An optical analysis for a band-arc telescope

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A band-arc telescope has a primary mirror which is curved in one direction (say, the x-direction), and flat in the other (the y-direction). The primary is shaped like a segment of a cylinder, with the axis of the cylinder parallel to the y-axis. The challenge is to design a secondary mirror which produces high-quality images of celestial objects.

The basic idea for the secondary mirror is straightforward. The design was chosen in analogy to the Maksutov telescope. In a Gregory-Maksutov, the primary mirror is concave spherical, while the secondary mirror (Cassegrain-class design) is convex spherical pointing toward the center of the primary. The two mirrors have a common center of focus. (I'm sure there is a better term for this geometrical commonality, but I don't know one. The idea is that parallel rays of light entering the telescope would reach a common focal point if directly reflected by either mirror or lens surface.)

The resulting images are rather poor, so a thick but weak meniscus lens whose surfaces again have the same common center of focus is positioned in front of the secondary mirror, which is now made by aluminizing a small spot on the back surface of the meniscus corrector. Figure 1 is of a Gregory-Maksutov telescope. The original 3.5" Questar telescope was a Gregory-Maksutov.

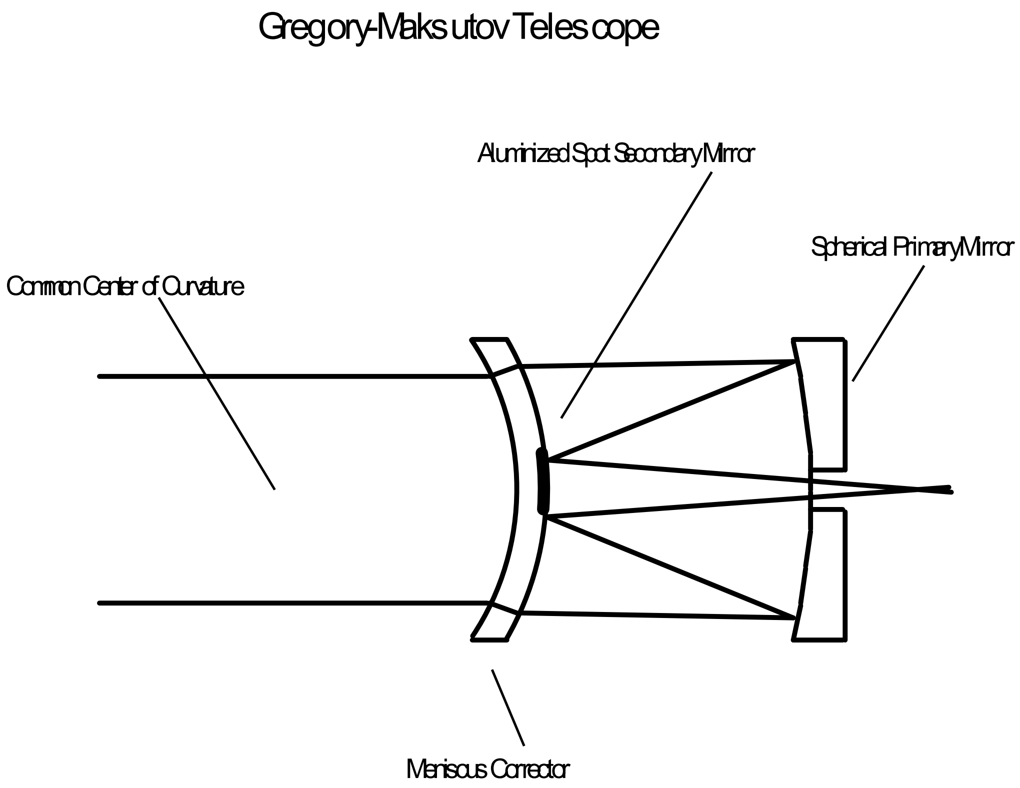

Figure 1. A Gregory-Maksutov Telescope

A diagram of a band-arc telescope appears nearly the same when looked at along the x-axis, the direction in which the primary mirror is curved. Figure 2 is a cartoon of such a telescope viewed along the 3 coordinate axes.

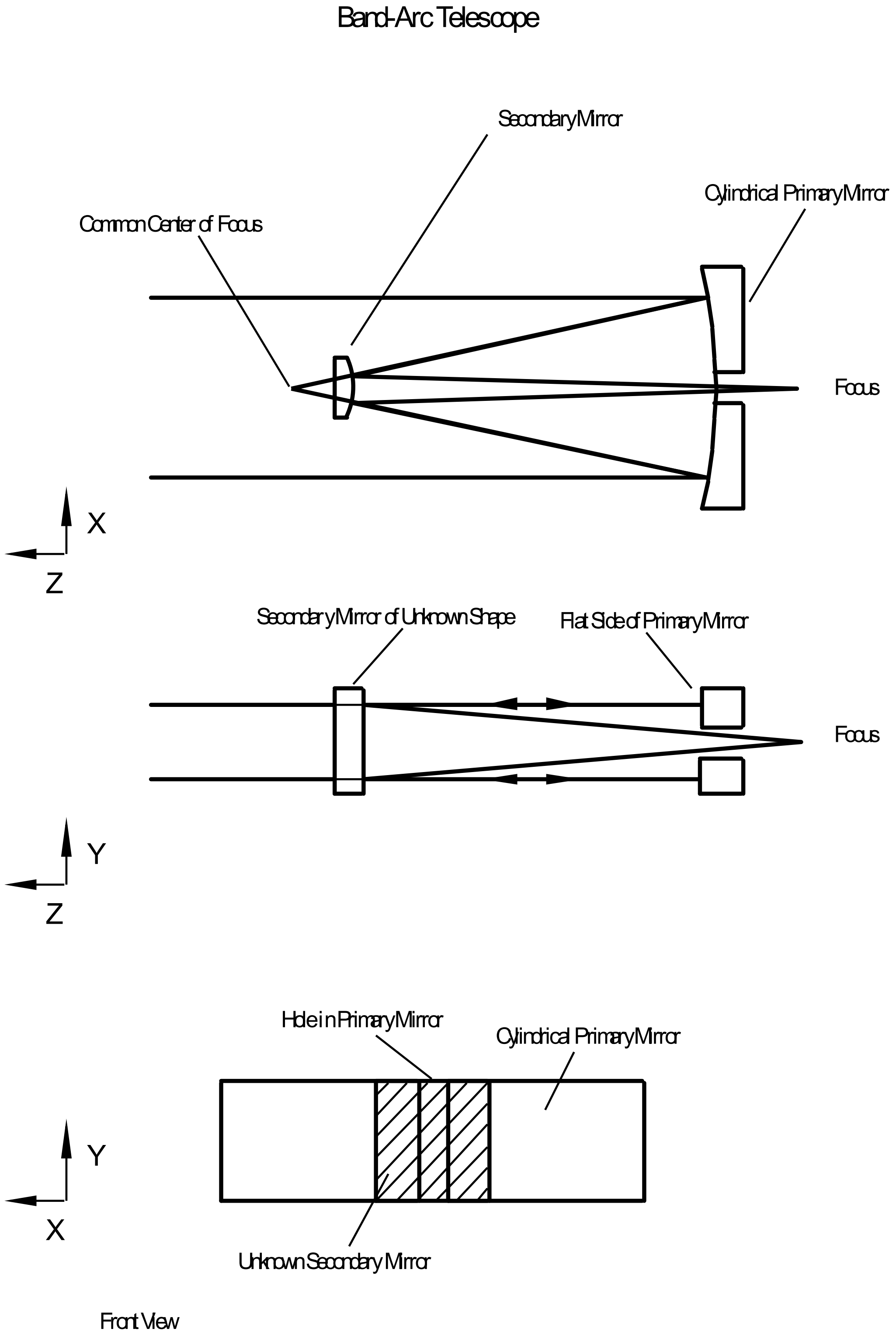

Figure 2. A band-arc telescope

You will see that looking along the y-axis, the band-arc telescope looks like a classical Cassegrain telescope, save that the two reflecting surfaces have a common center of focus. However, along the y-axis the telescope appears to be a flat primary, whose reflected light is reflected back to the same Cassegrain focal point by the as-yet unknown surface of the secondary mirror. (Note that the light reflecting from the primary mirror is bypassing the secondary on the left or right in the x-direction.)

Finally, the Front View gives a better perspective of the band-arc telescope. It becomes clear that it is elongated in the x-direction compared to the y-direction. This is intended to give excellent resolution while greatly reducing the mass and cost of the telescope relative to a full-diameter equivalent Cassegrain. The remaining issue is whether or not this can be done.

Ray Tracing

Well, it turns out it can. The shape of the surface of the secondary mirror is that of a torus sitting in front of the mirror as shown (not very clearly) in Figure 3 below.

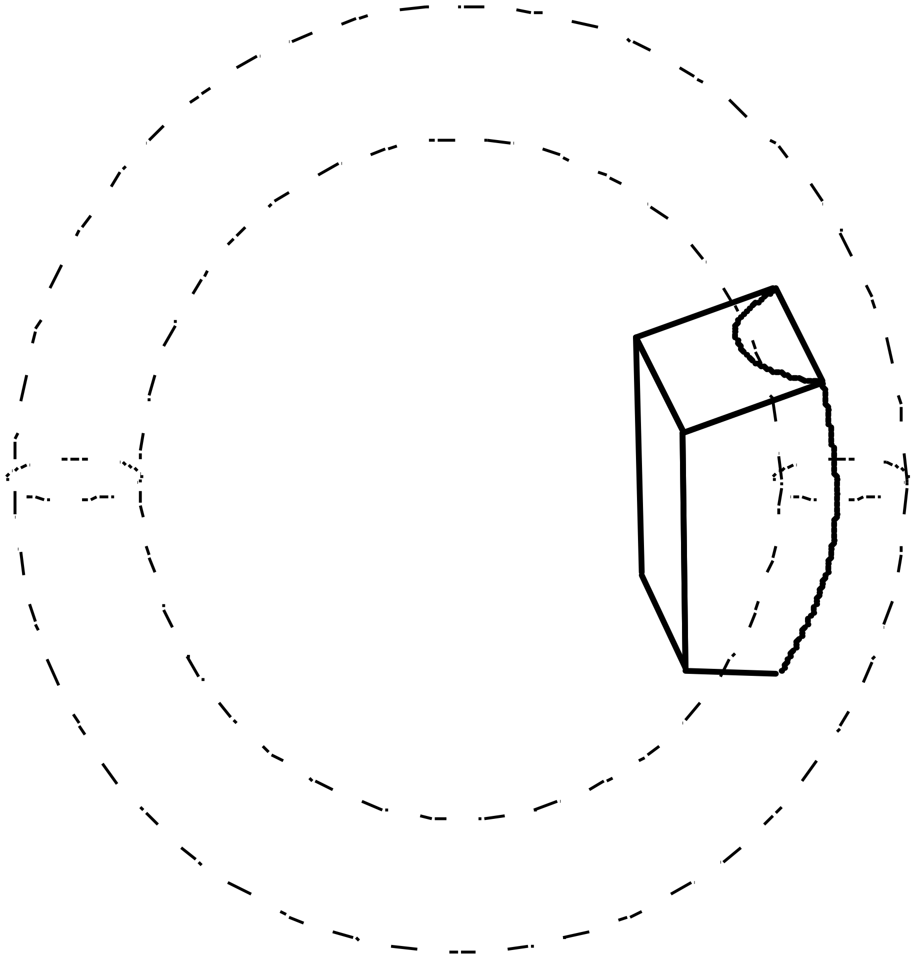

Figure 3. A band-arc secondary mirror.

The front surface of the secondary mirror in the x-axis has convex curvature with radius of curvature of the large radius of the torus, while the y-axis has concave curvature with radius of curvature of the small cross-sectional radius of the torus. The shape is rather like that of a saddle.

To set the shape of the secondary mirror more precisely, I set the curvature in the x-direction to have the same common focus as that of the primary mirror in the x-direction. That is, the XZ cartoon of Figure 1 is given the analogous dimensions of a Gregory-Maksutov. This has an important effect. A slit of light with the long axis of the slit oriented along the x-axis in the XZ cartoon will intersect the secondary mirror along a line of constant y. Along this line of constant y, the shape of the secondary is purely the convex shape of a Maksutov secondary. Such a long slit of light will then be focused to a point behind the primary mirror. However, with this geometry every long slit with x-axis orientation will be focused to the same point. Thus, if the secondary mirror only had its convex curvature, light illuminating the entire primary mirror along the z-axis will be focused to a line parallel to the y-axis. This line will have the length of the small side of the primary mirror, and will be focused to a tight focus along the x-direction. The important point here is that an incoming beam of light entering parallel to the Z-axis will focus behind the primary as a straight line of light parallel to the y-axis.

This geometry effectively decouples focusing along the x-direction from focusing along the y-direction. We do, however, want to arrange that the x-focus and the y-focus occur at the same Z position. Ideally the effective focal length of the x and y directions at the common focal point (behind the primary) would be the same, but this will not happen in this design. The remaining stretching of the image can easily be compensated for using image processing.

I took a particular example of a band-arc telescope to optimize. I did not choose the example in the problem (an f/0.71 cylindrical mirror) because the aberrations of such a fast mirror would probably obscure the more fundamental issues.

Here are the specs of the band-arc telescope I studied:

Size in the x-direction: 1m

Size in the y-direction: 0.1m

Cylindrical radius of curvature: 10 m

Primary cylindrical focal length: 5m

F ratio of primary: f/5.0

Separation between the primary and secondary mirror surfaces: 4m

Convex radius of curvature of the secondary mirror: 2.5m (set by the requirement that the center of focus of the primary and secondary mirrors be the same)

Concave radius of curvature of the secondary mirror: 9.82m (see below)

A quick ray-trace of the cylindrical telescope showed that the x-focus was at a position about 0.91 m behind the surface of the primary mirror. (It also showed nearly diffraction-limited performance in the x-direction on the focal plane.) The secondary-focal plane distance is thus 4.91m. This means that to reach a common focal point, it is necessary for the secondary mirror to have a concave radius of curvature of about 2x4.91m, or 9.82m. I used these measurements as a starting point for analysis.

I used a ray tracing program called Beam Four by Stellar Software (www.stellarsoftware.com). It is a bit painful to use in the free demo version, but the algorithms seem quite precise.

To make a long, long story short, here is the design I obtained.

Primary Mirror:

x-axis center of curvature: 10m (concave)

y-axis center of curvature: ∞ (flat)

x-axis length: 1m

y-axis length: 0.1m

central aperture: 0.1m (essentially the mirror is made in 2 parts. This can be altered to make a single mirror if required.)

Secondary Mirror:

x-axis center of curvature: 2.5m (convex)

y-axis center of curvature: 10.10m (concave)

dimensions: 0.3m x 0.1m rectangle (long side along x)

Focal Plane:

Location: 0.91m behind primary mirror surface

Stellar image size (x-axis x y-axis): ~8microns x 2 microns

Effective focal length in x-axis: 20.67 m

Effective focal length in y-axis: 4.91m

Magnifying power of secondary mirror along x-axis: ~4.1

Ray-tracing resolution in x-direction: 0.08 seconds of arc (ignores diffraction)

Ray-tracing resolution in y-direction: 0.08 seconds of arc (ignores diffraction)

Resolution is diffraction-limited.

Theoretical resolution: ~0.14 seconds of arc along x-axis; ~1.4 seconds of arc along y-axis

Equivalent light-gathering power: 0.357m diameter conventional telescope

Limiting magnitude (visual): 16.4

This study could profitably be extended in several directions:

- Is the focal plane flat?
- Evaluate coma, spherical aberration, and other aberrations.
- Consider additional optics to produce equal equivalent focal lengths on the x and y-directions.
- Evaluate faster telescopes (smaller f-number). These are likely to require aspherical surfaces for top performance.

Other questions could be addressed. However, the optimization process in this preliminary study resulted in a remarkably capable telescope – an encouraging result!