Calibrating the Plate Scale of a 20 cm Telescope with a Multiple-Slit Diffraction Mask

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Abstract: A multiple-slit Diffraction Mask was made and used with a 20 cm Maksutov-Cassegrain telescope and DSLR video imager to determine the plate scale of the imaging system independent of possible positional errors of stars in catalogs and databases. The device was found to give excellent, repeatable results to ± 0.002" per pixel.

Necessity of Plate Scale Calibrtation

I have been making measurements of the separation and position angle of double stars for the past two years with a 202 mm diameter, f/15.5 Maksutov Cassegrain telescope and a DSLR. The method known as 'lucky imaging' has been used. The accuracy of these measures of separation depend a great deal upon reliably knowing the focal length, and thus the plate scale, of the imaging system.

The plate scale of a telescopic imaging system is directly related to the focal length of the system. Unfortunately, the focal length of a telescope is not fixed but varies slightly depending on the type of telescope and certain other factors.

Refractor telescopes do change their focal length very slightly with temperature. For example, the change is in the 10 to 50 microns range per degree Celsius for various refractors from TEC Telescopes. (Petrunin, personal communication)

Compound telescopes such as Schmidt-Cassegrains and Maksutov-Cassegrains move the primary mirror to achieve focus. Moving the focus point by 1mm can change the focal length by 3mm or more.

Since, in most amateur applications, the imaging camera is re-installed for each observing run and the entire system may be set up in the field for each run, the focus position may change slightly, requiring that calibration images be taken during every observing run.

Calibration: Dependent or Independent?

A great number of double star measures depend upon 'calibration pairs' from the Washington Double Star Catalog (WDS) of the United States Naval Observatory (USNO). The WDS provides and keeps up-to-date extensive lists of these calibration pairs and pairs exhibiting rectilinear motion for use by any observer, professional or amateur. From the standpoint of amateur double star astrometry, most of the calibration pairs are too close, too faint or have too large a delta magnitude to be useful. Those pairs that are wide and bright enough for use for calibration in typical amateur telescopes often do not have well-determined orbits. Furthermore, the WDS itself warns potential users of these calibration pairs,

"*using measurements of double stars to calibrate the measurements of other double stars is certainly circular (or, if you will, Keplerian). We strongly advocate the use of other absolute calibration techniques.*" (6th Catalog of Orbits, WDS).

An absolute or independent method to determine plate scale used in professional observatories involves placing a double or multiple-slit diffraction grating in front of the telescope. (Hartkopf et al, 2000) Combined with the use of narrow, monochromatic filters the plate scale can be reliably found purely through the well-known laws of optical physics. In Robert Argyle's book, "Observing and Measuring Visual Double Stars", an entire chapter is devoted to the use of multiple-slit diffraction gratings to measure the separation and position angle of doubles. (Maurer, 2012) I saw an opportunity to use such a grating for calibration, rather than measurement as it removes any stellar positional errors and any catalog errors from the calibration process.

Double and Multiple Slit Diffraction Gratings

It has been known since the groundbreaking, early 19th century work of Thomas Young that if light is passed through two or more narrow slits, an interference pattern is produced with maxima occurring in an orderly, quantifiable pattern depending on only two variables: the spacing of the slits and the wavelength of the light.

The pattern consists of a central maximum, the so-called 0th-order maximum, flanked equally on each side by pairs of increasingly fainter maxima called the 1st-order, 2nd order maxima and so on. These maxima are at precisely known angular distances from the central maximum.

If multiple slits are used, the intensity of the maxima increases and the width of the maxima of the diffraction pattern decreases with the number of slits used but the spacing of the maxima remains the same. This is important for typical amateur-sized telescopes whose smaller apertures, compared to professional observatory scopes, struggle to capture enough light to image the pattern.

If white light (or the light of any single star) is used the 1st-order maxima in the diffraction pattern become small spectra which are far too elongated to be of any use to a double star observer trying to find the centroid of these maxima. Monochromatic light must be used. A convenient and modestly-priced monochromatic filter which works well for this application is the Hydrogen-alpha filter, commonly sold to astrophotographers for imaging emission nebulae. For under $200 a 1.25″ diameter H-alpha filter, centered on a wavelength of 656.281 nm with a 7 nm band pass can be purchased. Such a filter admits enough light to easily get useful 1st-order maxima from a 1st magnitude star with a 20 cm telescope.

The angle between the 0^{th} and the 1^{st} order maxima is given by

$$z = \frac{206265\lambda}{L + D}$$

where z is the angle in arc seconds, λ is the wavelength of light in mm, L is the slit width in mm, and D is the width of the opaque 'bar' between the slits in mm. (Maurer, 2012)

If the slits and spacing are equal then $(L + D)$ can be replaced by "S" which is the on-center spacing of the slits. Thus 6 mm slits with 6 mm bars will have an S value of 12 and is called, in this paper, a "12 mm grating" for example.

Choosing a Slit Spacing

My DSLR in 640x480 video crop mode on the 202 mm f/15.5 Maksutov has a field of view of about 2′ x 3′. A $2z$ value of about 100″ or so would be suitable. In Table 1 $2z$ values are shown for a variety of slit spacings.

The 1.5 mm spacing yields the brightest and sharpest 1st-order maxima. Slits this narrow, as well as 3 mm however, proved very difficult to construct from the card stock used and sagged under their own weight. The best compromise between smaller slit spacing and mechanical strength was found to be the 6mm spacing, yielding a $2z$ value of 45.122″.

Field Tests of Three Diffraction Masks

Two diffraction masks were cut from stiff cardboard stock with spacings of 12 mm and 6 mm using a laser cutter. Figure 1 is a photograph of the 6mm mask.

The first magnitude, single star Pollux (Beta Gem) was focused with a Bhatinov mask. Videos were then taken through each mask with the H-alpha filter in place and the DSLR in 640x480 video crop mode through the 202mm Maksutov. The images were aligned and stacked. Figure 2 shows the resulting diffraction patterns side by side.

Only three points of light are visible in each image, the central, 0th-order maximum flanked by the two 1st-order maxima. The 0th-order maximum is bloated and elongated, making it unsuitable for determining the centroid of its image. However, the two 1st-order maxima images are very round and 'stellar'. The angular distance between these two maxima is simply 2z from the formula above. It is these maxima that I have found to be most useful for calibration. A slit spacing must be selected so that these two maxima will fit com-

Table 1. 2z Values for Different Slit Spacings.

Slit Spacing (mm)	z (a.s.)	2z (a.s.)
24	5.640	11.280
12	11.281	22.562
6	22.561	45.122
3	45.123	90.245
1.5	90.245	180.490

Figure 1. Photograph of the mask with 6 mm slit spacing.

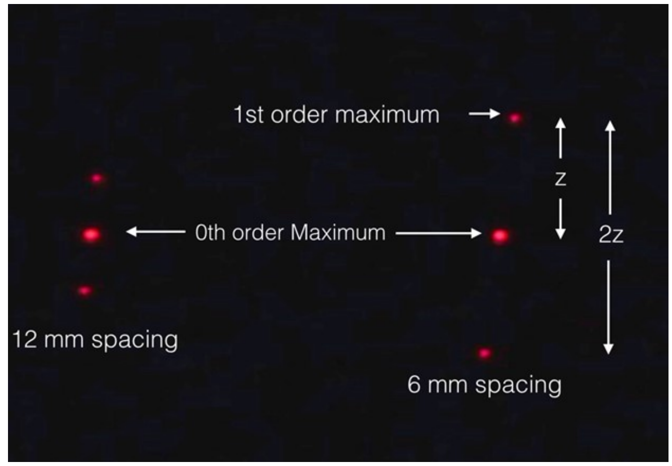

Figure 2: Diffraction patterns for 6 mm and 12 mm slit spacings.

fortably in the camera frame and, at the same time, be as wide apart as possible in order to have the largest possible sample of pixels to ensure measurement accuracy.

The separation between the 1st-order maxima were measured and the resulting plate scales obtained are given in Table 2.

As a check of these plate scales two wide, very slow-moving double stars were imaged immediately following the two diffraction mask images without changing any of the physical set-up of the camera or telescope. Iota Cnc, whose separation of 31.0″ has not changed since its discovery in 1777 and STTA 89 whose separation has changed very slightly from 76.7″ at its 1825 discovery to 77.0″ in 2004 were chosen. (6th Catalog of Orbits) The respective plate scales derived from measuring these pairs were 0.273″ / pixel and 0.276″ / pixel.

The variance among these five measures is ±0.002″ / pixel, which is a satisfactory result.

Conclusion

The multiple slit diffraction mask in combination with a hydrogen-alpha filter is a reliable calibration tool for use by amateurs. The masks can be easily and cheaply made with a laser cutter and stiff card stock. The mask acts as a 'calibration pair' of stars whose angular separation never changes due to erroneous measurements of other observers, catalog errors or the passage of time.

Table 2. Plate Scales Obtained for 2 Different Slit Spacings

Spacing	2z Value	Plate Scale
12	22.562	0.275
6	45.122	0.274

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