a factor $\mathbf{f}_{ob}/\mathbf{f}_{ep}$ - telescope magnification (valid for small angles, usually associated with the telescope image fields).

KEPLERIAN (ASTRONOMICAL) REFRACTOR

As the euphoria about the great new invention - Galilean refractor - started to grow, the seed of what will bring an end to it was already there. In his *Dioptrice*, published in 1611, Johannes Kepler mentions different instrument, using two convex lenses to form an inverted image, as a possible alternative to the just discovered Galilean refractor. However, the fact that it remained a mention, while he in the same publication gave a full analysis and optical explanation to the Galilean refractor, indicates that Kepler at that point in time wasn't aware of the crucial advantages of that alternative system. In fact, he never came up with such analysis. It took several decades before Manzini (*L'occhiale all'occhio*, 1660) and d'Orleans (*Dioptrique oculaire*, 1671) accomplished that; the former qualitatively, and the latter giving to it a complete optical analysis.

Due to such obscurity, what will become the "astronomical refractor" had very sporadic use for decades after the Dutch invention. On the other hand, potential for discovery of the Galilean refractor was exhausted already in 1611, with the only new discovery after that being Andromeda galaxy by Simon Marius in 1612. Main reason for it was the limit to field size in the Galilean (or terrestrial) refractor, ultimately setting the limit to magnification as well. In addition, being a system without exit pupil, Galilean refractor had no possibility for baffling the eyepiece, nor for optimal placement of observer's eye. As such, it was ultimately replaced by the "astronomical telescope" - the Keplerian refractor.

Here is raytracing example of it. To make the two directly comparable, will use objective and eyepiece of the same focal length as in the Galilean refractor above.



There is no appreciable difference between the two in the axial correction or chromatism. However, the geometry of imaging through the eyepiece clearly favors the Keplerian (for clarity, field angle for this illustration is doubled to 0.25 degrees). Not only that it converges all light pencils into an exit pupil, allowing the light of all field point to use the optimal, central portions of the cornea and eye lens, it also forms eye relief, for more comfortable eye placement. On the other hand, divergence of the field pencils caused by the negative eyepiece in the Galilean not only much larger eye pupil to pass them through without vignetting, the very divergence, by sending collimated pencils toward outer portions of eye's refractive surfaces at an angle, results in inferior imaging of these pencils by the eye. The former sets limit toward low magnifications, and the latter toward high magnifications, since the divergence increases inversely to the eyepiece focal length.

So, for two different reasons, eye has to be kept as close to the lens as possible, making observing uncomfortable even in the reduced range of magnifications. And eye strain directly diminishes its imaging quality.

The only disadvantage of the Keplerian was its inverted image, relatively unimportant for astronomical observing. It was simply more capable as an instrument, and the rest is history.

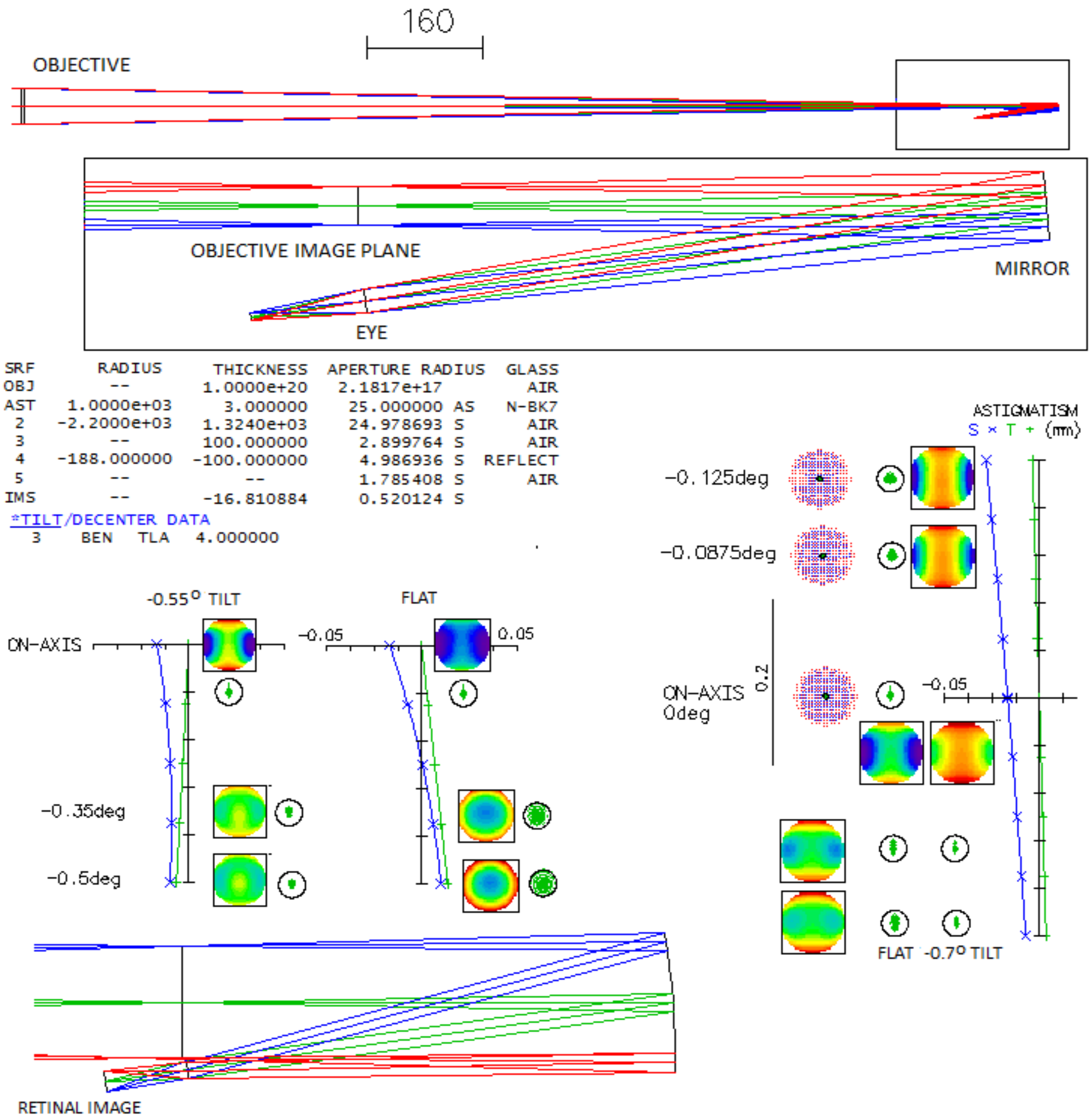
ELIZABETHAN TELESCOPE

During the 1990's, a few British authors (Ronan, Rienitz, Whitaker) tried to document the claim that telescope was invented in the 16th century Elizabethan England, decades before the Dutch invention in 1609. They based their case mainly on the writings of two 16th century English mathematicians, Thomas Digges and William Bourne. The two, however, never came up with a detailed description, drawing - let alone a prescription. They did have an idea of a telescope - or, generally, magnifying instrument - but lacked the knowledge to have it materialized. Bourne even sent a letter to Lord Burghley asking for patent of monopoly and patronage for his project, which was most likely left unanswered.

The idea was to use a convex lens objective and a concave mirror placed after its focus, so that the light reflected from it forms parallel pencils of light. The mirror would be tilted at a small angle, to allow observer to keep his head out of incoming light. But Bourne, who wrote about his idea much more extensively than Digges, had a faulty concept of magnification, thinking it is determined by lens' size, rather than focal length. That caused him to state that the objective has to be at least a foot in diameter. Singlet of that size would be pretty much useless in any practical length, due to chromatism, but appears that Bourne wasn't aware of it.

Anyway, the concept of using mirror for an eyepiece is valid, and interesting as well (so much so, that there is a "reconstruction" of the Elizabethan telescope in the *Louwman Collection of Historic Telescopes* in Hague; it is just a model, since with its 95 mm f/5 singlet objective and large mirror tilt wouldn't be able to produce usable image).

Here's how such telescope would raytrace. To make it comparable to the Galileo's and Keplerian telescope, will use identical objective and eyepiece (mirror) focal lengths (4th surface is "perfect lens" of 17mm focal length acting as a perfect eye). Surface 3 is dummy surface coinciding with the objective's focal plane, and showing image height in it. Chromatism plots, being practically identical to those of the other two, are omitted.



At 4-degree mirror tilt, the central spot has astigmatism that compares to a slightly less than 1/8 wave P-V of lower-order spherical aberration (bottom right). Field is slightly - less than 1 degree - tilted, so the best field error is slightly lower than the flat field shown (it should be within easy accommodation for most observers). As the graph shows, astigmatism is more than twice larger on the top vs. bottom of the field. Focus location is still too close to the incoming light, but at 6-degree mirror tilt axial astigmatism is already more than doubled (in proportion to the square of field angle). It could be diverted away from the incoming light with a small flat mirror. Since the mirror acts as an eyepiece, different magnifications would require mirrors of different focal length, with axial astigmatism increasing toward longer focal lengths (due to the larger footprint of the reflected beam). Similarly to lens eyepieces, that is offset by lower magnification.

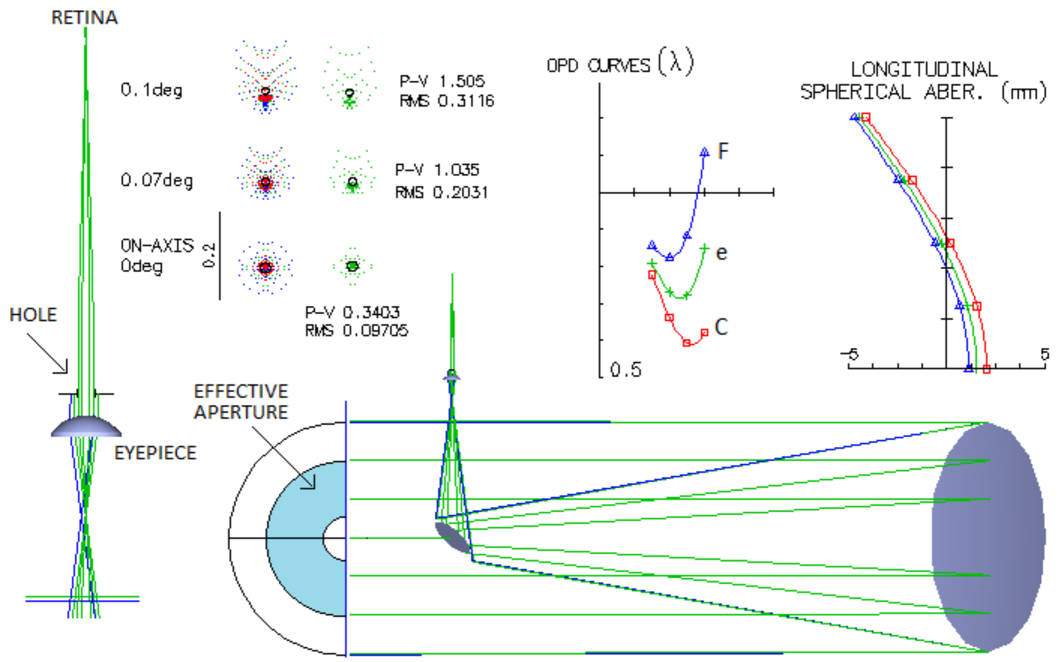
Extending field in the direction of diminishing asigmatism, the point of minimum error is found at about 0.5° off axis. Corrected for small image tilt there, correction is as good as 1/100 wave RMS. However, as the ray sequence shows (bottom left) observer's eye would be directly in the way of converging beam to that point. Still, some improvement in the field definition could be achieved with a relatively small shift to this direction.

Combination with a convex mirror inside the focus is also possible, but it would have the same negatives of the Galilean telescope.

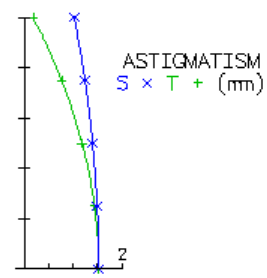
NEWTON'S REFLECTOR

In his "Optiks" (1704, London, Great Britain), Isaac Newton described his third telescope (1671/1672) as having the primary mirror two inches in diameter, with its surface conforming to a sphere of 25-inch diameter. The mirror, made by his "chamber fellow" John Wickins, was stopped down to 1.3" diameter at the surface, but the actual aperture was yet smaller, determined by (unspecified) hole in a diaphragm placed between the eyepiece and eye. The eyepiece was a plano-convex singlet, with the radius conforming to a sphere a bit smaller than 1/5 inch in diameter. It used a diagonal mirror at unspecified separation, but it is fairly certain that the final focus was very close to the tube wall.

That makes the whole primary an f/3.1, and f/4.8 when stopped down to 1.3 inches (probable reason for stopping down the mirror was to reduce unacceptably high spherical aberration - 1.5 wave P-V - while the hole on top of the eyepiece served to eliminate stray light). The final f-ratio was, according to the description, yet slower, but we'll assume not significantly. Here's what raytrace says about optical performance of this instrument:



SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS
OBJ	--	1.0000e+20	1.7453e+17	AIR
1	--	135.000000	25.235620 SX	AIR
AST	-330.000000	-135.000000	25.000000 AS	REFLECT
3	--	34.000000	4.781074 S	REFLECT
4	--	1.200000	2.000000	N-BK7
5	-2.500000	1.000000	2.000000	AIR
6	--	5.000000	0.963301 SX	AIR
7	--	5.000000	0.793435 S	AIR
IMS	-1.500000	10.850132	1.015234 S	

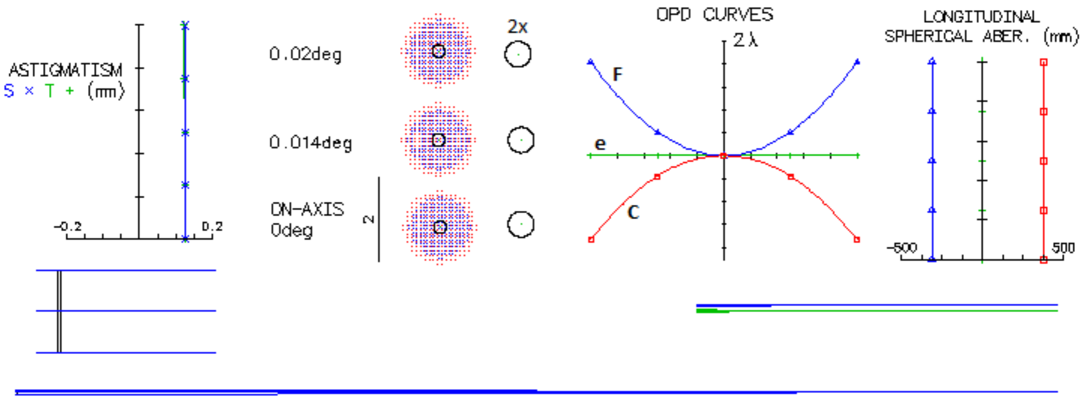


At the effective f/5, the system is slightly slower than in Newton's description. The actual stop is a hole above the eyepiece. The effective central obstruction is about D/3. The central line correction is at the level of 1/3 wave P-V of lower-order spherical aberration, about 3/4 of it coming from the mirror, rest from the eyepiece (reversed eyepiece generates four times more of spherical aberration, with the total error over 0.5 wave P-V). Field curvature seems unbelievably strong (ray spot plots are for -1.5mm curvature radius), but even on the flat field the error at 0.1° off axis - translates to 11° off axis apparent field - increases to only 0.37 wave RMS. Considering it's primary spectrum, chromatism of the eyepiece is not quite negligible, comparable to nearly 1/2 wave in F and C (averaged) with secondary spectrum.

This self-made instrument had ~35x magnification, and gathered 30 times more light than naked eye nominally; considering low speculum reflectance, however, it was only a dozen times brighter than naked eye, at best. Yet Newton could also see with it, among other things, the Galileo's Jovian moons and the crescent of the Venus. His British contemporaries, both scientists and nobles, were greatly impressed.

HEVELIUS' 45m TELESCOPE

Polish astronomer Johannes, or Jan Hevelius, the author of "Selenographia" (1647, Gdansk, Poland) and the man who named the famous variable star in the constellation of Cetus "Wonderful" ("Mira"), spent many nights observing without a telescope, making measurements with brass sextants while mapping the night sky. But he also built one of the most spectacular telescopes ever, a 45-meter long refractor, which he described and depicted in his "*Machina coelestis*" (1673). Its objective was a single plano-convex lens - customary in those times - of eight inch, or, 0.2m in diameter (~f/225). Long enough to eliminate chromatic aberration? Here's what raytrace says:



SRF	RADIUS	THICKNESS	APERTURE RADIUS	GLASS
OBJ	--	1.0000e+20	3.4907e+16	AIR
AST	2.3000e+04	11.000000	100.000000 AS	N-BK7
2	--	4.4000e+04	99.986193 S	AIR
IMS	-1.8000e+04	332.376408	15.477731 S	

Effective focal length: 4.4340e+04
Working F-number: 221.698726

The F and C lines average out at ~1.6 waves P-V, comparable to about 3 waves P-V with secondary spectrum. That is the level of a 100mm f/4 achromat. All other aberrations are entirely negligible. Same goes for eyepiece aberrations, even a plano-convex singlet. A relatively high 200x magnification would require a 222mm eyepiece f.l. which would need a 4-degree apparent field radius to cover the 0.02-degree (15.5mm) objective image radius.

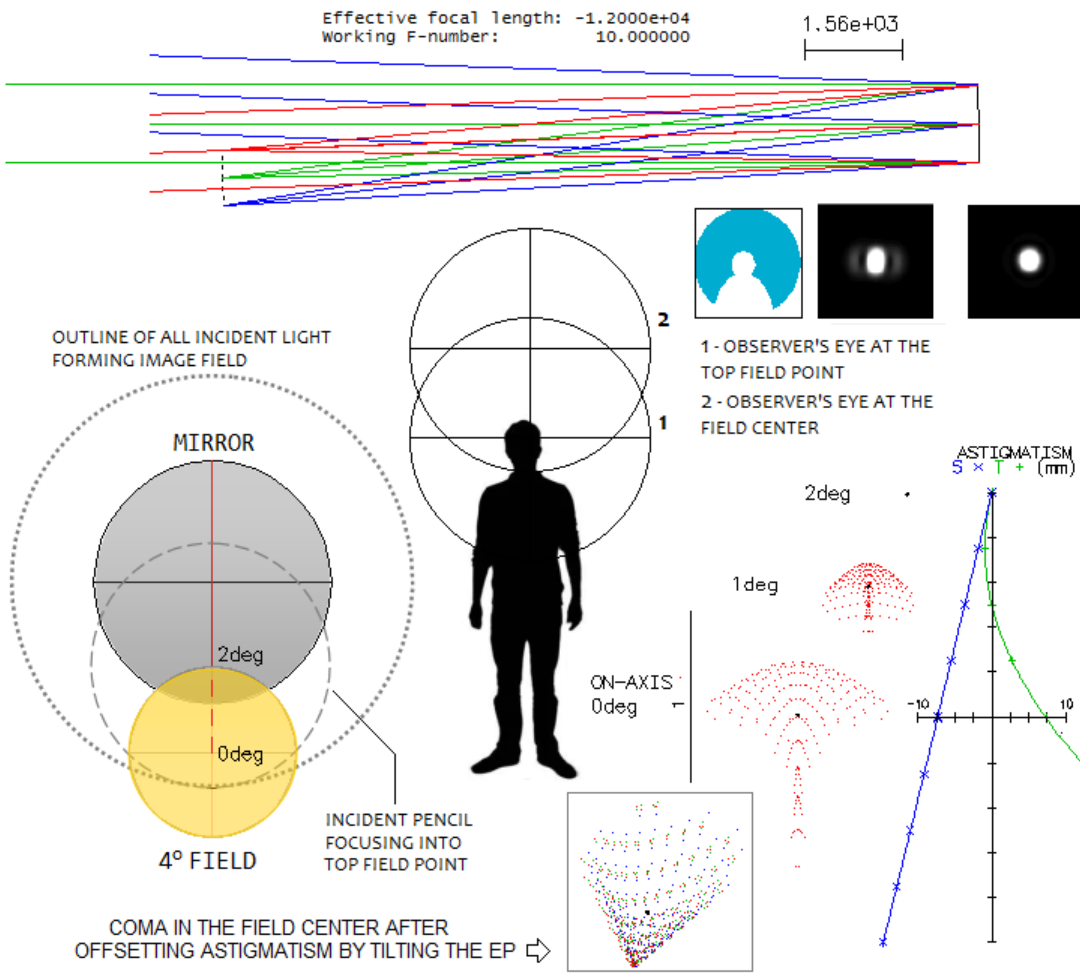
Others were using similar objective lenses, like Huygens in the Dutch Republic (for his "aerial telescopes"), and it is known that Newton had a lens of 8 inch aperture and 170 feet (nearly 52m) focal length, which he gave to the Royal Society in 1724. No doubt, the enormous light gathering power of these lenses for the time, with higher magnifications possible, was the main reason the astronomers went through the pains of building huge mounts to hold them, very awkward and limited in their motion range. At the time, due to the low reflectivity of speculum mirrors - a two mirror system, with obscuration, would transmit only about 1/3 of the incoming light - a comparable in light gathering power reflector would need to have over 0.5m in diameter.

HERSCHEL'S 40-foot REFLECTOR

Built in the late 1780s, Herschel's reflector was much shorter than Hevelius' refractor. But it used a 1-ton 48-inch (1.2m) diameter metal mirror, with reflectivity of about 66% (less in the blue, more in the red). While it also required massive mount, with observing platform on the side, it had much better stability and range of motion. To avoid further loss of light at the diagonal mirror, both due to transmission loses and obscuration, Herschel decided to tilt the mirror and observe its image at the side of the telescope's front end. That, of course, means that the image was significantly degraded by astigmatism and coma. How much?

In order to bring the final focus out of the incoming light, Herschel needed to have the axial ray reflected at 4°, i.e. to tilt the mirror by half as much, or 2°. That took the final focus nearly 9.5 inch out of the axial incoming pencil, but what tilt caused at the focus was horrendous, in the form of 36 waves P-V of astigmatism and coma in the field center. The asymmetric ray spot plot - and the diffraction image - are about 1mm large, which amounts to 17 arc seconds angular size.

Extending field radius toward incoming light shows diminishing error, but we need to go - expectedly - as much as 2° (over 0.4m) off to reach the point where coma and astigmatism disappear. Of course, that is the focal point of the 2° incoming pencil in the plane containing optical axis and field center. Rotating this field around mirror axis by 360° we can visualize the field at any point on the side of the mirror. Graph to the right of the ray spot plots shows how astigmatism explodes toward the farther half of the field (the astigmatic plot is for 1-degree tilted image field), hence we can concentrate on the half closer to the incoming light. The actual field that can be actually observed is only a small fraction of this expanded field: for a singlet eyepiece of 86mm focal length (140x), it corresponds to less than 10° apparent field radius, or 15mm (1/14 of a degree true field radius).



By tilting the eyepiece (double-convex singlet, as used by Herschel) astigmatism can be nearly cancelled out, but coma remains, in excess of 14 waves P-V. Also, lateral color quickly emerges away from field center, although it doesn't really matter considering the magnitude of coma. It is not possible to correct both, astigmatism and coma with this small singlet lens. While the coma blur is nearly as large as the original one - it is due to the corresponding blur size for given level of aberration being 2.5 times larger for coma - its effect is significantly smaller. Still, taking that some 80% of the energy is contained within the sagittal 1/3 of the coma blur, it comes to about 0.3mm, or 5 arc seconds in diameter - the level of a 22mm aperture.

What did Herschel do faced with the practically useless telescope at its intended focus? He could always stop down the aperture. In fact, at low magnifications - relatively speaking - it was unavoidably happening due to the eye pupil being smaller than the ep exit pupil. For the same 86mm eyepiece, the exit pupil was 8.6mm. If Herschel's night-time eye pupil was 6mm, it would effectively stop aperture by a 0.7 factor, reducing the center field error to some 15 waves P-V of astigmatism+coma. If he would then move 1° (little more than 8 inch) toward incoming light, it would be further reduced to less than 4 waves P-V, with his head only negligibly protruding into the incoming beam of the observed image. The aberrated blur would have been roughly ten times smaller, or some 1.7 arc seconds - not worse than the seeing blur most of the time (of course, it would make the combined blur nearly twice larger).

But at the smaller exit pupils, if he couldn't come up with some sort of sophisticated corrector, which we have no mention of, he could decide to stick his head - and possibly shoulders too - into the incoming light (it is known that early into using this telescope, Herschel would "hunt" good image holding eyepiece in his hand).

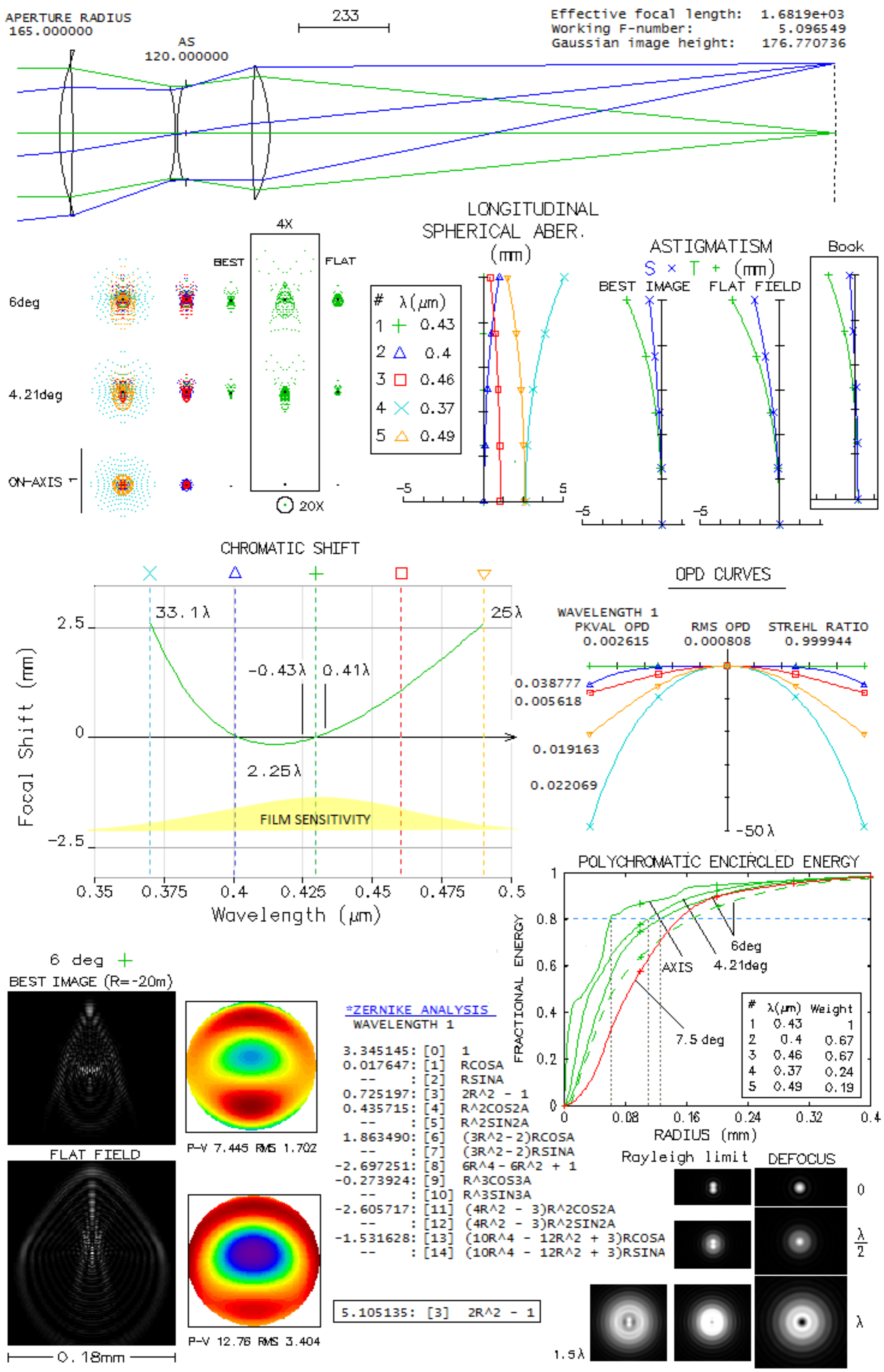
As gross as it seems, even observing at the point of best correction, with his entire head and a better part of his torso in the incident pencil of light, would still cost him only a half of the light he'd lose with a diagonal (even when observing at the original field center, his entire head would have been in the incoming 2° pencil, but would have been out of the incoming light for the observed field). And the diffraction effect due to the obscuration surely is not prohibitive. As the simulations show, it would somewhat deform and slightly tilt the central maxima, reshaping the first bright ring into two significantly brighter side lobes. Encircled energy wise, it would enlarge the 80% energy circle by 67% - comparable to the effect of D/3 linear central obstruction, **D** being the aperture diameter (of course, for that he wouldn't even need to tilt the primary).

Really minor compared to the magnitude of tilt aberrations, as well as other factors, like seeing, thermals and figure. We may never know how did Herschel actually use this telescope but, at least for now, can't exclude the possibility that, at high magnifications, his head was in the light he was looking at...

THE PLUTO TELESCOPE

Everything is relative, so a telescope from the late 1920s - which is actually astrograph - is an early bird when it comes to what has become the mainstay of professional astronomy: astrophotography or, nowadays, astronomical imaging. In its basic form, it is a 300mm f/5 Cook triplet, consisting of a three widely separated singlets (BAK1/F2/BAK1). Optical prescription is given in a book "*Telescopes, eyepieces, astrographs*" by Smith/Ceragioli/Berry (p407). Looking at its ray trace spot plots below, one would think it is pretty much useless - at least by today's standards - but it is the instrument used in the 1930. discovery of Pluto by Clyde Tombaugh (Lowell Observatory, Flagstaff, Arizona).

The triplet produces nearly flat field, whose curvature becomes not negligible only due to the very wide 7.5-degree field radius (178mm). The optimal image curvature, according to OSLO, is somewhat more relaxed than the one given in the book (20m vs. 15m radius), and it does not find the 2.2 wave P-V center-field defocus toward the curved edges given in the book beneficial - to the contrary. Otherwise, the OSLO output is very similar to that given in the book, and adds the colored output for five different wavelengths, as well as diffraction-based information on point-image energy distribution. The field here is limited to 6° radius since due to vignetting at the front lens illumination already falls down to about 80% (the actual instrument was used with 7.5° field radius). It is the price to pay for placing aperture stop just behind the middle lens, which reduces magnitude of off axis aberrations.

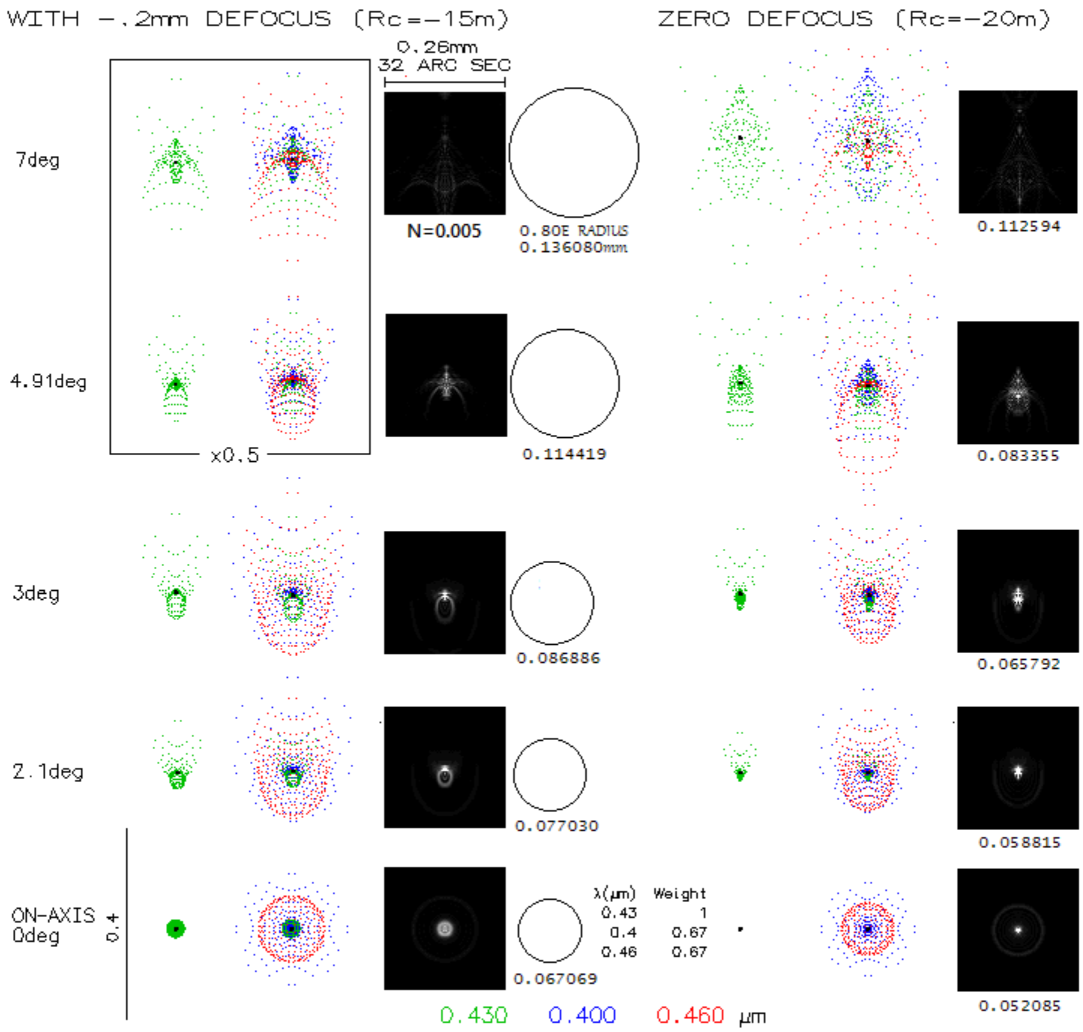


The ray spot plots tell immediately that chromatism significantly exceeds in magnitude monochromatic aberration across the entire image field (the little black dot is the 0.43μm wavelength Airy disc). The chromatic shift graph covers the 0.37-0.49 micron range with the photo emulsion sensitivity, normalized to 1 at 0.43μm wavelength, falling to about 0.2 at either end. Note that the graph shows defocus with respect to wavelength's paraxial foci, and differs from the respective total error at each wavelength, which can be either larger or smaller at the location of best focus, depending on the sign and magnitude of spherical aberration (longitudinal aberration graph indicates the total error larger at the shorter, and smaller at the longer wavelengths). The actual errors on axis are shown on the OPD (wavefront optical path difference) graph, where it reaches about 7 waves P-V (averaged) already at 0.4μm and 0.46μ wavelength). This excessive longitudinal chromatism makes mandatory filtering out all wavelengths outside this range, and probably some inside it as well (diffraction simulations bottom righ show the effect of defocus on double star resolution). Lateral color is negligible vs. blur size.

In the optimized 0.43 μm wavelength, there is no aberrations to speak of on axis; at 6° off, diffraction image (bottom left) is somewhat elongated, approximately 0.07x0.15mm, with much smaller brightest central area. With 1680mm focal length, this corresponds to 8.5x18.4 arc seconds. Looking at the 80% encircled energy radius, it is 0.126mm, 0.11mm and 6.2mm (14.5, 13.5 and 7.6 arc seconds) for 6°, 4.2° and 0° field radius, respectively (for the five wavelengths, with given sensitivity; somewhat rough number, but can be used as an indicator of the actual energy spread). The dashed plot represents the defocused, somewhat more strongly curved field as given with the original prescription; shown is for 6° field radius, with the similar difference vs. best field in OSLO at 4.2°. Evidently, for better resolution a further spectral range narrowing is needed, but it would mainly be effective toward field center.

Best field does not fall into the astigmatic field shown, because the graph shows only primary and the conventional secondary astigmatism, and not the effect of odd higher order aberrations present, which change the best image location. Zernike terms for the optimized wavelength at 6° (best image field) indicate that the dominant terms are primary spherical aberration (#8) and secondary astigmatism (#11), followed by primary (#6) and secondary coma (#13). However, since any spherical aberration is practically non-exsistent on axis, the primary spherical term can only be lateral spherical aberration (one of the secondary Schwarzschild aberrations), which has identical form but increasing with the square of field height. Similarly, the primary coma and astigmatism (to some extent) terms are actually lateral coma, of the same form like primary coma but increasing with the cube of field radius, and lateral astigmatism, of the same form as primary astigmatism but increasing with the 4th power of the field height. Zernike terms are nearly identical for the flat field, except that the dominant term becomes defocus (#3, boxed). To illustrate the extent of higher-order aberrations here, just omitting the tertiary spherical aspheric (i.e. 8th order) term on the 4th surface would result in over two waves P-V of tertiary spherical on axis.

Below is shown the difference between the defocused mode, described in the book as the actual operating mode, and the one above, better according to OSLO. Best image surface in OSLO is initially determined based on the P-V/RMS wavefront values. They are not always reliable indicator with large errors, but this time they did correspond to image surface with nearly smallest spots, as well as the smallest encircled energy radii (for 80% EE). The output is limited to the three wavelenghts used in the book, with added diffraction simulations corresponding to the ray spot plots (normalized to 0.005 of the central diffraction intensity).



Both, ray spot plots and 80% encircled energy radius favor the focused image. The choice for defocused image was probably made based on the dense portion of ray spot plots becoming more even in size across the field, with a logical assumption that defocusing toward the curved edges will also decrease the error in the outer field. Neither one is correct, according to OSLO. The very low normalization value, needed to show at least a hint of the wide halo of energy spread around central diffraction maxima (mostly due to chromatism closer to axis, and due to both chromatism and off axis aberrations farther off) makes diffraction images somewhat deceiving, suggesting that most of the energy is in the bright central part. For instance, at 3° off axis with the defocused image, the central bright spot fits in about 1/6 of the 80% energy circle, and contains only about 25% of the energy (which is well over a magnitude loss, or effectively correponding to the twice slower photographic speed). At the 5-degree radius, images are noticeably larger, and at 7° they are roughly half arc minute in diameter.

It is interesting that simply by using SF2 instead of F2 for the middle element - with weaker aspherics, and somewhat stronger front radius to bring F and C best foci together - this objective becomes nearly as optimized for the yellow-green centered spectrum.