A family of 2 mirror unobscured wide field telescope and collimator designs

Richard F. Horton
A family of 2 mirror unobscured wide field
telescope & collimator designs

Richard F. Horton
ad hoc Optics LLC, 317 Hathaway Circle, Mid Valley Air Park, Los Lunas, NM 87031
RFHorton7@aol.com

Abstract

A new family of 2 mirror unobscured telescopes of compact “Schieffspiegl”, off axis Cassegrain geometry, incorporating aspheres, tilted and decentered secondary, and tilted focal surfaces, will serve as fast, high resolution, moderately wide field telescopes / collimators. Designs range from f/5 to f/16. The nCUB designs provide a focal surface normal to the gut ray for visual use. The tCUB designs provide collimator telescopes with focal surfaces tilted so that any light reflected from the reticle is eliminated.

Keywords: 2 mirror telescope, unobscured, off axis Cassegrain, schiefspeigler, tilted focal plane

1. Introduction

The purpose of this paper is to introduce a family of moderately wide field of view, diffraction limited, compact, two mirror unobscured telescopes which have been designed for f/5 to f/16. The examples to be cited will all be scaled to a nominal 10" aperture. The systems all can be made using testable off axis Conic Section mirrors, and they are all of a layout which will permit a simple baffle configuration. The family name, “CUB”, stands for Conic - Unobscured - Baffled.

The general description would be that of an Off Axis Cassegrain, or Kutter - Schiefspiegler layout, but much faster than the Schiefspiegler, with tilted and decentered aspheric secondary mirror surfaces. The design allows for systems as fast as f/5 and provides a reasonably wide, diffraction limited, field of view over a tilted, relatively flat, low distortion focal plane. The single issue unique to these designs is control of the focal plane tilt.

We have found that the tilt and decenter of the secondary can be used, along with the several other geometric variables to control the tilt of the focal surface, which can be normal to the gut ray, as in the “nCUB” family, for visual use, as in figure 1 and 2, or tilted at a specific angle to the gut ray to control reflections from a focal plane mask, as in the “tCUB” family, shown in figure s 3 and 4. The low f/number nCUB designs are specifically well suited for visual use, the tCUB specifically for use as high resolution wide field collimators or IR scene projectors. All can be used as wide spectrum telescopes, or objective lenses for array cameras. Examples will be described and compared to other designs.

Figure 1 - 10" f/7 All Reflecting “nCUB” Telescope
Since the popularization of affordable reflecting and refracting telescopes, there has been argument between the two camps of amateur astronomer - telescope owners. Reflecting telescope have no color aberrations, but the central obscuration from the Newtonian or Cassegrain secondary causes diffraction effects which degrade the image. The central obscuration in the pupil causes a reduction of the Strehl ratio of a point image and a decrease in mid spatial frequencies in the Optical Modulation Transfer Function, or MTF. In addition, the secondary mirror support, or “spider”, give rise to the familiar “star” shaped diffraction pattern about bright stars.

Refracting telescopes suffer from color aberrations, which can usually be only partially corrected, which are not present in reflecting telescopes. Further, refractor apertures are smaller for the same price, affording less light gathering capability.

More complicated optical systems, such as the many variations of Schmidt-Cassegrains, etc, with refractive correctors, can, like their cousins the refractors, only be optimized in a particular region of the spectrum and quite often suffer from surface complexity compromises made to lessen the cost of the optical system.

Unobscured all reflecting telescopes designs suffer from neither MTF degradation nor color aberrations. Still, very few unobstructed system designs have been produced in any quantity due to other issues. The designs in the literature are typically of small aperture, high f/ number, and perhaps too complicated in alignment and mounting.

Quoting from the conclusion of a recent review article [1], “The World of Unobstructed Reflecting Telescopes” by José Sasián:

“The known designs cover very well the span of small (3 to 5 inches) and medium apertures (6 to 8 inches) with great practicality and transportability. However, for larger apertures (10 inches or more), there is a need for very compact and moderately fast designs, (f/8 to f/15). These designs will probably require three mirrors and a double-curvature surface like the large Tri-Schiefspiegler discussed in section ...”

2. Two examples of CUB family telescopes

A first example of a nCUB telescope system is shown above in figure 1. This f/7 optical system has an unobscured 10 inch aperture and is compact, approximately 24 inches in overall length. The focal surface is normal to the gut ray. In addition to having diffraction limited performance over a quarter degree FOV in the visible and quite reasonable optical performance over a 0.75 degree field, the focal plane is exactly perpendicular to the axis of the gut ray, allowing eyepieces of all fields and power. Overall, the field performance is favorably comparable to a 10” f/7 Newtonian. Figure 2 shows a ZEMAX [*] screen for the f/7 nCUB at 0.55 um.

![Figure 2 - A ZEMAX screen - Prescription and Properties of 10”](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)
The second CUB family to be presented is the “tCUB”. The f/10.7 tCUB system shown in Figure 3 is optimized for a modest tilt of the focal plane surface, so that reflections from a reticle situated at the focal plane are just prevented from going back through the system. This system is well optimized for use as wide field infrared collimator and will be used as an example for a discussion of the system family properties. The properties shown are that for this system at 1 um, in the ZEMAX screendump shown in Figure 4.

![Figure 3 - f/10.7 tCUB Collimator w/ focal plane reflection and absorber](image1)

When tCUB optical systems are used as a collimator or IR scene generator, with an appropriate opaque (and reflective), target reticle at the focal plane, the tilted focal surface can be of significant advantage. The target reticle is illuminated from behind by a light source, (typically a 2 inch diameter black body infrared source), and the resulting projected image transmitted to an optical system under test. That is the primary function of a the collimator. Because of the tilted
target reticle surface in the tCUB system, the optical system under test can not “see” its own image reflected by the projection reticle, since this element, which can act as a mirror at the focal plane, is tilted sufficiently to send this light to the absorber. If the reticle were normal to the system, this reflection would pass back through the collimator optics to be reimaged by the system under test. This eliminates the problem referred to as Narcissus [2], when a cooled focal plane imaging system sees its own, unwanted cold reflection, due to reflections from its own optical surface or those of the test optics.

In addition to the elimination of Narcissus, this absorber can be maintained at a set temperature and, even though significantly out of focus, will provide a uniform background field irradiance at points where the target scene would otherwise be “black” allowing one more variable, the background thermal temperature to be controlled in the system.

These same optical systems should prove quite useful for eliminating “cats eye” type reflection signatures from visible and infrared focal planes used in optical systems for covert imaging.

Since these all reflecting two mirror systems have no color aberrations whatsoever, and the aberrations are totally geometric, these aberrations scale linearly with aperturesize. Two scaling effects can be noted. First, smaller apertures will yield larger diffraction limited fields of view at any given wavelength, and second, at the same aperture, increasing the wavelength will increase the diffraction limited field of view. For example, one 10 inch aperture system can have a diffraction limited field of view of about 0.25 degree in the visible, (0.55 um), while a re-scaled 5 inch aperture system of identical f/number will have a diffraction limited field of view of approximately 0.5 degree. Similarly, the same 10 inch aperture system will have a diffraction limited field of view of about 0.5 degree when used at an infrared wavelength of 1 um, the diffusion limited field of view being a function of the wavelength.

3. Unobscured Reflecting Telescope Systems

As mentioned earlier, a number of unobscured reflecting telescopes have been designed and built, many not in a fast, compact form. So far nothing like the CUB family have been designed and built. Originally started as a “what if” replacement to the ubiquitous 10” Schmidt - Cassegrain, to solve color and field curvature issues, the CUB family of designs is potentially more usefull than just an amateur astronomy telescope design.

3.1 Single Mirror Telescopes - The Herschel Telescope

The simplest form of unobscured telescope is a Herchellian telescope [3], which was first used by Sir William Herchel in 1789. Light from the single concave spherical mirror is reflected to the side of the entrance aperture and the observer, looks directly at the light in this bundle coming back up the tube. The 49.5 inch mirror with the 480 inch focus used by Herchel used a spherical mirror operating at f/9.7. This was very early in the history of modern astronomy and optics. The defining problem with the telescope was the mirror material - speculum metal - which would have to be repolished frequently, often changing the figure of the mirror.

3.2 Unobscured Two Mirror Telescopes - Yolo and Kutter - Schiefspeigler

Two workable high f/ number telescope systems are the Yolo telescope [4], and the Kutter - Schiefspeigler [5]. Both use spherical mirrors and buck aberrations of one tilted mirror of against the other resulting in a decent optical axis but aberrations which get large as the field angle increases. Because the aberrations to be cancelled are astigmatism, typically the field performance is not rotationally symmetric or even near, and the field supporting good performance is quite small. Variations include bending of one of the elements to correct the astigmatism, but we are still limited to a high f/ number small field telescope. The Kutter - Schiefspeigler in the Zemax screen dump, Figure 5, is a 4.25 inch diameter system designed by Oscar Knab, which was re-scaled to 10 inch for comparisons.

3.3 Other Two Mirror Systems - Unobscured Newtonian

Recently there has been a small activity in unobscured Newtonian Telescopes. While they certainly have their place in amateur astronomy, they are often quite long and cumbersome, having fairly slow f/ numbers, as a result of the primary mirrors being chopped out of fast parent parabolas. Because of a newtition diagonal, they are easy to baffle. There are some problems with the field tilt as the f/ number decreases, limiting them to small fields of view for visual use.
3.5 Off Axis Cassegrains - Schiefspiegler Geometry

Cassegrain and Gregorian telescopes are centered axially symmetric two mirror systems and have obscured primary mirrors, due to the shadow of the secondary mirror. The Cassegrain uses a concave primary mirror and a convex secondary mirror. In Gregorian telescopes both are concave. Gregorian telescopes have a real focus between the primary and secondary mirrors. Cassegrains do not. Cassegrains are usually preferred for two reasons - a more compact size and less obscuration for a given f/number system. We will consider only variations of the two mirror off axis Cassegrain for these same reasons. This geometry is commonly referred to as a Schiefspiegler geometry. This German word translates literally to “crooked mirror”.

Ironically, Richard Buchroeder, Dietrich Korsh, David Schafer and other brilliant optical designers have sent a great deal of time studying unobscured optical system geometries, and generally have held to rotationally symmetric off axis system designs, quite possibly because they can be dealt with analytically. Usually the designs which have been proposed use extra mirrors to effect system optimization. Two mirror, Off Axis Cassegrains, held to the requirement of axial symmetry have very few degrees of freedom to work with. The CUB systems secondary tilt and decenter, adds an extra two optimization variables, to the system optimization, and this, somewhat surprisingly, allows new, and hopefully quite useful systems to be modeled.

4. The CUB Telescopes compared to Off Axis Cassegrain

Consider designing an axially symmetric Off Axis Cassegrain system as an unobscured optical system. We will use the Ritchey - Chrétien like practice of allowing both mirrors to be variable hyperbolic conic constants for optimization. Both mirrors are rotationally symmetric about the same vertex axis, and, the center of the focal surface is centered, and normal to this axis. The layout for this system is relatively straightforward, and we will impose two more optimization requirements. First, we will want the system to be compact, requiring approximately the same separation between the
Figure 6 - Nominal Unobscured Cassegrain - with Baffles and 9.5 degree focal surface tilt to Gut Ray

primary and the secondary mirrors as between the secondary mirror and focus. Second, we will require that the system be well baffled. Figure 6 shows our nominal Off Axis Cassegrain.

Figure 6 shows two things. First, as baffling goes, the analogs of the inner cone baffle and the outer cone baffle, used by centered Cassegrain systems, are simply screens, and in order to work correctly the stray light path, (line), from the rear edge of the front baffle across the front of the rear baffle must fall outside of the focal region. Second, the focal plane makes a 9.5 degree angle with the gut ray. If the system is compressed radially, to lessen the angle of the gut ray with respect to the focal surface, the baffling will eventually fail as the angles of the stray light path is diminished.

Figure 7 - Image tilt in the eye for a 70x visual Off Axis Cassegrain

The incidence angle of the gut ray to the focal plane surface causes problems for the system when used visually. As the $f'$ numbers are reduced, or as power and field of view of an eyepiece increase, the focal surface of the image in the eye diverges from the retina. This is demonstrated in figures 7 and 8. Figure 7 shows an “ideal” paraxial optical model of a $f'7$ Off Axis Cassegrain with 9.6 degrees of focal plane tilt. Assuming a 1" efl eyepiece and a 1" efl eye, (70x), the
image tilt on the back of the eye is 9.6 degrees. This situation worsens with increase in power. With a ½” efl eyepiece, (140x), as shown in Figure 8, things are a factor of 2 worse, with the image tilt on the back of the eye now 19.2 degrees.

This is not a particular problem for imaging systems with film or a CCD array at the focal lane. On the other hand, for visual imaging with an eyepiece, this may be a serious problem, especially at system f/numbers of f/8 or less. This would also be a problem with the off-axis Newtonian Telescopes at lower f/numbers although the baffling requirement makes this more severe for the Cassegrain.

### Figure 8 - Image tilt in the eye for a 70x visual Off Axis Cassegrain

![Figure 8 - Image tilt in the eye for a 70x visual Off Axis Cassegrain](image)

#### 4.1 Earlier Off Axis Cassegrain Systems

In 2000 Moretto and Kuhn published papers (OSA and SPIE) on a very interesting set of three designs for 4 meter - Off Axis Cassegrain [7]. Figure 9 (in both the OSA and this text, ironically), is seen in both papers. It shows a very interesting f/9.13, two mirror off-axis Cassegrain system. The other two designs were for: 1/ an f/10 3 mirror system, and 2/ an f/16 system using two mirrors plus four refractive field corrector elements. The 2 mirror f/9.13 system used the same secondary as the f/16 system used, with tilt and decenter of the secondary, resulting in a tilted 3 arc minute FOV. Enough of the optical prescription is given in the paper to rescale the f/9.13 4 m system to a 10 in aperture. A ZEMAX screen is shown as Figure 11, with a nCUB f/9 screen shown as Figure 12. Several things are worthy of note. The f/9.13 system - scaled to a 10 inch diameter is almost diffraction limited, and supports a FOV of reasonable utility out to about 0.1 degrees at with a focal surface tilt of about 1 degree from the normal. The 10 inch nCub is diffraction limited out to about 0.2 degrees and has a FOV of at least 0.5 degree, normal to the gut ray. The nCUB is more readily baffled and has a slightly longer secondary to focal surface dimension.

![Figure 9 - RC off-axis, f/9.13 design. The same off-axis primary mirror M1 that was optimized to the f/16 design and the same secondary M2 optimized to the f/10 design was used to get a two-mirrors bare design over 3.0 arc min FOV.](image)
Figure 11 - Rescaled 10" f/ 9.13 Moretto - Kuhn Off Axis Cassegrain @ 0.55 um

Figure 12 - 10" f/ 9 nCUB Telescope @ 0.55 um
5. CUB Telescope design families

The following figures show the variation of several relevant geometric factors for the CUB family of telescopes from f/5 to f/16. Again, all are scaled to an aperture of 10 inches. All optical analysis for the nCUB optical systems are shown for a single visible wavelength of 0.55 um, all tCUB for an infrared wavelength of 1.0 um. Since there are no color effects, other than diffraction, all aberrations are purely geometric and because of this, the performance of any sized system at any wavelength can be found by the appropriate scaling.

Note that in ZEMAX the decenter and tilt the secondary is measured with respect to the vertex axis of the decentered primary mirror, and the tilt and decenter of the focal plane may be measured relative to the vertex axis of the decentered secondary mirror. In practice, the focal plane angle is best measured with respect to the pointing axis of the system, while normal to the gut ray.

5.1 nCUB Visual Telescopes

For systems which have been optimized for a focal surface orthogonal to the axis of the gut ray, we have found a family of nCUB optical systems from f/5 to f/16. These systems are described by the optical prescription parameters from ZEMAX, which are shown in figures 13 - 14. Figure 13 shows spreadsheet compilations and plots of mirror radii and spacings. Figure 14 shows spreadsheet compilations and plots of conic constants, decenters and tilts.

5.2 tCUB Collimator Telescopes

For systems which have been optimized for a focal surface tilted to the axis of the gut ray, for collimator use, we have the family of tCUB optical systems, also from f/5 to f/16. These systems are described optical prescription parameters from ZEMAX which are shown in figures 15 - 16. Figure 15 shows spreadsheet compilations and plots of mirror radii and spacings. Figure 16 shows spreadsheet compilations and plots of conic constants, decenters and tilts.

6. Conclusion

We have found that the tilting and decentering the secondary of the off axis two mirror system allows control of the tilt and position of the focal surface. By optimizing the tilt and decenter of the secondary in addition to other optical variables, we can, in a general way, control the tilt of the focal surface relative to the gut ray in these two mirror - off axis Cassegrain - Schiefspiegler geometry telescopes, while at the same time optimizing the image over a reasonably wide FOV. Being an all mirror system, there is no color aberrations, and the aberrations in general scale with aperture for a given f/number system.

The design family name is “CUB” which stands for Conic - Unobscured - Baffled

This paper describes 2 such families, the first family of telescopes are designated nCUB, having the focal plane normal to the gut ray, and thus being a good design for compact wide field visual telescope.

A second family of telescopes is designated tCUB, for a tilted focal plane. The tCUB optical systems are designed to be used as Collimator Telescopes, and have the reticle for the target projection situated at the tilted focal plane so that reflections from this reticle are sent to an absorber and controlled.

We are currently in the process of building a 12.5 inch f/10.7 telescope of the tCUB example design. Simple interferometric tests for the conic surfaces have been designed for the two mirrors and system, allowing straightforward mirror testing, manufacturing and alignment. We are currently building the design in glass, but have explored the use of diamond turning of the aspheric off axis elements in metals, such as aluminum. This would allow CTE matching of the optical elements, optical mountings and structure, which will allow for a “thermally congruent” system design.

We have filed for patents on the optical system designs and would be more than willing to discuss the design optimization and fabrication of these optical systems to address individual needs.
Figure 13 - nCUB Mirror Radii and Spacings

Figure 14 - nCUB Mirror CC, Decenters and Tilts
Figure 16 - tCUB Mirror Radii and Spacings

<table>
<thead>
<tr>
<th>tno</th>
<th>Pradius</th>
<th>Sradius</th>
<th>Sphi</th>
<th>Sfl</th>
<th>SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>-136</td>
<td>-3.99</td>
<td>45</td>
<td>45</td>
<td>0.015</td>
</tr>
<tr>
<td>14</td>
<td>-117</td>
<td>-0.018</td>
<td>41</td>
<td>41</td>
<td>0.034</td>
</tr>
<tr>
<td>12</td>
<td>-102</td>
<td>-5.69</td>
<td>35</td>
<td>35</td>
<td>0.134</td>
</tr>
<tr>
<td>18</td>
<td>-93.64</td>
<td>49.93</td>
<td>31</td>
<td>31</td>
<td>0.135</td>
</tr>
<tr>
<td>10</td>
<td>-84.56</td>
<td>46.41</td>
<td>29</td>
<td>29</td>
<td>0.095</td>
</tr>
<tr>
<td>9</td>
<td>-75.41</td>
<td>40.85</td>
<td>36</td>
<td>36</td>
<td>0.077</td>
</tr>
<tr>
<td>9</td>
<td>-67.55</td>
<td>-36.26</td>
<td>23</td>
<td>24</td>
<td>0.060</td>
</tr>
<tr>
<td>7</td>
<td>-61.5</td>
<td>-32.83</td>
<td>21</td>
<td>21</td>
<td>0.089</td>
</tr>
<tr>
<td>6</td>
<td>-54.93</td>
<td>-31</td>
<td>-19</td>
<td>19</td>
<td>0.061</td>
</tr>
<tr>
<td>5</td>
<td>-51</td>
<td>-30.17</td>
<td>-19</td>
<td>14</td>
<td>0.065</td>
</tr>
</tbody>
</table>

Figure 17 - tCUB Mirror CC, Decenters and Tilts

<table>
<thead>
<tr>
<th>tno</th>
<th>P cc</th>
<th>S cc</th>
<th>S decenter</th>
<th>S tilt</th>
<th>F H</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>-1.353</td>
<td>-7.617</td>
<td>-0.015</td>
<td>0.003</td>
<td>0.059</td>
</tr>
<tr>
<td>14</td>
<td>-1.0902</td>
<td>-7.676</td>
<td>-0.001</td>
<td>0.029</td>
<td>0.044</td>
</tr>
<tr>
<td>12</td>
<td>-1.172</td>
<td>-6.295</td>
<td>-0.134</td>
<td>0.475</td>
<td>0.621</td>
</tr>
<tr>
<td>10</td>
<td>-1.1156</td>
<td>-6.166</td>
<td>-0.162</td>
<td>0.028</td>
<td>0.307</td>
</tr>
<tr>
<td>10</td>
<td>-1.2671</td>
<td>-4.418</td>
<td>-0.107</td>
<td>-0.28</td>
<td>0.616</td>
</tr>
<tr>
<td>9</td>
<td>-1.134</td>
<td>-8.389</td>
<td>-0.117</td>
<td>-0.448</td>
<td>0.746</td>
</tr>
<tr>
<td>8</td>
<td>-1.1362</td>
<td>-6.336</td>
<td>-0.554</td>
<td>-0.97</td>
<td>1.076</td>
</tr>
<tr>
<td>7</td>
<td>-1.088</td>
<td>-6.353</td>
<td>-0.429</td>
<td>0.341</td>
<td>1.000</td>
</tr>
<tr>
<td>6</td>
<td>-1.1271</td>
<td>-9.669</td>
<td>-0.269</td>
<td>-0.94</td>
<td>2.367</td>
</tr>
<tr>
<td>5</td>
<td>-1.141</td>
<td>-13.23</td>
<td>-0.372</td>
<td>0.126</td>
<td>3.836</td>
</tr>
</tbody>
</table>
7. References

[*] ZEMAX Optical Design Software, a product of ZEMAX Development Corporation is used exclusively in this paper for the analysis of the optical properties of the modeled optical systems. ad hoc Optics is a licenced user of ZEMAX. A totally comprehensive ZEMAX manual in PDF form can be obtained from www.zemax.com.


[4] ibid, 143

[5] The Oscar Knob design of the Kutter-Schiefspiegler is described at www.telescopemaking.org/schief.html
