Building a 6-Inch Unobstructed Yolo-Newtonian

I have designed an optical system that can be thought of as an unobstructed Newtonian telescope. This system uses a standard paraboloidal primary and a small secondary mirror. In this telescope, however, the secondary is not flat but is concave and cancels the aberrations introduced by the tilted primary; the resulting image quality is good as long as the primary is slow.

The optical system can also be considered an extreme case of a Yolo; therefore the formulas given in "How To Design a Yolo Telescope" (*Telescope Making #37*) can be used to predesign it. Because the tilt of the secondary is quite large, it is necessary to optimize the predesign using ray tracing software.

My design uses a 6-inch f/12 paraboloidal primary. The characteristics of the system are given in the table with the same notation used in "How To Design a Yolo Telescope." The field performance was evaluated using spot diagrams for the on-axis image, and five positions around a semifield of view of 1/4 degree. The field is limited by about 1/2 wave of linear astigmatism, and the image plane is tilted 8 degrees. The image anamorphism is 1.4 percent.

TMs who do not have access to a computer still can design their own unobstructed Newtonians. This can be done by optimizing their predesigns using my optimized design as a guide. To do this, design my system using the formulas given, estimate the percentage error, and then correct the design.

The correction is first applied to the secondary angle of tilt, then to the secondary long radius of curvature. The correct setting of these parameters make the secondary cancel the on-axis coma and astigmatism produced by the primary. This method will work provided the systems considered are similar to my design, say, for systems using a 6-inch primary with a focal ratio between f/10 and f/14. Scaling can also be done to specify smaller systems.

It must be remembered that minor adjustments to correct residual on-axis aberrations due to fabrication errors and slight calculation errors can always be done after the optics have been made. These adjustments are done changing the secondary position and tilt.

Making the Secondary

The surface of the secondary mirror is a section of a concave oblate ellipsoid that has two principal radii of curvature. The first step to make the mirror is to grind a long radius of curvature sphere. Because the difference in the radii of curvature, R_s and R_t is large, the double curvature must be generated during the last stage of fine grinding. For this purpose, long unidirectional grinding strokes are performed with the mirror on top of a full-sized grinding tool. This shortens the mirror's radius of curvature in the chosen direction.

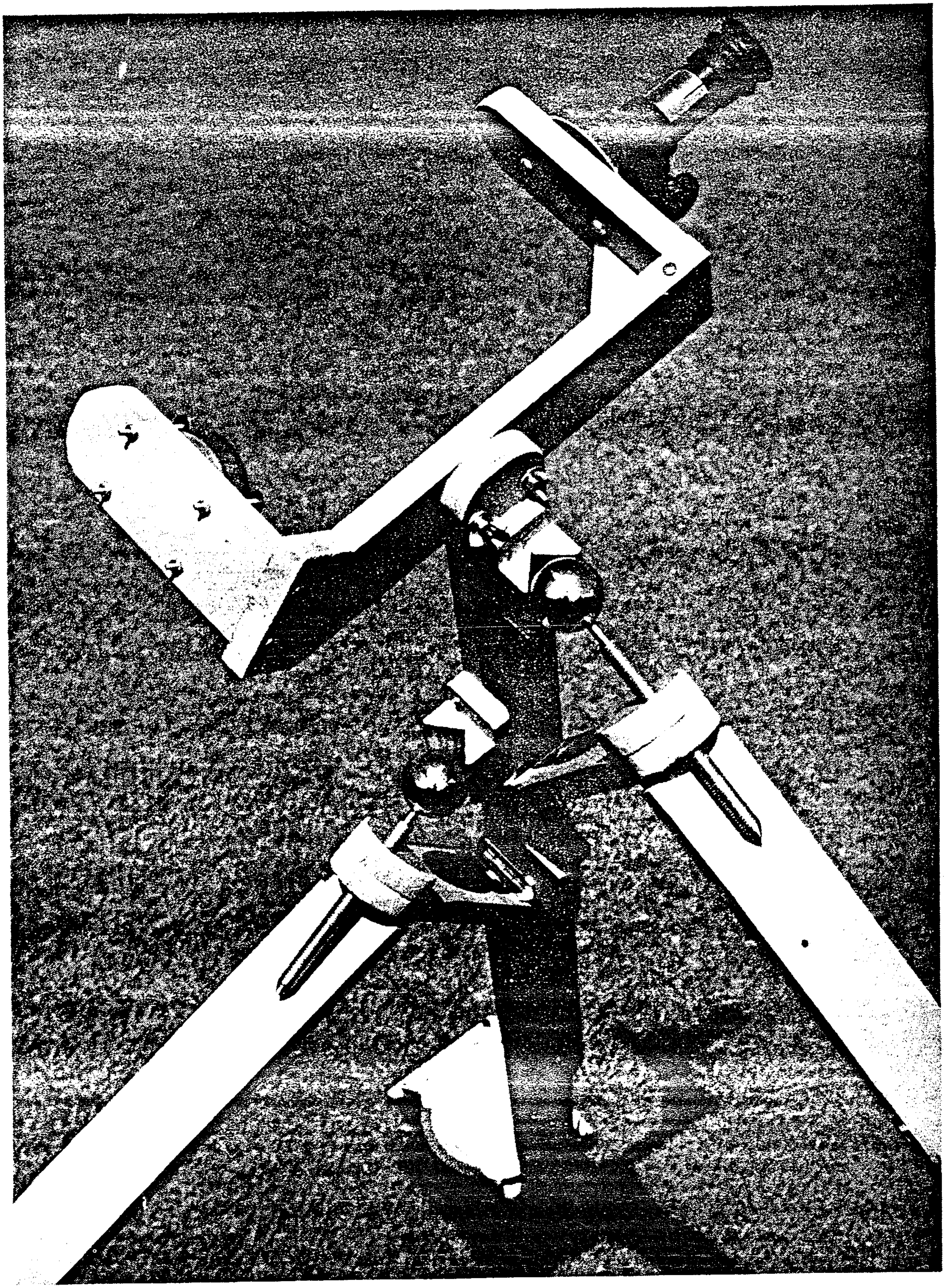
This process is very similar to traditional grinding except that the well-known sequence of events happens unidirectionally. Namely, a deep excavation in the center of the mirror is made using a long stroke, and then the rest of the surface is made uniform in curvature by reducing the stroke length. In fact, for this surface smoothing, you can perform normal grinding strokes in all directions doing only translational movements.

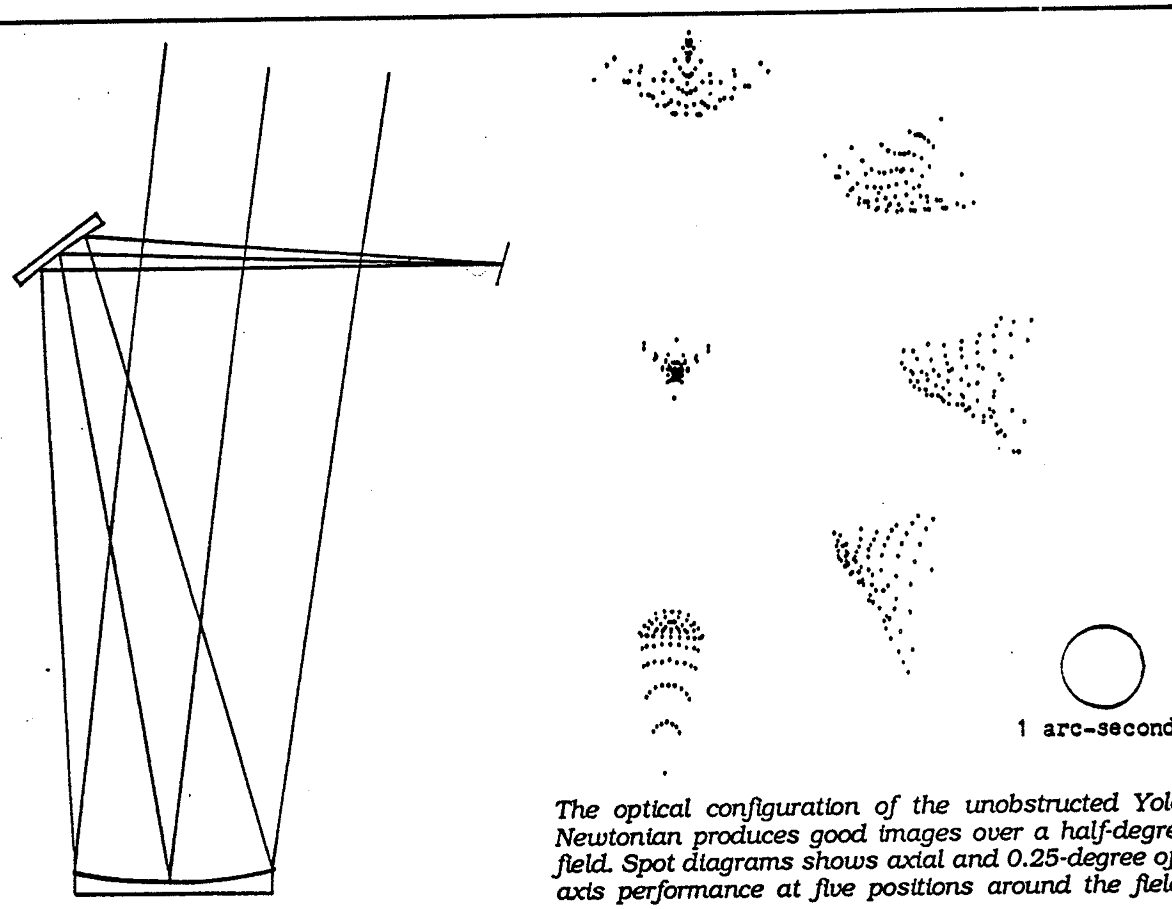
In my article in *TM#37*, I suggested a double four-bar linkage to constrain the rotation of the grinding or polishing tool, but the entire process can be done by hand. For this optical system the difference in sag of the two principal sections is so large that maintaining the parallelism between tool and mirror to within a few degrees becomes important. One can easily feel the effects of a small rotation in the grinding or polishing movements, and eventually one learns to direct his or her hands very precisely. Because the surface has two perpendicular planes of symmetry, you can rotate the mirror 180 degrees once in a while.

To monitor the generation process, I painted the mirror surface with a China marker, a waxy type of pencil. After removing the excess paint by scraping it with a razor blade dragged almost parallel to the blank, the surface became shiny enough to reflect light and made an optical test possible. The appearance of a ground surface before and after the scraping is illustrated in the photo.

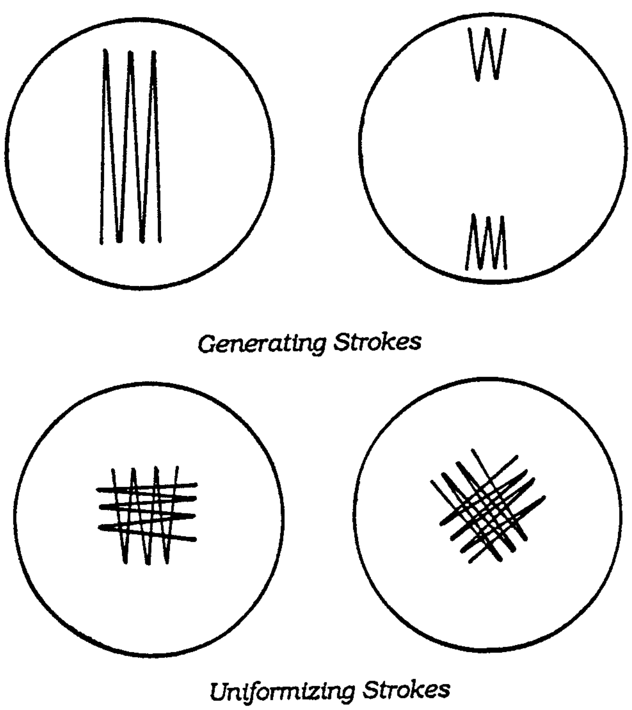
You can null test the mirror at its conjugate focii, but I tested the secondary using the aluminized primary

This novel optical design on its novel mounting makes for a very unusual-looking telescope. The Yolo-Newtonian offers an unobstructed aperture and an optical system consisting of just two elements.





The optical configuration of the unobstructed Yolo-Newtonian produces good images over a half-degree field. Spot diagrams shows axial and 0.25-degree off-axis performance at five positions around the field.



Typical generating and uniformizing strokes for secondary mirror; zig-zag lines show the path of the mirror center over the tool. Only translational movements are allowed.

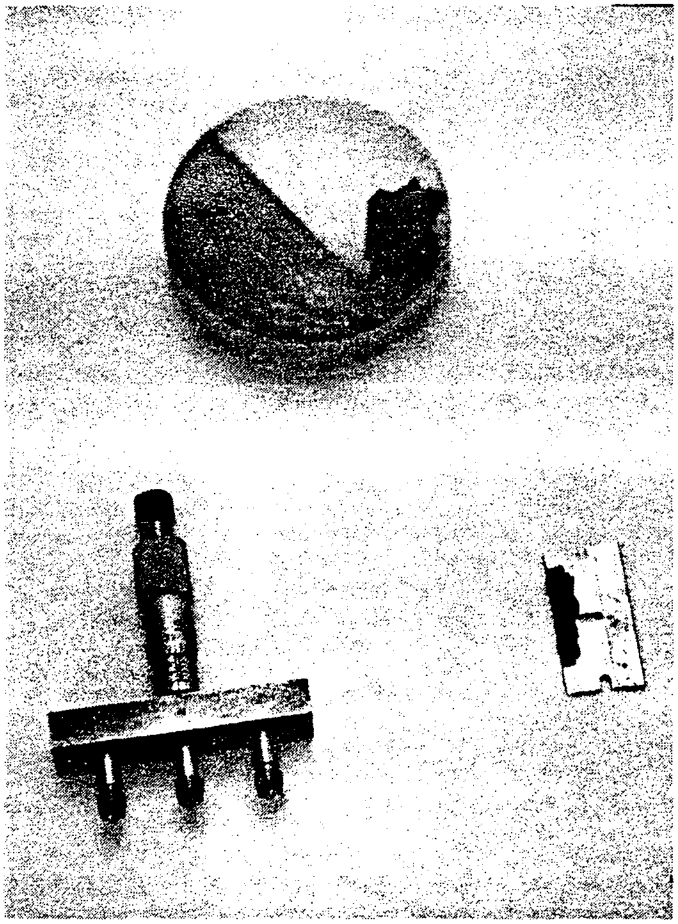
mirror. I prefer the test in which the secondary is placed at a specific angle with respect to the axis of the aluminized primary mirror because of the reduced test distances.

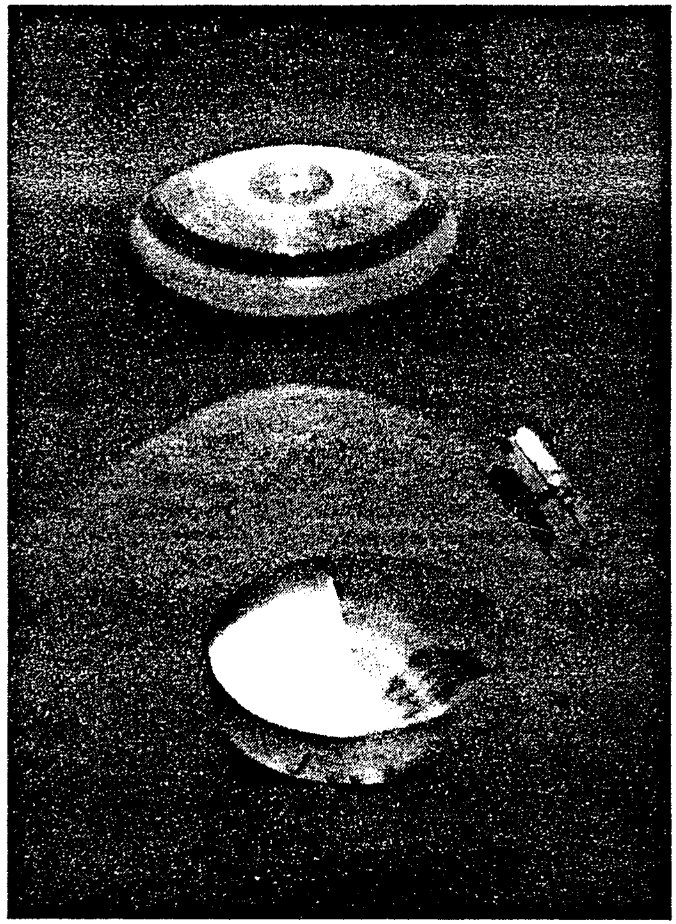
The purpose of these tests is to verify that no astigmatism is present when the secondary is tilted by the angle α, as calculated using the formula given in the above-mentioned article. These tests insure that the appropriate difference in curvature has been generated. The astigmatism can be detected by looking at the image of a point source with an eyepiece or by projecting the image on a fine ground glass.

Once the double curvature is generated, make a full-sized polishing lap and polish the secondary in a manner similar to the polishing of a standard mirror but doing only translational polishing movements. Either one of the methods mentioned can be used for the final test of the secondary. The second method using the primary is not a null test, and some residual coma will be observed. However, a smooth surface must be obtained.

The blank for my secondary is 3 inches in diameter, considerably oversized to allow for a turned-down edge. This problem could easily result if significant movements of rotation happen during the polishing. The clear aperture of the secondary is elliptical as in a regular Newtonian. The smaller diameter, that is, Φ_s, is the one used in the calculations. The large diameter, without considering the field size, is given approximately by $\sqrt{2}\cdot\Phi_s$.

The curvature of the starting long radius sphere was measured with a two-leg spherometer. The sag to measure was so small, about 0.001 inches, that a verification was necessary. This was done during the test in which the primary was used. Knowing the radius of the





primary R_p, the power of the secondary,

$$P_s = 2 \cdot \cos(\alpha)/R_s ,$$

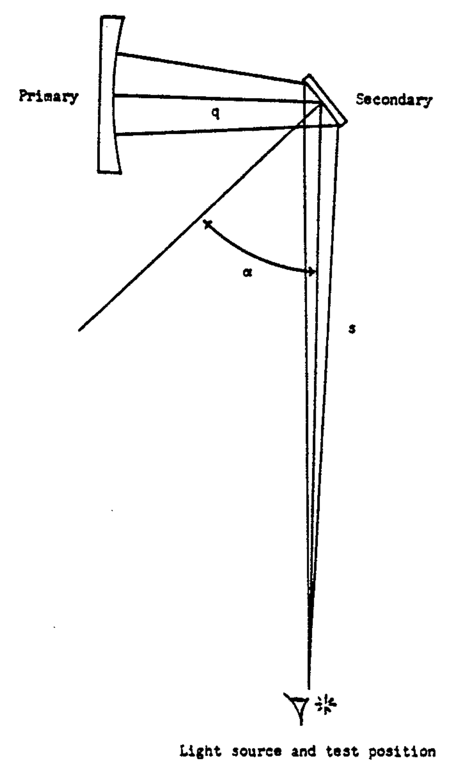
the primary to secondary test distance q, and the secondary to test point distance s, you can find out the short radius of the secondary from the relation:

$$P_s = (1/s) - (1/(R_p - q)) ,$$

which is the well-known lens formula.

To recap, then, here are the steps you should follow in making the ellipsoidal secondary:

1. Use an oversize blank (3 inches) and fine-grind it to a sphere of radius R_t.
2. Grind in the short radius by doing long, unidirectional grinding strokes for 30 minutes, with the mirror on top. Occasionally rotate the mirror or tool a full 180°.
3. Uniformize the surface by doing normal-length unidirectional strokes for 20 minutes.
4. Determine the difference in radii using either method. Method 1: Measuring the sag in the two principal meridians using a two-leg spherometer. Method 2: Coat the fine-ground surface with a waxy pencil, scrape off the excess with a razor blade, and determine the angle α at which you see no astigmatism.
5. Proceed toward the correct difference in radii, by repeating steps 2 through 4, until you see the correct sag in both meridians or until you see no astigmatism at the angle α specified by the design. Make sure the surface is uniform before proceeding.
6. Polish with a full-size polishing lap using translational strokes only; do not rotate the tool or mirror.



A simple test configuration for checking the radii of the ellipsoidal secondary mirror. The long radius meridian of the secondary must lie in the plane of symmetry of the test system.

Data for Three Unobstructed Yolo-Newtonians

(dimensions in millimeters)

Focal Ratio of Paraboloid	f/10	f/12	f/14
Φ_p	150	150	150
Φ_s	40.2	33.42	28.64
t	1100	1400	1700
I_p	3.00°	2.25°	1.95°
I_s	42.0°	42.75°	43.05°
R_p	3000	3600	4200
R_s	5140	5900	5944
R_t	10252	11780	11869
b	360.2	365	365.2
α	44.92°	44.95°	44.95°
System f/number	8.97	10.92	12.75
Focal Length	1346	1638	1913
Tilt of the Image Plane	8°	8°	8°

Strokes should be normal in length; avoid long strokes.

7. Test the figure and smoothness of the secondary. Apply methods analgous to those used in standard mirror-making to correct figure errors.

Generating the curvature difference took me about 3 hours using 5-micron aluminum oxide abrasive, and polishing took 6 hours using cerium oxide.

Mounting the Optics

I started making the optics of this telescope with no idea of how to mount them. I wanted a mounting as simple as possible and decided to mount the primary and secondary mirrors and the eyepiece holder on a single wood board working as an open tube. I realized that such an arrangement would be very susceptible to vibration if it were mounted on a traditional mount, so I chose a different approach, which is illustrated in the photos.

This kind of tripod mounting consists of a principal leg on which the optics are mounted, and two auxiliary legs to stabilize the pointing of the optics. These auxiliary legs, mounted at right angles with respect to each other, are connected to the principal leg with two intermediate wood links. All these are joined with ordinary door hinges. Each of the intermediate links carries a screw that serves to produce slow motion, and each screw tip has a ball to smooth out the interaction between the screw and the principal leg. The balls also serve as knobs to turn the screws.

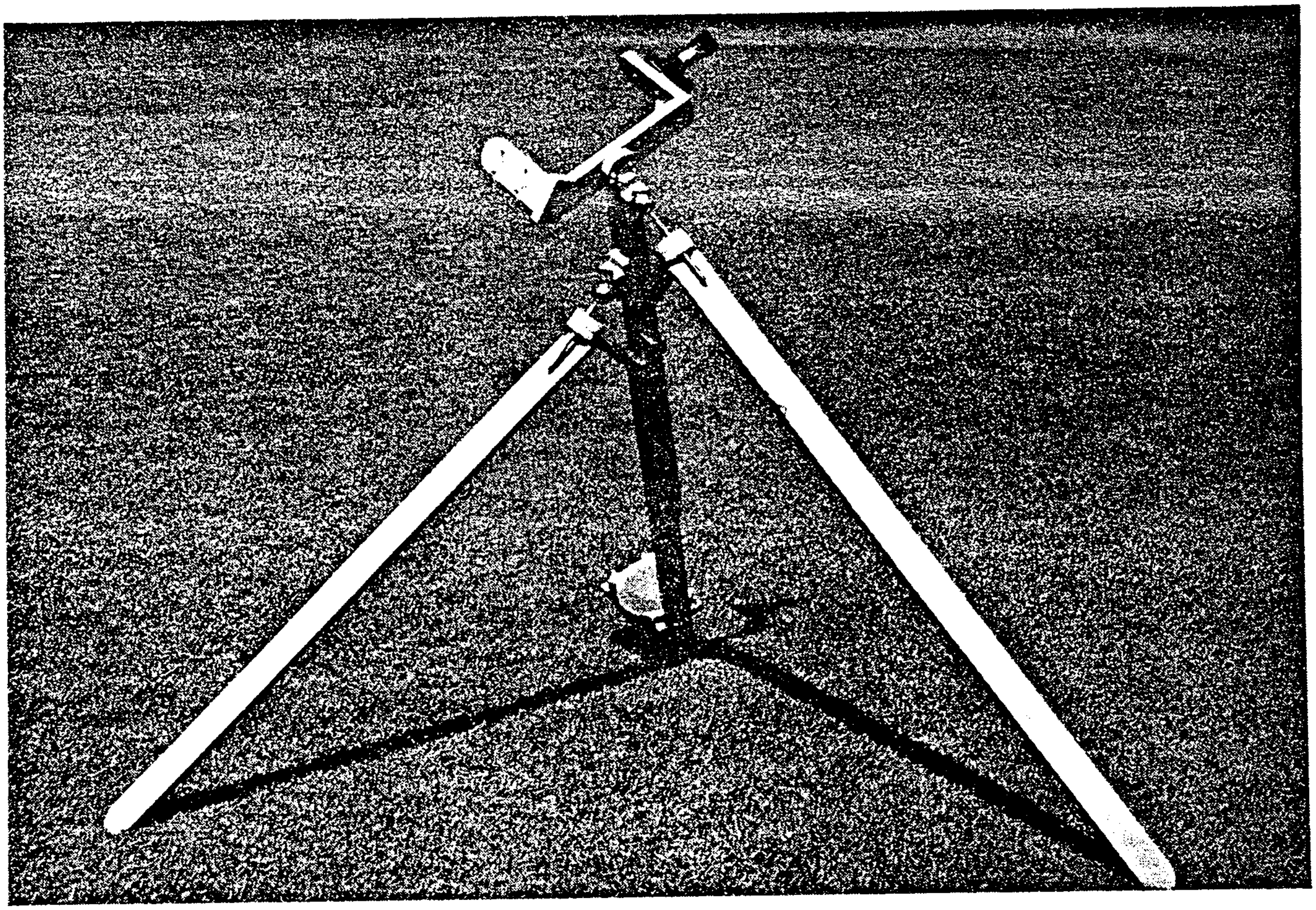
This mounting has two operational modes. In the first, called the guiding mode, the balls are in contact with the principal leg and its position is determined by the auxiliary leg apertures and screw positions. Guiding is done by turning the screws. In the second, called the aiming mode, the principal leg is not in contact with the screw balls and it is free to pivot on its lower end to aim within a limited range. The auxiliary legs follow the principal leg through the intermediate links, but they are not locking the principal leg position.

To aim this telescope the auxiliary legs are set to point the optics approximately at the desired sky object. Then, by pulling the principal leg, one goes to the aiming mode and positions the object of interest in the finder. Then the mount position is locked by bringing the screw balls in contact with the principal leg, which is done by changing the opening of the auxiliary legs. Finally, the object is brought to the eyepiece field using the slow- motion screws.

The advantages of this mounting are its great simplicity, portability, reduced weight, and most important, its inherent nature of being little susceptible to vibrations. The obvious disadvantages are that it is not an equatorial mount and its limited range of aiming. However, because the telescope is intended to observe the Moon and planets, the latter drawback is not a serious problem. The length of the auxiliary legs sets the aiming range. For my mount I can observe objects above an altitude of 45 degrees.

Telescope Alignment

Even though I made the secondary radii of curvature slightly off the nominal values, R_s was about 5,300mm, adjusting the telescope optics was relatively easy. I rotated the secondary mirror and changed its tilt to cancel the on-axis astigmatism. This operation made the defocused diffraction rings of a star circular indicat-



The Yolo-Newtonian optical system may be mounted in a conventional tube, if desired, on an open spar, or in a tube sealed with a precision window. If the mirrors have a smooth finish, images should be superb.

ing good alignment. Astigmatism varies rapidly with the secondary rotation, but the setting of this adjustment variable was not difficult because I could rotate the secondary while I was looking at the star image. It must be remembered that the meridian of the secondary's long radius should coincide with the telescope's plane of symmetry.

Coma was not a problem because it varies slowly as a function of the secondary tilt. Any coma residual will be small. The primary introduces about 2 waves of this aberration. Most of it would have been canceled by the secondary even if it were off in tilt by several degrees. However, coma varies rapidly with the primary tilt and secondary spacing, so it is important to set these parameters correctly.

When you set up your optics for the first time, follow this alignment procedure:

1. Set the primary-to-secondary distance and the tilts of both mirror as close as possible to the specified values.

2. Examine the image of a star and rotate the secondary to make sure the long radius of curvature meridian coincides with the telescope's plane of symmetry. (As the secondary is rotated, a large amount of astigmatism will be seen; rotate the secondary until no astigmatism is observed, or until any residual astigmatism is aligned with the telescope's plane of symmetry.)

3. Examine the image of a star and change the tilt of the secondary to remove residual astigmatism. You will have to move the eyepiece holder when you do this adjustment.

4. Examine the image of a star. If you observe residual coma, change the distance between the primary and the secondary slightly, until the coma is removed.

5. Carry out subsequent realignments by rotating the secondary and changing the primary's tilt. Note that the secondary must maintain its tilt with respect to the eyepiece holder and the primary mirror when you realign the system. This is relatively simple compared to first-time alignment because you will not have to change the location of the eyepiece holder when you change the tilt of the primary.

In testing the finished telescope critically, I found that the primary mirror is slightly overcorrected; therefore, I had to stop it down to about 5.25 inches to observe intra- and extra-focal diffraction rings with equal contrast. After this unfortunate discovery and subsequent repair, very good star images were observed.

After the Riverside Conference on a night of good seeing, I readjusted the optical system and could see very well, at 400x magnification, the Airy diffraction pattern of a star. This shows that very good performance can be achieved with this system. The double-double, Epsilon Lyrae, was very well split, and there was a distinct black region between the stars of both pairs.

I would like to thank Richard Sumner for providing the materials and allowing me the use of facilities to make the optics for this telescope.

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Designing a YOLO Telescope

It has been twenty-four years since Arthur Leonard presented the unobstructed Yolo reflector, and yet the Yolo has not been as popular as it should be. I believe there will come a day when the Yolo scope will be very popular.

This instrument has not reached the place that it deserves because very little has been written about it, the advantages it has over other telescopes have not been fully documented, and a guide for its design and fabrication has not been published.

The Yolo telescope is an instrument mainly for observing the Moon, planets, and double stars. Its main feature is that it provides an unobstructed aperture in which a secondary does not degrade the image contrast and resolution. The Yolo optical system has the potential to provide excellent images over relatively wide fields.

It is true that the schiefspiegler telescope, which is also an unobstructed reflector, is easier to make than a Yolo. However, in order to have a good image, the focal ratio of the schiefspiegler optical system must be about 26, which results in a rather slow system. Three spherical mirror unobscured systems like the trischiefspiegler can be designed to have lower f/ratios. However, more work is involved in making and maintaining a third mirror, there is an increase in alignment difficulty, and there is slightly less contrast due to a third surface.

These facts make such systems less attractive to consider as an alternative. Other aspects to take into account when comparing unobscured systems are: image plane tilt, telescope maintenance, instrument size and portability for a given aperture and focal ratio, and the relative position of the observer in actual telescope use.

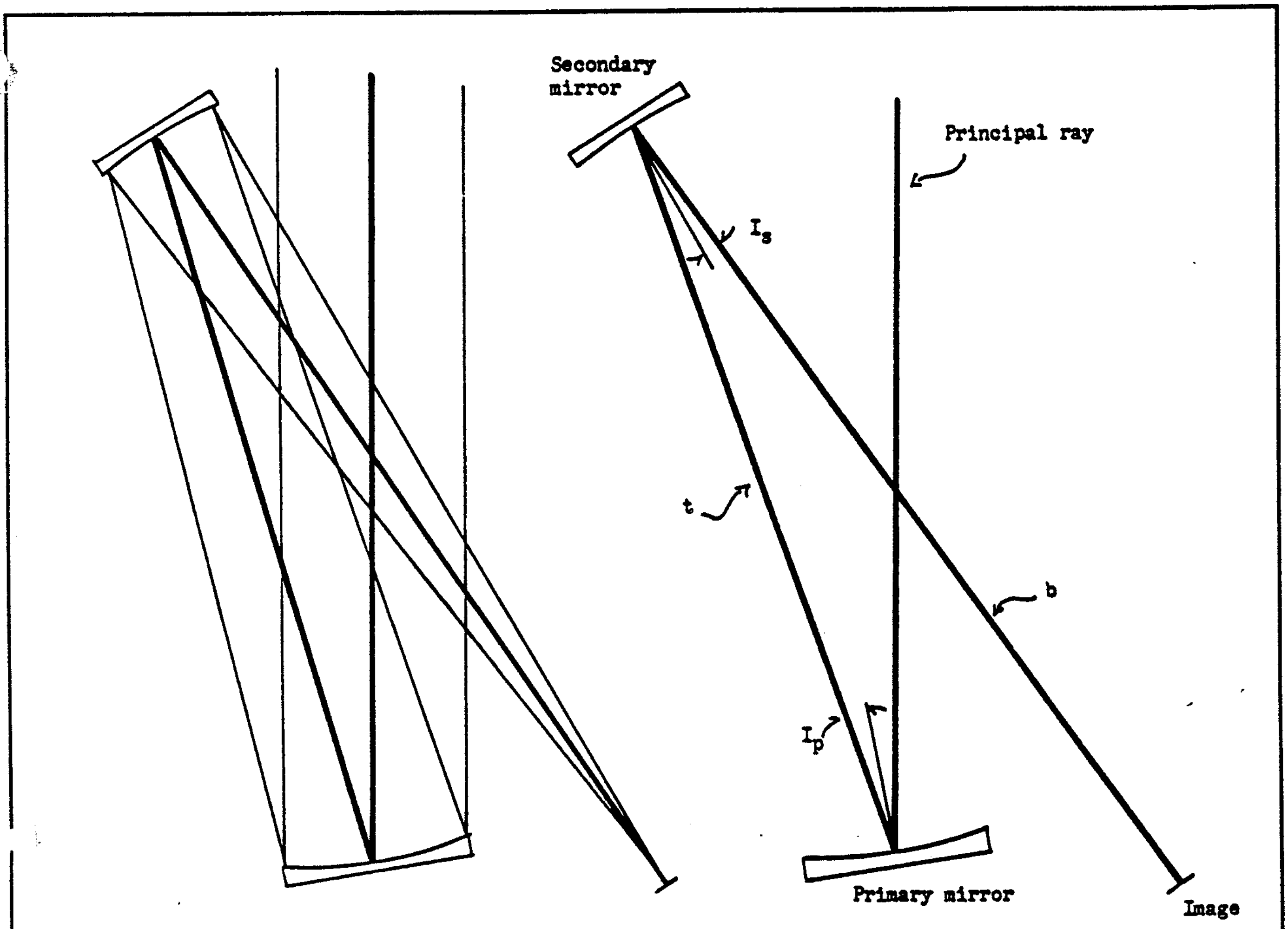
In its simplest version the Yolo optical system uses a spherical primary mirror and a secondary with a surface of double curvature to correct the on-axis astigmatism. The tilt of the primary is used to place the secondary out of the incoming light beam, and the tilt of the secondary is used to correct the on-axis coma.

These on-axis aberrations arise as a consequence of the mirror tilts, the latter can be canceled out but the former must be corrected by generating an oblate ellipsoid section on the smaller secondary.

In addition, spherical aberration can be corrected by making an axially symmetric hyperboloid primary. Then it is possible to design a 6-inch f/10 Yolo performing over a field of view 0.5 degrees better than an f/5 Newtonian of the same aperture. This would be the slowest design recommended for a 6-inch Yolo in which no field correction is considered.

The performance of a Yolo can be significantly improved if the tilt of the secondary is used to correct linear astigmatism and if the asphericities of both mirrors are used to correct on-axis astigmatism, coma, spherical aberration, and linear coma. This correction, however, increases the fabrication difficulty. Linear coma is the usual coma of a Newtonian telescope that increases linearly as a function of the field of view; linear astigmatism increases over the field in a manner similar to linear coma.

It is a fortunate circumstance for telescope makers that the image plane tilt and image anamorphism of a Yolo are quite small for most practical systems. This is so because the contributions of each mirror tend to cancel each other and because their radii of curvature are comparatively long.



The Optical Layout and Notation Used to Describe the Yolo

Design Formulae for a Yolo

The first step in designing a Yolo scope is to decide the primary and secondary apertures Φ_p and Φ_s, and their radii of curvature R_p and R_s. Then the tilt of the primary is calculated, that is, the angle of incidence of the principal ray to have an unobscured light path. It is given by:

$$I_p = (\theta + \arcsin((\Phi_p + \Phi_s)/2t))/2 .$$

where θ is the desired field of view in degrees and t is the mirror separation measured along the principal ray. (See below for a relation giving t.)

The angle of tilt of the secondary mirror, that is, the angle of incidence of the principal ray to correct on-axis coma is given by:

$$I_s = \arcsin((\varepsilon^2 \sin(I_p))/(\kappa^3 (1+2\varepsilon/\kappa))).$$

where

$$\varepsilon = R_s/R_p$$

and

$$\kappa = \Phi_s/\Phi_p.$$

Note that I_p and I_s are half the principal ray angles of deviation. The ratio R_s/R_t between the short R_s and long R_t radii of curvature of the secondary mirror to correct on-axis astigmatism is given by:

$$R_s/R_t = 1 - ((\varepsilon/\kappa^2)\cdot\sin^2(I_p) + \sin^2(I_s)) .$$

The primary K-factor to correct spherical aberration is given by:

$$\text{K-factor} = -1 - (1+(2\varepsilon/\kappa))^2\, \kappa^4/\varepsilon^3 .$$

The primary focal and secondary focal lengths are given by:

$$f_p = R_p/2\cos(I_p) ,$$

and

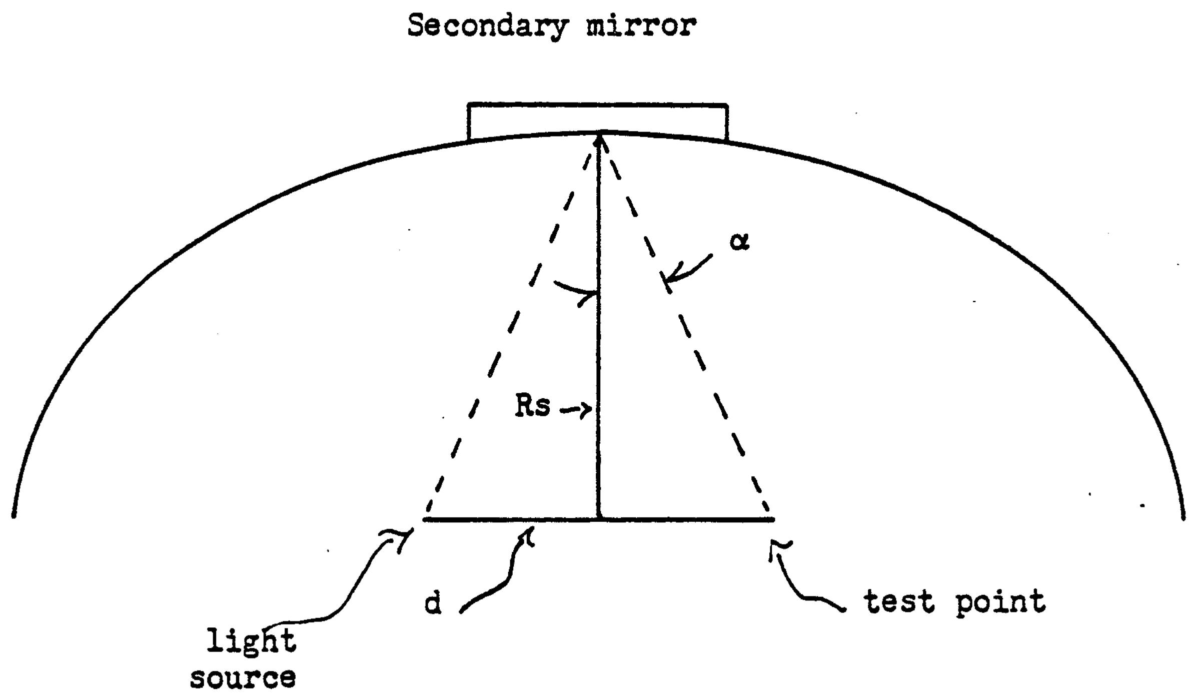
$$f_s = R_s/2\cos(I_s)$$

and the effective focal length is given by:

$$F = 1/((1/f_p)+(1/f_s)-(t/(f_p f_s))) .$$

The mirror separation is given by:

$$t = (1-\kappa)\cdot f_p .$$



Configuration Used and Notation for Testing the Secondary Mirror

The final secondary diameter, to have an unvignetted field of view, is given by:

$\Phi_s + t \cdot \tan(\theta)$.

Note that t depends on $\cos(I_p)$ and can be approximated by:

$t \cong ((1-\kappa) \cdot R_p)/2$

to start the calculations. The distance b from the secondary mirror to the image plane along the principal ray is given by:

$b \approx F \cdot \kappa$.

It is worth commenting that some of the equations are not exact, but they give an excellent approximation of the necessary quantities when the angles of tilt are small, which is the case for the Yolo system.

Design Example: Albert Priselac's Yolo

After the publication of "A Practical Yolo Telescope" (*S&T*, August 1988), Albert Priselac, an amateur telescope maker from Uniontown, Pennsylvania, brought to my attention the weird size I chose for the mirrors of the aplanatic Yolo telescope. He wrote: "Sometimes motivation is governed by certain situations, I think convenience is the one that counts. . . ." I appreciated the philosophy stated in his comment, so I decided to design a Yolo for him using standard 4.25- and 6-inch Pyrex blanks.

The radii of curvature of both mirrors were chosen to be 5,150mm. Thus, $\varepsilon = 1$ and $\kappa = (101\text{ mm})/(151\text{ mm}) \cong 0.67$. The secondary is actually 108mm in diameter, which allows the system to have an unvignetted field of view of 0.5 degrees for a mirror separation of 855mm.

The primary and secondary angles of tilt are:

$I_p = 4.5°$

and

$I_s = 3.8°$.

The long radius of curvature of the secondary is 5,245mm. The primary K-factor is K = –4.2, and its effective focal length is 1,547mm. The f/ratio of the complete telescope is 10.2, and the distance from the secondary to the image plane is 1,035mm.

For the design of other Yolo systems, it is recommended to minimize the angles of tilt and verify the optical layout by making a drawing to scale. For an 8-inch aperture Yolo the minimum recommended focal ratio would be 12, and for a 12-inch aperture the minimum focal ratio would be 16.

Comments on Fabrication

The longitudinal spherical aberration at the primary mirror center of curvature is given by:

$$\Delta Z = KY^2/2R_p,$$

where Y is the normal ray height on the surface. This correction is K times the asphertzation needed for the equivalent paraboloid mirror (source and knife-edge moving together). Considering the small amount of glass to be removed, the telescope maker must be careful not to overcorrect the primary mirror.

Perhaps the main reason that TMs do not undertake the fabrication of a Yolo is the belief that producing the secondary double curvature is very difficult. However, the only way to really know how easy or how difficult the fabrication of the secondary is, is actually to make one.

Although it can be made to work satisfactorily, the mechanical "warping" harness proposed by Mr. Leonard to deform the mirror has not been accepted by amateurs as the ideal solution to produce the shape necessary to correct on-axis astigmatism.

A simple method to generate and maintain the surface required for the secondary mirror is to allow only translational polishing movements using a double four-bar linkage. I described this in "A Practical Yolo Telescope." A double curvature mirror has two mutually perpendicular planes of symmetry, which is a rather symmetric surface form.

This shape, if appropriately encouraged by constraining in rotation the polishing movements, will develop naturally. After all, professional opticians have to be very careful to reduce to a minimum the amount of astigmatism on their optical surfaces because there is no such a thing as a perfect mirror. TMs will find surprisingly little difficulty generating the Yolo secondary double curvature using a double four-bar linkage and polishing principles similar to the ones used in making standard mirrors.

The secondary mirror can be thought of as being part of an ellipsoid. It can be tested at its focii, which are separated by a distance d given by:

$$d = 2\,R_s \cdot \tan(\alpha).$$

The angle α is found from the relation:

$$\cos(\alpha) = \sqrt{(R_s/R_t)}\,.$$

For the design presented above:

$$\alpha = 7.7°$$

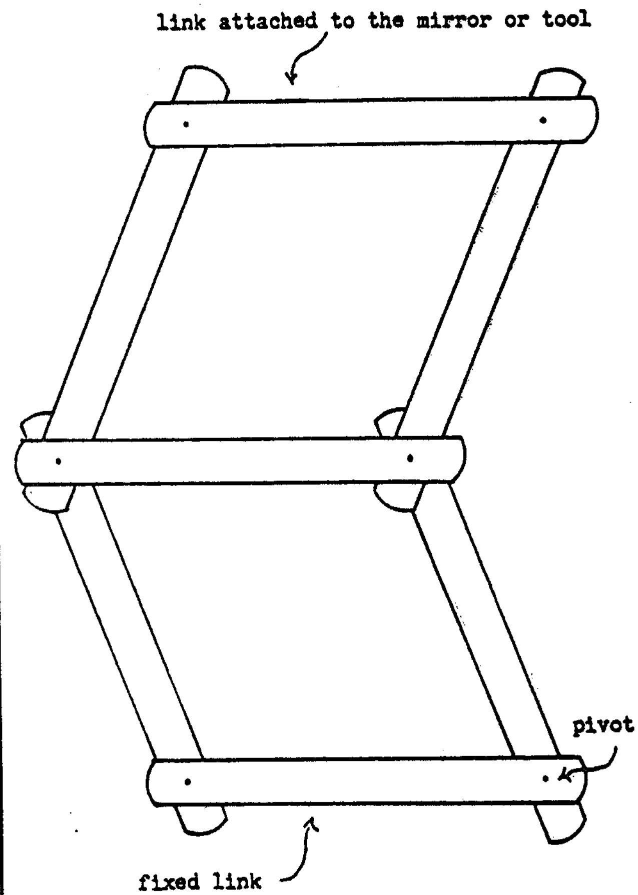
and

$$d = 1401 \text{ mm}.$$

It is worth mentioning that the Ronchi test is particularly useful for testing the secondary because it allows any surface asymmetry to be readily detected.

Final Adjustments

When aligning a Yolo the TM must be sure that the long radius meridian of the secondary coincides with the telescope plane of symmetry as defined by the mirror tilts. Assuming that this requirement is met, it may happen that after finishing and assembling the Yolo telescope some residual on-axis astigmatism, or coma, or both will be detected. These aberration residuals can be corrected by changing the mirror separation and the secondary tilt.



Linkage to Prevent Rotation during Polishing

One must remember that on-axis astigmatism increases as the square of the aperture and the square of the secondary angle of tilt, and on-axis coma increases linearly with the angle of tilt and cubicly with the aperture. Thus, on-axis coma is more rapidly varied by changing the mirror separation, and on-axis astigmatism by changing the secondary tilt.

I would like to thank Dean Ketelsen for his valuable suggestions.

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Reference

Mackintosh A., *Advanced Telescope Making Techniques*, Willmann-Bell, Inc., 1986.