

## **Techniques of Designing Eyepieces using ®*ATMOS***

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## 1) Introduction:

Ray tracing eyepieces requires skills of the sort one must muster for tracing any design, but inventory and management skills must be incorporated to achieve good results. R. Kingslake's, *Lens Design Fundamentals* (Chap. 15, *Eyepiece Design*, pp335-345) is a good tutorial on the process and should be referenced by interested persons (other titles are H. Rutten and M. van Venrooij's *Telescope Optics*, Chap. 16, *Eyepieces for Telescopes*, pp157-191, and A. Conrady's *Applied Optics and Optical Design*, Chap. X, *Ordinary Eyepieces*, pp480-512, and Chap. XVIII, *Analytical Solutions for Simple Systems with Remote Stop*, pp760-777).

This paper isn't intended to be a primer on eyepiece design but rather a description of methods and techniques the author has learned and used while designing eyepieces, studying and deriving designs from those of historical note, and *hand optimizing* designs using *ATMOS* (<http://www.atmos-software.it/>) and other software packages. I have applied these methods and techniques using *ATMOS* and will assume the reader is handy with edition 7.2 or later.

## 2) Tools & Procedures:

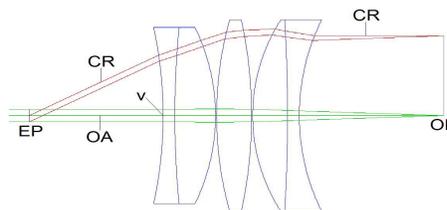


Fig. 2-1

### Determining the Pupil Distance:

Fig. 2-1 provides a designer's view of an eyepiece. The rays proceed from left to right as is the convention, but here the eyepiece is reversed because bundles of parallel rays cross at the eye point *EP* and are conveniently assumed to have encountered a stop. Of course *EP* has other names specific to its many functions, but I will refer to *EP* as the *eye point* and its diameter as the *Ramsden disk*. The other labels are, *OA*, the *optical axis*, *CR*, the *chief ray*, *v*, the *vertex* of first surface, and *OF*, the *objective focus* (where the "front focus" of the eyepiece is placed). The angle between the chief ray and the optical axis between *v* and *EP* is half the field angle of the eyepiece. The distance between *EP* and *v* is the *pupil distance*. Notice *CR* is parallel with *OA* on the right-hand side. Under this circumstance, distance *EP*-to-*v* equals the *bfl*, the *back focal length*.

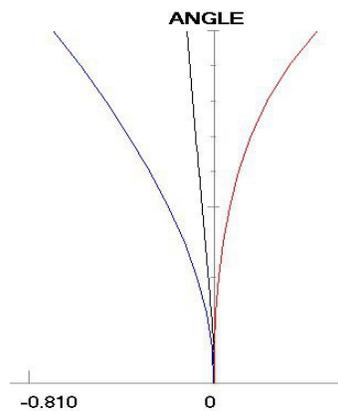
Later editions of *ATMOS* have features users of the software may not be familiar with that make eyepiece design easier. Two that should be known are the *2D* and the *Real Ray* windows. The *2D* (also called *2D-Layout*) window provides a 2-dimensional diagram of the optical (eyepiece) design, the lenses, the spacings, and the rays that proceed through, and the *Real Ray* window, a listing of the system ray-trace data for rays at chosen pupil coordinates. The *2D* window permits a "blow up" (*Zoom In*) of the region where the rays exit the design and converge to a focus at the appropriate height.

Why would one want to magnify this region? One will learn the pupil distance is correct when the chief ray is parallel with the optical axis on the right-hand side of the design, as is shown in *Fig. 2-1*. One may verify that the correct ray is the chief ray by noting that the chief ray intersects the optical axis precisely at *EP*. One may finger trace it over to the right side to determine whether it is parallel with the optical axis there. If it isn't then the pupil distance, *EP-to-v*, requires revision. While this is only a visual check, it is surprisingly accurate as can be seen by comparing the height of the chief ray as it exits the last lens surface with its height at the final focus. These values may be read directly from the *Real Ray* data sheet, assuming an input of zero for the *X* and *Y* entrance-ray coordinates on the sheet. Visualizing the parallelism of the chief ray with the optical axis is easily accomplished; one simply verifies the plotted line representing the ray contains no steps showing a presence in adjacent pixel rows (to an approximation).

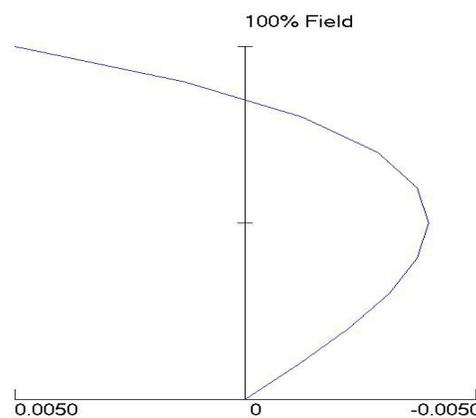
Using this method of determining the pupil distance is important; it eliminates reversing the design and doing trial *OF-to-EP* ray traces in order to calculate the pupil distance. The *EP-to-v* distance must be adjusted after alteration of design parameters to assure parallelism between the optical axis and the chief ray as final focus is approached. One thus learns to appreciate the freedom from having to reserve the design each time one must determine the resulting pupil distance.

Determining the pupil distance is part of a proper hand optimization procedure that includes, (1) altering chosen design parameters, including *EP-to-v* distance and glasses, based on review of various plots, graphs, and tables, (2) initiating design trace using the *OK* button, (3) checking for parallelism of the chief ray and the optical axis as the chief ray converges on the final focus, (4) repeating design trace with altered *EP-to-v* distance if step 3's parallelism condition was not met, (5) repeating step 4 as necessary to assure *CR* and *OA* are parallel as *CR* approaches final focus, (6) evaluating aberrations and parameters and deciding whether to repeat the process starting with step 1.

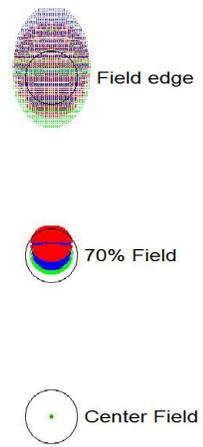
The "various plots, graphs, and tables" in *ATMOS* includes *2D* and *Real Ray* mentioned before, *Parx* (*Paraxial Analysis*), *Spherical Aberration + Coma*, *Field Curvature/Astigmatism*, *Multi Spot Diagram*, *Lateral Color*, and *Distortion*.



*Fig. 2-2*



*Fig. 2-3*



*Fig. 2-4*

### Reading the Plots:

The utilities of *2D* and *Real Ray* have been described. *Parx* (*Paraxial Analysis*) may be used as a quick method of determining which surface contributes the most to an aberration, and a careful analysis may permit the reduction of several aberrations. Trends in the changing coefficients in the *Seidel Coeff.* list may be determined with small “test” modifications to the curvatures of chosen surfaces. The aberrations listed are spherical, coma, tangential, distortion, and Petzval curvature (not the same as “best-fit” field curvature). Generally, only the first three are considered. At some point, one may prefer to reference the *Spherical Aberration + Coma* window and plots. All eyepieces suffer some degree of spherical aberration, but it isn’t usually a problem except for certain older designs such as the Huygens. As long as the *F/no.* the eyepiece is used with is reasonably slow, spherical aberration is usually ignored. For this reason, I prefer to compare eyepiece designs with a “set”, slow *F/no.* Still, one may prefer to monitor spherical aberration as the design proceeds, and I prefer to keep it as small as I reasonably can. Likewise, coma isn’t often a significant issue, but with some manipulation of curvatures, it may be reduced to near zero.

*Distortion* may be ignored for eyepieces with moderate fields, say, no more than 45° but designs with fields of 50° and higher should be checked. The magnitude of the distortion shouldn’t exceed 10%, but the eye can tolerate a bit more in observing.

Plots for *Field Curvature/Astigmatism*, *Lateral Color*, and *Multi Spot Diagram* require more involved discussion. *Fig.s* 2-2, 2-3, and 2-4 are provided.

*Fig. 2-2*, the plot for *Field Curvature/Astigmatism*, may be the most important plot one will access. The figure was taken from *ATMOS*, but the black curve representing the best-fit, field curvature was added. The curve falls per field angle halfway between the blue sagittal curve on the left and the red tangential curve on the right. The differing sweeps of the red and blue curves indicate the presence of astigmatism, and these curves may even switch sides depending on the design’s parameters.

The plot for *Lateral Color* is presented in *Fig. 2-3*. Lateral color, second in importance only to astigmatism, is chromatic aberration expressed per field angle (traditional, longitudinal chromatic aberration may be ignored for most designs as a check will show of the *Longitudinal, Spherical Aberration* plot for the limit wavelengths, usually the *C* and *F* lines, in the *Spherical Aberration + Coma* window). *Fig. 2-3* plots the angular difference (arc minutes) between the field rays of the limit wavelengths per %-field height. Notice the sweep of the curve in the plot essentially balances the plus and minus extensions on the horizontal axis, a desirable outcome. However, some designs permit a balancing with three rather than two.

Referencing *Fig. 2-4* was left to the last because understanding the figure and the content of the window, *Multi Spot Diagram*, will permit the designer to monitor the design’s behavior and will clue where to emphasize the changing of parameters. To be sure, one will consult the various tables and plots described previously, but at the very least, the *Multi Spot Diagram* can confirm the results of a successful design effort. The spot diagrams in *Fig. 2-4* are displayed vertically and labels were added to indicate the useful, field locations. The circles are *ATMOS* comparison devices indicating diameters of 0.025mm (25 microns). I prefer to compare eyepieces of the same, 25.4mm focal length working at *F/15*, and will rescale designs in progress to hold these parameters. These circles, for a focal length of 25.4mm, have angular diameters of (0.025mm)(360°)

$(60\text{min/deg}) \div (2\pi \cdot 25.4\text{mm}) = 3.4$  arc-minutes. The human eye has a resolution of 1 minute of arc at field center and 5 minutes of arc at its field edge (H. Rutten and M. van Venrooij, p166), so a comparison circle of 3.4 arc minutes works well over the field. One may choose instead a comparison circle diameter of 1 arc minute, which requires a focal length of 85.9mm, or one of 5min, requiring a 17.2mm focal length. The designer designs for the speed of the objective the eyepiece will likely accompany. I choose  $F/15$  because it is historically ubiquitous, but one should realize the spots will swell by the ratio of the design- $F/\text{no.} \div$  used- $F/\text{no.}$ . Thus, the diameter of a one-arc-minute spot at  $F/15$  will increase to 3 arc-minutes at  $F/5$ .

The spot array of *Fig. 2-4* occurs over a best-focus, field curve like that plotted in black in *Fig. 2-2*. Window *Field Curvature/Astigmatism* provides an *Average Field Radius* per field angle, and I prefer using the field radius for 70% of the full field angle. The *Multi Spot Diagram* contains an entry box at the lower left for the chosen *Field Curvature Radius*. One should care that the correct value *and* sign are entered. At mid-left is the *Show Scale* box from which the *Circle 25 micron* may be chosen. The *Zoom* is set with a value large enough to permit seeing the internal details of the spots, made with the tracing of a quantity of rays, *Rays per Color*, sufficient for generating those details (I usually choose 1300 or 2436). The colored *Wavelengths* boxes will offer as options the wavelengths chosen in the *Wave lengths Selection* at the upper right of the main page. For visual design, only the *C* (0.6563 microns), *e* (0.5461 microns), and *F* (0.4861 microns) lines need be used, and I prefer to match the wavelengths (entered from a pull-down menu) with their colors, so that the *C*-line is red, the *e*-line is green, and the *F*-line is blue. The top-down, green, blue, and red boxes in the *Multi Spot Diagram* window should be checked. *Update Multi-Spot* at the window bottom will plot the spots.

What do the spots in *Fig. 2-4* mean? Let's begin with the plot labeled "Center Field". The 3.4-arc-minute circle surrounds mostly empty space except for the smallest of spots at the center, which when closely inspected contains dark colors at the center of a slightly larger green spot. With an application of the *Zoom* function in the *Multi Spot Diagram* window, one would see blue and red spots at the center of a larger green. This spot is obviously much smaller than one arc minute in the three design colors, and we can say the longitudinal aberrations, spherical and chromatic, are very well corrected.

At *%70 Field*, the diameters of the spots have expanded to nearly fill the 3.4-arc-minute circle. That the spots are symmetrical in X and Y indicates the absence of coma, which would present an asymmetrical spot on the Y-axis. The ovalish spots are swollen, which indicates the presence of astigmatism given the proximity of this spot virtually on the field curve. Note the vertical shift in the colored ovals with green at bottom, blue at middle, and red at top. This is the manifestation of lateral color, but at reaching of the *Field Edge* plot, we see the order has changed so the red spot is lower than the blue. The negative extent of the blue with respect to the red in *Fig. 2-3* would indicate a lower height for the blue whereas a positive extension would indicate the red having the lower height. At the *Field Edge*, the blur has increased to a bit more than 5 arc minutes in the horizontal and 7 arc minutes in the vertical.

So much about the performance of a design may be determined by carefully reviewing the spot array, which will permit providing the reader with performance details without having to review countless graphs. However, one *will* need the radius of the best-fit, field curvature provided in the *Field Curvature/Astigmatism* window.

## Applying the Results;

Assume we have completed a design and wish to make application of it, but we realize there can be many manifestations of the *recipe* design. We have designed our eyepiece without accounting for the role of the objective, and we have made no effort to accommodate the eye, so these become first responsibilities. Some simple mathematics will assist, and we will determine whether and when scaling is a reasonable thing to do. We'll also look at spherical aberration of the exit pupil.

### ***Pupil Distance when the Eyepiece is in the Telescope:***

When an objective is present at its proper location in the optical system, the *Ramsden disk* the eyepiece generates is the image of the objective. As a result, the pupil distance lengthens and is modestly longer than the back focal length, *bfl*:

$$EP\text{-to-}v = bfl + f_e^2/f_o, \quad (1)$$

where  $f_e$  = eyepiece focal length and  $f_o$  = objective focal length (*Amateur Telescope Making, Book III*, Scientific American, 1953, p 488). As an example, assume  $f_o = 2286\text{mm}$  for an F/15, 152.4mm-aperture objective. With  $f_e = 25.4\text{mm}$ ,  $f_e^2/f_o = 0.28\text{mm}$ , a small amount to be added to the *bfl*. One will likely find the spots will remain essentially unchanged when *EP-to- $v$*  is increased by this amount. Still, as  $f_o$  decreases and/or  $f_e$  increases, the significance of the calculation increases. Here's another utility, consider the  $f_e^2/f_o$  term. The magnification of the telescope-eyepiece system is  $m = f_o/f_e$ . Thus, a convenient form for the term is  $f_e^2/f_o = f_e/m$ , which for the example is  $25.4\text{mm}/90$ . Were the example in units of inches, the result would be even simpler,  $f_e/m = 1/90$ .

### ***Considering the Eye's Accommodation:***

Most of the readers of this on-line magazine will be familiar with the relation between the focal length of a "simple" lens and the distance conjugates it influences (*Optics*, 2<sup>nd</sup> ed., M. Klein & T. Furtak, J. Wiley & Sons, 1986, p166):

$$1/d_i + 1/d_o = 1/f \quad (2)$$

where  $d_o$  is object distance ( $S^*$  in M. Klein & T. Furtak),  $d_i$  is image distance ( $S$  in M. Klein & T. Furtak), and  $f$  is the focal length of the simple lens. Then,

$$1/f - 1/d_i = 1/d_o \rightarrow d_o = d_i f \div (d_i - f). \quad (3)$$

Written in terms of diopters,

$$1/D_o = (d_o/1000\text{mm}) = d_i f \div [1000\text{mm}(d_i - f)]. \quad (4)$$

Define  $\Delta$  as the longitudinal difference between the best-fit, field curvature at field center versus field edge (ref. *Fig. 2-2*), and let  $d_i = f + \Delta$ . Substituting,

$$D_o = 1000\Delta \div [f(f + \Delta)]. \quad (5)$$

$\Delta$  may be determined directly from the *ATMOS* window, *Field Curvature/Astigmatism*. The window lists under the headings, *Z-sagittal* and *Z-tangential*, the longitudinal distances from the sagittal (blue) and tangential (red) curves to the y-axis. The z-axis coordinates of the not-plotted, best-fit, field curves may be determined from these. If the blue and red curves fall on the same side of the y-axis, one merely needs to average the z-coordinates (retaining the sign) for the half-field angle desired on the y-axis. Most likely, one will want to work with the maximum half-field angle (the specified half-angle in the box in the lower, right-hand corner of the main page). If the red and blue curves fall on opposite sides of the y-axis, one can add the z-coordinates for the chosen half-field angle (ignoring the signs), halve the results, then add the z-coordinate for the curve on the negative side of the y-axis (alternatively, one could subtract the z-coordinate for the curve on the positive side of the y-axis, but don't forget to change the sign of the result).  $\Delta$  equals this signed value. If the result is negative, the best-fit field curve will curve left and up, and if positive, it will curve right and up. When  $\Delta > 0$ ,  $D_o > 0$ , and when  $\Delta < 0$ ,  $D_o < 0$ . Of course when  $\Delta = 0$ ,  $D_o = 0$ .

While an eyepiece is not a simple lens, *Eq. (5)* provides a reasonable estimate (*Eyepieces, Telescope Making # 25*, R. Buchroeder, p26) short of doing a full analysis of the problem of accommodating the eye. The equation is identical except that  $f = f_e$ :

$$D_o = 1000\Delta \div [f_e (f_e + \Delta)]. \quad (6)$$

The values of  $D_o$  that are “eye-friendly” are somewhat limited. In general,  $-1 < D_o \leq 0$  (H. Rutten & M. van Venrooij, p162), but the magnitude of the negative values should be kept as small as possible (R. Kingslake, p 340).

A best-fit, field curvature plot that is convex to the right, like that in *Fig. 2-2*, will have an accommodation value of  $D_o < 0$ . It will also present convex to the eye, a situation difficult and tiresome for the observer, especially as the magnitude of  $D_o$  increases. Therefore, best-fit, field-curve plots that remain for all values of z to the left of the y-axis should be checked for the design's accommodation value,  $D_o$ , and the design revised if necessary. Nevertheless, the astigmatic curves of a number of published, eyepiece designs have best-fit, field curvatures with modest, negative values. These are likely examples specifically matched to their objectives or to other optics.

### **Scaling:**

There are incentives to upscale a mature, eyepiece design beyond the need to provide a more modest power with an instrument or to increase its field of view. Other reasons are to increase eye relief, to improve accommodation, or to increase the distance between the exterior face of the field lens to the objective's focus (to add a reticle, for example). Longitudinal and angular aberrations scale with the design, but their tolerances do not, so a design must be very well corrected to permit a scale up. Spot diagrams scale, but the reference circles available in the *Multi Spot Diagram* window (like the *Circle 25 micron I*

like to use), squares, or whatever is used to gauge the spots do not. *Average Field Radius* (*Field Curvature/Astigmatism* window) scales, but the magnitude of the accommodation actually lessens! Assume  $f_e$  and  $\Delta$  are doubled, becoming  $2f_e$  and  $2\Delta$  respectively. Then per Eq. (6),  $D_o = 1000(2\Delta) \div [2f_e(2f_e + 2\Delta)] = 500\Delta \div [f_e(f_e + \Delta)]$ , one half the starting value. So an eyepiece having an accommodation of -1 achieves -1/2 on doubling its size.

***Detecting Spherical Aberration of the Exit Pupil:***

The *2D* window and the *Real Ray* data sheet can indicate whether a design suffers from *spherical aberration of the exit pupil*. In the upper left-hand corner of the *2D* window is a toggle box labeled *Field Angle*. By repeatedly clicking on the right-hand arrow button of the box, one can get the half-field angle to step through from maximum degrees to zero. As this is done, one will notice the ray path in the diagram shifting in height and general direction through the system. Assuming one has manipulated the design so that the exiting chief ray, *CR* (ref. Fig. 2-1), is parallel with the optical axis (*Determining the Pupil Distance*), in the absence of spherical aberration of the exit pupil, the chief ray will remain parallel with the optical axis as its height changes with field angle. Most eyepieces, however, contain some of the aberration but not in any quantity that the eye would notice (see *Telescope Making*, H. Rutten and M. van Venrooij, p176, for a description of how the aberration affects the observer). The angle between the chief ray and the optical axis remains small. If as the step through proceeds the chief ray-optical axis angle becomes large, spherical aberration of the exit pupil is a problem. Consider as an example, the *Nagler 1* (H. Rutten and M. van Venrooij, p169), fortunately in my *ATMOS* files and a design known to suffer from significant spherical aberration of the exit pupil. I measured the angle between the chief ray and the optical axis as I stepped through the half-field angle, 40° to 4°, in the *Field Angle* box. Here are the results:

Half-Field Angle	Angle between CR & Optical Axis
40°	0.0°
36°	4.1°
32°	6.6°
28°	8.1°
24°	8.6°
20°	8.1°
16°	7.3°
8°	4.0°
4°	2.4°

*Table 2-1*

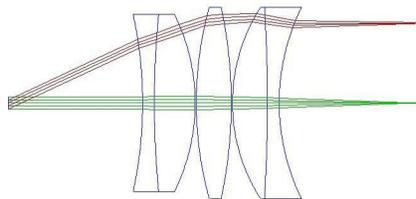
These angular deviations from the desired 0° are significant.

The *Real Ray* data sheet can provide the same information but in terms of the exiting ray heights. With a 0° angle between the exiting chief ray and the optical axis, the height of the chief ray leaving the last optical surface and its height at *Image* (same location as *OF*, Fig. 2-1) should be the same. Of course, there’s likely some deviation, but again, it shouldn’t be large. The *Real Ray* data sheet shows large differences for the chief-ray heights at the last optical surface and at *Image* for the *Nagler 1* for all half-field angles below the 40° listed in *Table 2-1*.

### 3) Example Designs:

Having collected many eyepiece designs through the decades from print, patent, and Internet sources, tinkering with them was probably inevitable. This was especially so after the advent of reasonably-priced software packages such as *ATMOS*. I have included from these four designs I've modified, in some cases extensively (and not necessarily the last time), using techniques like those I've described. The four I will discuss are the *Astroplanokular Aplanat*, the *Konig with Smyth Lens*, the *Airy 4-Lens*, and the *Warmisham 5-Lens*. Full-size diagrams and recipes follow. Seen here is a new term: *ffl* is the distance from the vertex of the last surface to the *objective focus*, *OF*.

#### A) Astroplanokular Aplanat:



Accommodation = -0.19 diopter, *ffl* 19.306mm, 25° half field

Surf	A.Stop	Half-Dia	Curv.Radius	Thickness	MEDIUM	Glass/Index
1	AS	.8465	0	17.9	AIR (Posit)	+ 1
2		11.75	-54.9976	1.565	SCHOTT	+ SF10
3		11.75	122.0835	5.443	SCHOTT	+ SK2
4		11.75	-26.4362	.15	AIR (Posit)	+ 1
5		12.75	47.5619	4.673	SCHOTT	+ SK7
6		12.75	-60.2638	.15	AIR (Posit)	+ 1
7		12.75	23.4307	4.673	SCHOTT	+ SK7
8		12.75	-201.6418	1.565	SCHOTT	+ SF10
9		12.75	28.6821	0	AIR (Posit)	+ 1

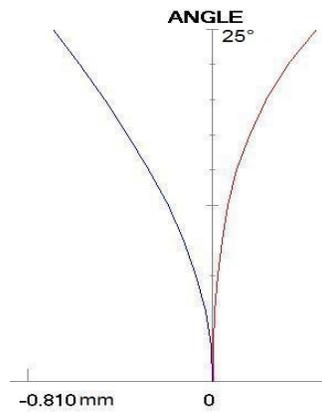
The *Astroplanokular* was developed by Zeiss in 1955 for astronomical applications. I scaled the 100mm focal-length design provided in *Telescope Making 19*, p35 (*Six Eyepieces Compared*, H. Rutten and M. van Venrooij), to 25.4 mm focal length in preparation for optimizing. Residual coma and field curvature were present in the original design (perhaps necessary in the specific application), but I desired the full correction of coma and the minimization of field curvature. The latter would likely result in increasing the astigmatism, but a blur with angular diameter of no more than five minutes of arc near the field edge would be acceptable. All other aberrations were to remain as well corrected as in the original out to the field edge.

Since I had resolved not to change the glasses, the component locations, or the doublet-singlet-doublet configuration, I had only the manipulation of the powers and curves of the lenses as tools. Mapping the system's response to modest changes in the curvatures of the three components would provide valuable guidance, the Seidel

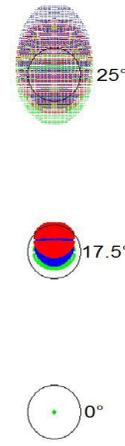
coefficients in the *ATMOS* window *Parx* proving convenient for this effort. The original design's coma coefficients were high in magnitude, though of opposite sign, for the last surface of the eye lens and for the first surface of the center singlet. The optimization would begin with these surfaces.

Applying this process for the various surfaces as well as periodically monitoring the *Lateral Color* window (there are no Seidel coefficients for lateral or longitudinal color) will permit the designer to converge on a likely solution. Once a convergent trend is noticed, the designer will want to access more windows for reviewing aberrations. The usefulness of the Seidel coefficients will diminish as the aberrations become smaller, but monitoring the aberrations with various *ATMOS* windows, including the *Multi Spot Diagram*, will serve.

*Fig. 3A-1* plots astigmatism, the tangential curve in red and the sagittal in blue. Best-fit, field-curvature radius is about -272mm (70% zone, 17.5°). *Fig. 3A-2* provides the spots at field center, 70% field, and field edge. Notice the oval spot at the field edge exceeds the reference circle of 3.4 minutes diameter. The vertical spread of the oval is about 7 minutes, violating the 5-minute criterion somewhat (the criterion holds to about the 22° half field).

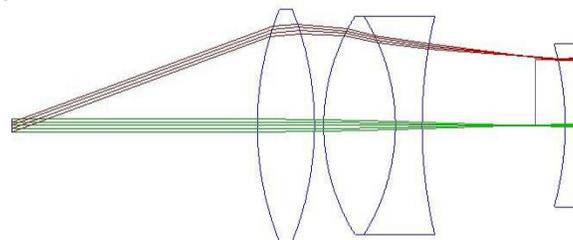


*Fig. 3A-1*



*Fig. 3A-2*

B) Konig with Smyth Lens:



Accommodation = -0.77 diopter, *ffl* -5.944mm, 20° half field

Surf	A.Stop	Half-Dia	Curv.Radius	Thickness	MEDIUM	Glass/Index
1	AS	.8465	0	32.416	AIR (Posit)	+ 1
2		15.2	40.378	7.565	SCHOTT	+ SK14
3		15.2	-40.378	1.23	AIR (Posit)	+ 1
4		14.18	26.478	9.456	SCHOTT	+ SK5
5		14.18	-26.478	3.546	SCHOTT	+ SF6
6		14.18	61.277	18.913	AIR (Posit)	+ 1
7		10.64	-39.717	2	SCHOTT	+ BK7
8		10.64	0	0	AIR (Posit)	+ 1

This design began with the 3-element, *RKE* eyepiece example included in *Oslo* 6.1 optical-design software. The design focal length was 28mm, but I wished to shorten it. I also wanted to moderate the design's astigmatism and diminish its field curvature. Coma was well corrected, but modest internal (positive) coma was permissible. I chose to drop the field to 40° from 45° and sought to improve lateral color. I desired to retain the symmetrical convex lenses, and chose to add the BK7 Smyth lens (the plano-concave lens) just to the right of the objective focus. In this position, the Smyth lens would have full effect on the field curvature and astigmatism of the system while remaining relatively benign with respect to the other aberrations. Substitutions for the glasses of the eye lens (the only component with any *real* power) and the negative lens of the doublet were made, which ultimately brought the lateral color into control. This was accomplished by “trying” glasses that were very similar in dispersion (Abbe' or *V*-number) but differed somewhat in *d*-line index. Thus, the SK5 (589613) eye lens became SK14 (603606) and the flint component of the field lens SF4 (755276), to SF6 (805254). When the overall system was well balanced for aberrations and dimensions, the design was scaled for a focal length of 25.4mm.

Fig. 3B-1 provides the tangential (red) and sagittal (blue) curves in the finished design. The best-focus field curve falls half way between the two curves and has a radius of -78mm at the 70% zone (14°) as compared with the -66mm of the original, 28mm-focal-length design. The eye relief is about 26% greater than that of the older design.

Adapting the 3-element Konig design (this is a Konig-style design despite the *RKE* moniker) to take a Smyth lens seems a solution that can result in good performance with minimal effort. Fig. 3B-2 contains spot diagrams referencing the best-fit field curvature.

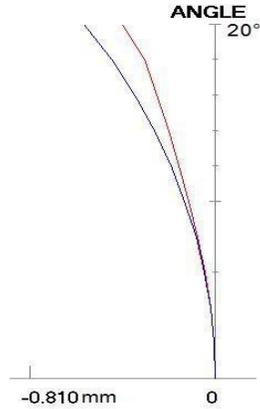


Fig. 3B-1

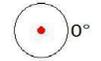
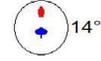
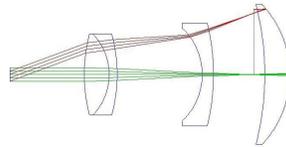


Fig. 3B-2

### C) Airy 4-Lens:



Accommodation = -0.24 diopter,  $ffl$  -4.725mm, 20° half field

Surf	A.Stop	Half-Dia	Curv.Radius	Thickness	MEDIUM	Glass/Index
1	AS	.85	0	9.736	AIR (Posit)	+ 1
2		5.24	20.811	3.257	SCHOTT	+ SK16
3		5.24	-7.589	1.052	SCHOTT	+ F2
4		5.24	-19.845	11.158	AIR (Posit)	+ 1
5		6.03	-8.277	1.471	SCHOTT	+ BK7
6		6.69	-28.214	6.742	AIR (Posit)	+ 1
7		9.08	-36.217	3.29	SCHOTT	+ LF5
8		9.08	-13.159	0	AIR (Posit)	+ 1

This one began as a simple Airy (*Amateur Telescope Making III*, pub. 1953, p495, eyepiece no. 18), two lenses spaced as in a Huygens, but with the eye lens a “crossed” lens (*Lens Design Fundamentals*, pp 118-119, R. Kingslake) and the field lens, a positive meniscus. The short-radius surfaces of these lenses face the objective. Like the Huygens, the Airy has a focus falling between the two lenses (the objective’s focus falls just to the left of the field lens). The Airy was conceived by Sir G. Airy to reduce the spherical aberration of Huygens’ older design, but like the Huygens, the Airy possesses a strong curvature of field. I placed a BK7 plano-concave lens just to the left of the intermediate focus between the two lenses. At this location, the negative lens would contribute full power to the field curvature without significantly altering the system’s other aberrations. The plano-concave lens became meniscus under the influence of some simple optimization. Since the strong curvatures of lenses can be reduced when glasses of high optical density are incorporated, I assigned SK16 glass to the field and eye lenses of the Airy. The eye lens became nearly equi-convex as a result. And while the spot diagrams

were rather condensed, the system could just tolerate an aperture ratio of  $F/20$ , a value one could achieve with a traditional Huygens design. To improve the correction of lateral and longitudinal color, a “buried” surface (R. Kinglake, p 176) was inserted within the eye lens, and the SK16 eye-lens singlet became an SK16/F2 doublet. Further optimization bared the chromatic excess of the field lens, but a final change in the glass of the field lens to LF5 provided the solution. As a bonus, the correction of spherical aberration was significantly improved and the system’s performance at  $F/15$  became quite good.

The best-focus field curvature is -153mm at the 70 % zone ( $14^\circ$ ). It tracks halfway between the graphed curves of Fig. 3C-1 for the tangential (red) and sagittal (blue). Coma is absent, and the diameter of the blur spot at the field edge is 5 arc minutes, seen in Fig. 3C-2. The spots are plotted referencing the field radius of -153mm and a small defocus of -0.1mm (moderating the accommodation, which becomes -0.09 diopter).

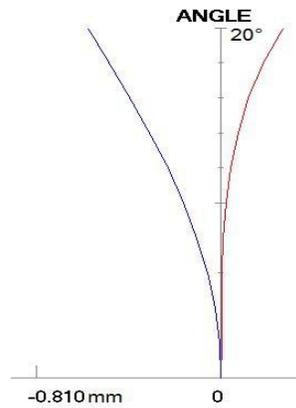
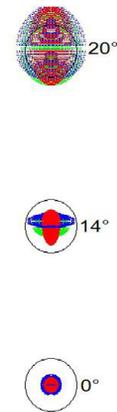
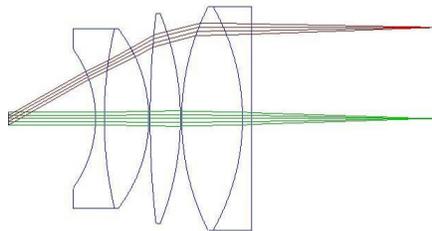


Fig. 3C-1



3Fig. C-2

#### D) Warmisham 5-Lens:



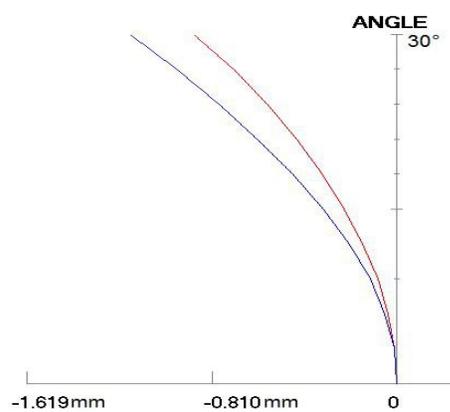
Accommodation = -1.16 diopter over  $25^\circ$  half-field,  $ffl$  24.655mm,  $30^\circ$  half field

Surf	A.Stop	Half-Dia	Curv.Radius	Thickness	MEDIUM	Glass/Index
1	AS	.85	0	11.425	AIR (Posit)	+ 1
2		9.3	-16.202	1.153	SCHOTT	+ SF15
3		12	54.2	5.865	SCHOTT	+ SK16
4		12	-19.941	.167	AIR (Posit)	+ 1
5		14	126.152	3.998	SCHOTT	+ SK16
6		14	-38.435	.167	AIR (Posit)	+ 1
7		15	34.003	8	SCHOTT	+ SK16
8		15	-31	1.246	SCHOTT	+ F2
9		15	0	0	AIR (Posit)	+ 1

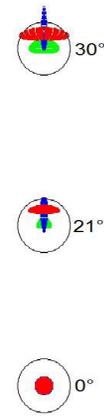
Warmisham's 4-lens design appears in British Patent no. 565851, ex.1. The principal changes I made to the design were to make the thick, SK16 plano-convex field lens a doublet of SK16 and F2 and reduce the small air space between the components of the eye lens to zero. F2 was chosen because it shares a common,  $d$ -line index of 1.620 ( $dn = 0.001$  difference at the  $e$ -line) with the SK16 of the field lens. Thus, one may work with the monochromatic aberrations as if the doublet were a singlet and leave the correction of chromatic aberration to later (R. Kinglake, p 176). This design "solved" rather quickly as compared with the Astroplanokular-Aplanat, which illustrates the importance of recognizing that a design has elements (the thick, SK16 plano-convex field lens) that can be rather easily modified to produce the performance one desires.

*Fig. 3D-1* shows the tangential and sagittal curves trending nearly in the same direction. Radius of best-focus, field curvature is -76mm at 21° half field. The accommodation at 30° half field is  $-1.67 < -1$ . However, at 25° half field (equal that of the eye) the accommodation is -1.16. Were the design scaled by 1.16 (becoming 29.5mm fl), at 25° half field the accommodation would become -1.

Spots are displayed in *Fig. 3D-2* showing excellent correction ref. the best-focus field curvature at the 70% zone (21°). Scaled at 1.16, the correction remains excellent.



*Fig. 3D-1*



*3Fig. D-2*

There is an important lesson one can learn here. Note surface 2 (the first glass surface) has a radius -16.202mm and the *Thickness* from the Ramsden disk to surface 2 is 11.425mm. Surface 2's center of curvature is 4.777mm to the left of the Ramsden disk. At  $F/15$ , any light reflected from the observer's cornea to surface 2 and reflected back toward the eye will miss the eye's pupil, but at faster  $F/\text{no.s}$ , this may not be so. A simple construct shows a pupil diameter of a bit more than 7mm might collect some of this reflected light. However, the  $F/\text{no.}$  that would come close to permitting this is  $15(2 \cdot 0.85\text{mm}/7\text{mm}) = 3.64$ , a speed the eyepiece isn't likely to encounter in a telescope. In any case, the performance of the eyepiece at that speed would be very poor.

#### **4) Conclusion:**

Techniques for "hand" designing eyepieces with *ATMOS* software have been presented (similarly-endowed software packages may permit the same). The designer will realize the benefits of his inventory skills when his research and process notes lead to the effective management of his design using *ATMOS* windows. My hope is that this paper will encourage amateur telescope designers to attempt eyepiece design and become more proficient in it.