Comparison of On-Axis Three-Mirror-Anastigmat Telescopes

M. Lampton and M. Sholl

Space Sciences Laboratory, University of California at Berkeley 94720 USA

ABSTRACT

We compare and contrast the Korsch (1972) full-field three-mirror anastigmat telescope (TMA) to the Korsch (1977) annular-field TMA. Both TMAs offer flat fields with comparably good aberration correction and comparably good telephoto advantage. Both offer good accessibility of the focal plane. The advantages of the FFTMA are its extremely uniform focal length over its field, its nearly telecentric final focus, and the fact that there is no hole in the center of its field. The advantages of the AFTMA are its complete accessible cold stop (essential if a warm telescope is to be used to image the sky at near-IR wavelengths) and its low sensitivity to mirror location error. Either alternative can deliver diffraction-limited visible-wavelength images over a one degree diameter field with a two meter aperture.

Keywords: three-mirror anastigmat telescopes, space astronomy, wide-field imaging.

1. THREE-MIRROR ANASTIGMATS

It has long been recognized that the field limitations of the one-mirror and two-mirror telescope configurations can be ameliorated by going to optical configurations that use three powered mirrors. Of those, some are fully coaxial, which makes efficient use of aperture but suffers from significant central pupil obstructions. Most (e.g. Paul[1]; Baker[2]; Angel[3]; Willstrop[4]) are also severely limited in their available telephoto advantage, defined as the ratio of the system effective focal length to the optical package length. Others are off-axis in either pupil, field, or both (Cook[5]; JWST[6]), which can simplify stray light baffling but leads to inefficient use of potential light collection area or sky survey area. A useful review of three mirror telescopes is provided by Wilson[7].

With three powered mirrors there are nine parameters available for design optimization, listed in Table 1. Within the space defined by these parameters, a wide field survey telescope will have to deliver near-zero spherical aberration, coma, and astigmatism (i.e. be an anastigmat). Other practical features are important as well: the focal plane should be flat, the primary should be the largest mirror, the central obstruction should not be too extreme, the tolerances should be manufacturable, and (for space flight) the focal length should match the diffraction pattern size to the pixel size. Because there are more adjustable parameters than there are design constraints, there is additional freedom to stretch or shrink the locations of the optical elements to best configure the system to meet requirements for blocking stray light and avoiding vignetting.

Contact: mlampton@SSL.berkeley.edu tel: 510-486-5047

Table 1: Three-mirror telescope design parameters	
Primary mirror	curvature
	asphericity
	spacing to secondary mirror
Secondary mirror	curvature
	asphericity
	spacing to tertiary mirror
Tertiary mirror	curvature
	asphericity
	spacing to focal plane

With modern ray-tracing design methods, of course, it is not necessary or desirable to set the classical Seidel aberrations to zero. A higher performance solution is obtained when a merit function that senses the full field performance in a least-squares sense is optimized. In this paper, for illustration, we have generated examples using a least squares merit fuction computed on a grid of field locations that spans a one degree diameter sky field. This approach allows small nonzero values of the classical Seidel aberrations to remain, in exchange for reducing the aggregate effects of aberrations of all orders.

Korsch (1972[8], 1977[9], 1980[10]) presented two key ideas that permit light to be extracted from a TMA and directed to a potentially large focal plane located away from the telescope axis. The ideas are (1) to arrange that the Cassegrain focus field "CF" and the exit pupil "EP" should be nearly colocated along the telescope axis, and (2) to arrange that they have significantly different linear sizes, so that a tilted oval or annular mirror at that location can extract light from the CF or the EP with little or no interference with the EP or CF. It is a remarkable fact that the elasticity in TMA design space --- evidenced by the greater number of design parameters than constraints --- allows these two additional conditions to be met in two distinct ways. With the Korsch arrangements, the bulk of the focal plane and its ancillary equipment need not shadow either the pupil or the field. Moreover this separation between focal plane and telescope can be arranged to yield rigorous baffling against stray light and stray heat.

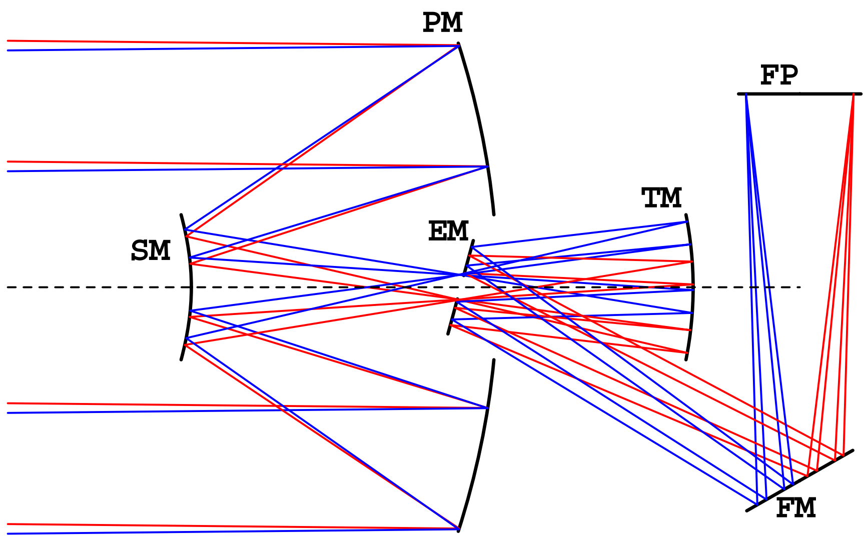
In this paper we compare four Korsch-type three-mirror anastigmats that work on-axis in pupil and field. These four have many features in common: their primary and tertiary mirrors are concave ellipsoids while their secondary mirrors are convex hyperboloids, they offer large telephoto advantages, they have efficient aperture utilization with aperture size equal to the envelope diameter, and each has a flat focal surface that is disposed completely around the optical axis for maximum aberration-limited field coverage. For concreteness in our comparison examples we adopt an aperture size of 2.0 meters and a package length not to exceed 3.5 meters. We seek a working field of one degree in diameter and to match reasonable pixel sizes to the diffraction limit at visible wavelengths we stipulate a focal length of 22 meters (107 microns per arcsecond).

2. Two Full-Field TMAs

One example of a full-field TMA is the optical configuration shown in Figure 1 below. Here, the primary and secondary mirrors form a quasi Cassegrain system whose focal length is short. The Cassegrain field is imaged near the vertex of the primary mirror. A usably large effective system focal length is achieved by operating the tertiary relay at a large magnification of the order of 4x. In this way the relatively small Cassegrain image can fit comfortably within the central blind zone of the exit pupil formed by the tertiary optic. There is no light loss at this intersection because that zone has been shadowed by the secondary mirror. The entire Cassegrain field can be recovered by the tertiary relay. No portion of the Cassegrain field of view is obstructed.

We adopt the notation of Korsch 1977[9]: configuration I has the tertiary mirror (TM) on the principal axis defined by the primary mirror (PM) and secondary mirror (SM), and configuration II has the tertiary off this axis, receiving light from a tilted flat on-axis mirror. The full-field TMA arrangement was described by Korsch (1972[8], Fig 1b) with a small central mirror at the Cassegrain field, as in configuration II. Either configuration I or II can deliver the full field without loss of pupil coverage beyond the secondary shadow loss, because in either arrangement the exit pupil surrounds the Cassegrain field.

Due to the large magnification of the tertiary, there is a relatively long light path needed between the tertiary mirror and the focal plane. This path can be accommodated within a compact package by adding a second flat folding mirror off the PM-SM axis.



6 surfaces Fig1.OPT

X	Z	pitch	mir?	Curv	Aspher	Diam	diam
0	0	0	mir	-0.3126554?	-0.98063?	2.1	0.6
0	-1.25	0	mir	-0.9772446?	-3.48512?	0.6	
0	0.8	0	mir	-0.6467372?	-0.62193?	0.6	
0	-0.15	-15	mir	0		0.4	0.1
-0.8	1.2356406?	-60	mir	0		0.5	
0.8	1.2356406e	90	FP	0		0.5	

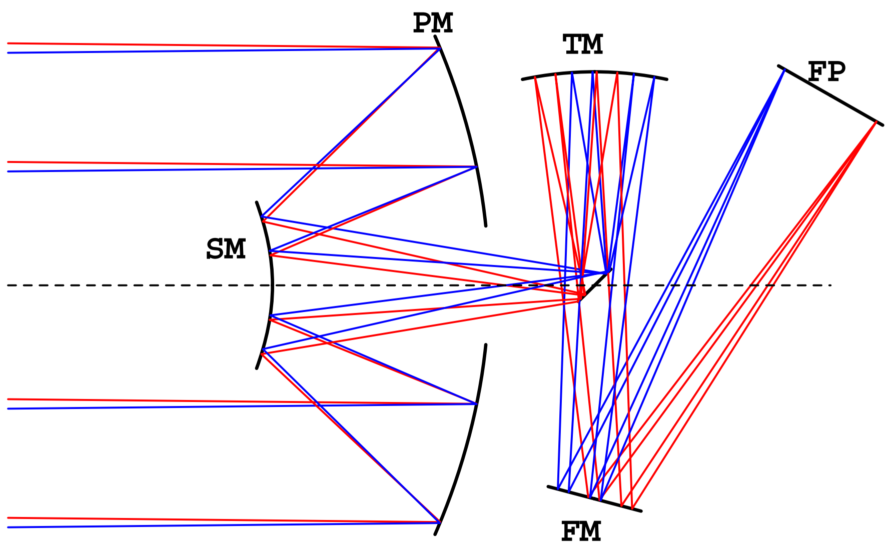
Figure 1 (Upper): A full field TMA with the tertiary mirror on the main axis, configuration I . Stray light and stray heat baffling are not shown. The Cassegrain focus field is small, and passes through the hole in the angled extraction mirror EM to illuminate the tertiary mirror TM. (Lower): prescription for this TMA example. Coordinates are in meters, angles are in degrees, curvatures are in reciprocal meters.

The FFTMA with configuration I was proposed by the ESA Wide Field Imager study group[11]. They adopted a strongly convex aspheric focal surface rather than Korsch's flat focal surface.

Due to the very short Cassegrain focal length and the large subsequent magnification, the optical tolerances of both the front-end portion (primary and secondary) and the rear end (tertiary relay mirror) are tightened, which can be an issue in telescopes subject to environmental stresses. For this example, to fit into a short overall envelope, the primary mirror operates at f/0.8 which can pose significant difficulties in manufacture and testing, and imposes unusually critical requirements for secondary mirror positioning and alignment. Because the focal plane directly views the front end optical train through the hole in the extraction mirror EM, the stray light treatment (not shown) for the outer baffle, inner baffle, and secondary mirror baffle becomes critical. This FFTMA has an accessible Cassegrain focus, located in the central hole of the EM, where a field mask can be placed to help control stray light.

Stray heat can be a problem if the FFTMA is to be run at ambient temperature and its sensors are to operate in the near IR. The exit pupil (image of the primary mirror) is large and is necessarily located far from the focal plane. There is no easy way to tightly enclose the exit pupil with a cold stop to block the sensor's view of the warm telescope structure. For use in the near IR, the telescope would have to run cold. For visible wavelengths only there is no cold stop requirement and the FFTMA becomes more attractive. In particular it enjoys a nearly uniform focal length and a nearly telecentric final image. Both features are thanks to the large distant exit pupil.

A configuration II FFTMA is shown in Figure 2. Here, the extraction mirror is a small tilted flat on the principal axis that directs the CF light towards the tertiary mirror TM. Unlike Korsch (1972 Fig 1b), we place the transverse TM axis behind the PM. This configuration shares many of the advantages and disadvantages of the FFTMA I. To have the TM operate at a large magnification, a long lever arm is needed on the output side of the tertiary mirror; again we deal with this long final focus by adding a flat folding mirror FM. As in configuration I, the exit pupil is larger than the Cassegrain field by the same ratio that the PM is larger than the SM, so that the light loss past the extraction mirror is negligible. The EM will need to be supported by a spider, but this support could be shadowed by the spider supporting the SM. Like the FFTMA I, the FFTMA II is difficult to baffle, but enjoys a highly uniform focal length and a nearly telecentric final image.



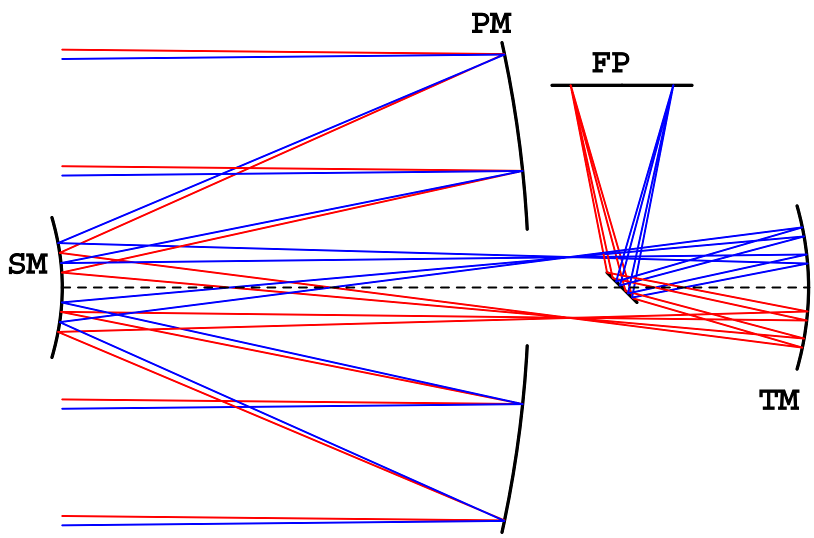
6 surfaces Fig2.OPT

X	Z	pitch	mir?	Curv	Aspher	Diam	dia
0	0	0	mirPM	-0.4059429?	-0.98380?	2.1	0.5
0	-0.9	0	mirSM	-1.1423599?	-2.55954?	0.7	
0	0.44	-45	mirEM	0			
0.9	0.44	90	mirTM	-0.7074022?	-0.66695?	0.6	
-0.9	0.44	-105	mirFM	0			
0.8	1.4214955?	60	FP	0			

Figure 2 (Upper): Full field TMA with the tertiary mirror off the main axis (configuration II in the notation of Korsch 1977) . Stray light and stray heat treatments are not shown. This arrangement is similar to the configuration I, except that the small central CF field is reflected to the TM rather than passing through the hole in the extraction mirror. (Lower): prescription for this TMA example.

3. Two Annular-Field TMAs

Annular field TMAs have been described by Korsch in both configurations I (Korsch 1977 Fig. 1) and configuration II (Korsch 1977 Fig. 2). These optical system use three powered mirrors plus one flat extraction mirror. The key advantage of the annular field TMA, as recognized by Korsch, is the very complete stray light baffling that its accessible exit pupil permits, particularly in configuration II. With a cold stop and heat shield surrounding the exit pupil, Korsch 1977 II allows complete baffling of its detector complement against heat emitted within the telescope outer baffle and therefore allows near-IR astronomy observations to be conducted with a warm (300K) telescope structure.

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5   surfaces                     Fig3.OPT
    X       Z      pitch  Curvature    Aspher     Diam   diam   Mirror?
---.---:---.-----:-----:---.-------:---.-------:------:------::----------:---
    0   :  0.0     :      : -0.2078487? -0.9831629? 2.1  : 0.5  ::mir pri   :
    0   : -2.0000 :      : -1.0055416? -1.9357465? 0.6  :      ::mir sec   :
    0   :  1.2     :      : -0.8001814? -0.6005692? 0.7  :      ::mir tert  :
    0   :  0.4     : 45  :           :           :      :      ::mir fold  :
  0.867?  0.4     : 90  :     0      :           : 0.6  :      ::FP        :
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Figure 3 (Upper): An annular-field Korsch TMA has its Cassegrain field much larger than the exit pupil. In configuration I shown here, the light from the tertiary mirror is extracted at the exit pupil by a small flat mirror. The tertiary magnification is ~1.5x. (Lower): prescription for this TMA example.

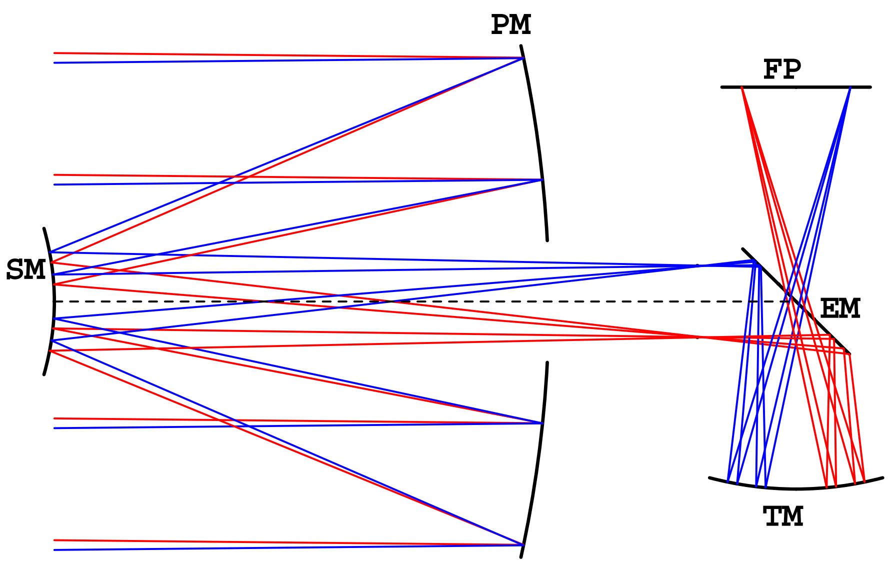
The Korsch AFTMA design embodies a large Cassegrain focal field and a comparatively small exit pupil. This exit pupil defines the central optical blind spot. Since its size is linearly much smaller than the Cassegrain field, the central blind spot need not severely compromise its efficiency in sky survey work. A benefit is the Cassegrain system has a focal length nearly as large as the final effective focal length, so that the tertiary magnification need not be large (ranging from 1 to 2) thereby allowing the front-end and rear-end optics to be relatively tolerant of misalignment. The disadvantages of the AFTMAs are consequences of the close working distance between the EP and the FP: the image is strongly nontelecentric and suffers from significant pincushion distortion (but see below). An AFTMA I optical layout and optical prescription are shown in Figure 3 above, and an AFTMA II is shown in Figure 4 below.

A variant of the AFTMA configuration I has been developed by the DUNE team[12, 13] who largely eliminated the field distortion of this configuration by introducing two modifications: (1) increasing the magnification by the tertiary mirror by enlarging the light path between tertiary and focal plane and, for compactness, adding a folding mirror to that light path; (2) allowing for a slightly concave focal surface. With these changes, they find the optical distortion to be small enough to allow image recording by means of time delay integration.

The Korsch AFTMA configuration II has been adopted by the SNAP space telescope team[14,15,16,17]. The SNAP optical train includes a four-blade shutter and an extensive stray light treatment at CF, whose access requirement lengthens the package somewhat beyond what is necessary for purely optical reasons. The advantage of the configuration II is the extreme baffling capability between the exit pupil and the focal plane, rejecting stray heat from an ambient temperature telescope yet allowing a cold sensor environment for near-infrared capability.

The Korsch AFTMA configuration II has also been adopted for the PLEIADES High Resolution (HR) instrument[18], where a long focal length and a speed of f/20 was sought in a compact and robust package.

An annular-field TMA was proposed by Nariai and Iye[19], wherein the flat folding mirror of Figure 4 is broken into two flats joined at 90 degrees on the optical axis. Each flat feeds a dedicated half-field tertiary mirror. These tertiaries in turn illuminate two separated image planes, each of which is a nearly complete semicircle.



5 surfaces Fig4.OPT

X	Z	pitch	Curvature	Aspher	Diam	diam	Mirror?
0	0.0		-0.2049195	-0.9826577	2.1	0.5	mir pri
0	-2.0000		-0.9479331	-1.7968547	0.6		mir sec
0	1.0	45					mir fold
-0.77	1.0	-90	-0.7506071	-0.6114183	0.7		mir tert
0.88	1.0	90	0		0.6		FP

Figure 4 (Upper) : An annular field Korsch configuration II TMA. The extraction mirror on the axis directs the Cassegrain field CF onto the tertiary mirror TM. The hole in the EM allows the TM to illuminate the focal plane FP. The exit pupil lies within the hole in the annular flat mirror. A conical cold stop structure can extend from EP to the FP without blocking light. (Lower): prescription for this TMA example.

4. COMPARISON

A summary of the salient properties of the AFTMA and the FFTMA is listed in Table 1, below. We emphasize characteristics that are most important in wide field space astronomy missions. In particular the field flatness and telephoto advantage of both systems are satisfactory, allowing image aberrations of subpixel size -- just a few microns -- when instrumented by a one square degree flat detector array working at a 22 meter (f/11) focal length. The primary speed and Cassegrain focal ratios listed here for the AFTMA are practical and impose no particularly severe construction difficulties, while those parameters for the FFTMA are more demanding but can still be achieved with careful engineering. The low distortion of the Korsch configurations that employ a large tertiary magnification (FFTMAs and some AFTMAs) is advantageous for applications in which images are to be captured using time-delay integration.

Table 1: Comparison of the two classes of Korsch TMA

	Full Field TMA EP surrounds CF		**Annular Field TMA CF surrounds EP**	
Effective system f/number	f/11		f/11	
Cassegrain focus f/number	f/3		f/8	
PM speed	f/0.8		f/1.2	
Geometrical total aberration	4 um rms		3 um rms	
SM sensitivity	5 um blur per micron		1 um blur per micron	
TM sensitivity	0.5 um blur per micron		0.1 um blur per micron	
Korsch (1977) configuration	I	II	I	II
TM axis and location	on PM-SM axis	off PM-SM axis	on PM-SM axis	off PM-SM axis
EM size & shape	EP; annular	CF; central	EP; central	CF; annular

PM=primary mirror; SM:=secondary mirror; TM=tertiary mirror; CF=Cassegrain field; EP=exit pupil.
Sensitivities shown are slopes of rms blur per unit piston of optic when displaced from optimum location.

5. CONCLUSIONS

We conclude that both the FFTMA and AFTMA will continue to find applications in wide field imaging. For the planned SNAP mission we have adopted the AFTMA since the central blind spot poses no particular problem in conducting wide field surveys and since its extreme baffling against stray light, stray heat, energetic radiation and contamination is advantageous for safeguarding survey sensitivity. Moreover since SNAP will conduct weak lensing shear mapping, its point spread function stability will be important, and the low sensitivity of the AFTMA PSF to slight misadjustments is attractive. However, for applications at visible wavelengths or with cooled telescopes the stray heat issue would not be a significant driver. In these applications a large tertiary magnification Korsch FFTMA or AFTMA may be preferred because of its reduced distortion.

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