Subject: Understanding the DeVeny Astigmatism and Collimator Focus
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1 DeVeny Optical Layout

Figure 1 shows the KPNO Gold Spectrograph, which I assume to be a structural clone of the KPNO White Spectrograph (a.k.a. the DeVeny Spectrograph), modulo details such as shutter, filters, slit viewing camera, etc.

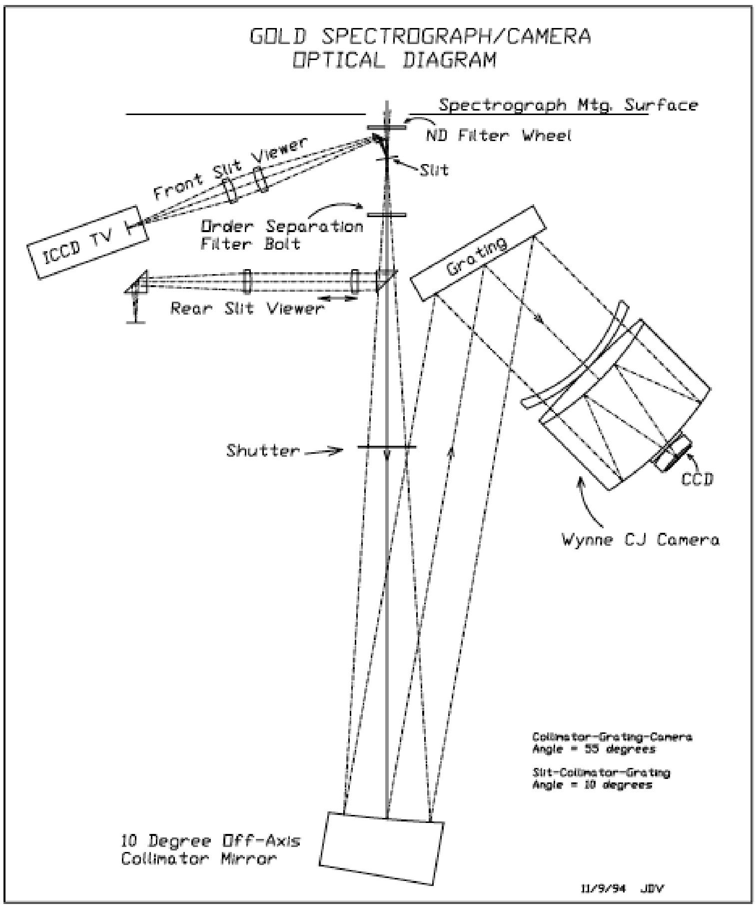

Figure 1: KPNO Gold Spectrograph Optical Diagram. The DeVeny Spectrograph is a close cousin of the KPNO Gold Spectrograph (according to P. Massey), with some differences. Drawing by James DeVeny,

Of particular note are the three angles that define the system:

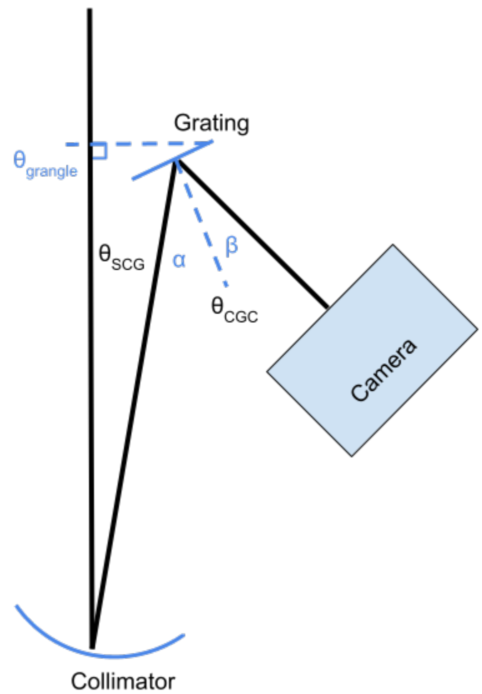

Figure 2: Angles in Deveny.

- the Slit-Collimator-Grating angle $\theta_{SCG} = 10°$,
- the Collimator-Grating-Camera angle $\theta_{CGC} = 55°$, and
- the Grating Tilt angle θ_{grangle} (user selectable).

Because we illuminate the collimator mirror off-axis, this introduces some astigmatism in the system, **but that is not the chief astigmatism we're interested in, is it?** In the diagram in Figure 1, the length of the slit is perpendicular to the page, so as to be parallel to the grooves in the grating.

Q: Is the collimator mirror an off-axis paraboloid, or is it a centered paraboloid illuminated off-axis?

In Figure 2, the relevant angles within the spectrograph are labeled. In particular, the incoming and outgoing angles for a ray hitting the center of the camera are:

- $\alpha = \theta_{\text{grangle}} + \theta_{SCG}$, and
- $\beta = \theta_{CGC} - \alpha$.

The rays hitting the grating in the plane of α and β diffract to the camera in such a way that the beam width changes as a function of α and β, whereas rays incident on the grating in the perpendicular plane have the same beam width going in and coming out (see Fig 3). Because there is a difference between the beam widths for the two planes, there will be different magnification levels (Schweizer, 1979). Whenever perpendicular planes have different magnifications, this is called "anamorphic" (de)magnification. Schweizer (1979), however, thinks the term "anamorphic magnification" is somewhat inaccurate, and prefers "grating magnification". The DeVeny manuals and IDL code use "anamorphic", so we continue that there. The resulting magnification in the direction of dispersion due to the grating, arising from the differentiation of the grating equation, is:

$$r = \frac{-d\beta}{d\alpha} = \frac{\cos\alpha}{\cos\beta} \tag{1}$$

(Schweizer, 1979). Since our gratings operate with a tilt angle $20^\circ < \theta_{\mathrm{grangle}} < 48^\circ$, this means that $|\alpha| > |\beta|$, and r will always be less than 1. In our case, the change in magnification is in the direction of the slit width, hence our quoted "anamorphic demagnification of slit width".

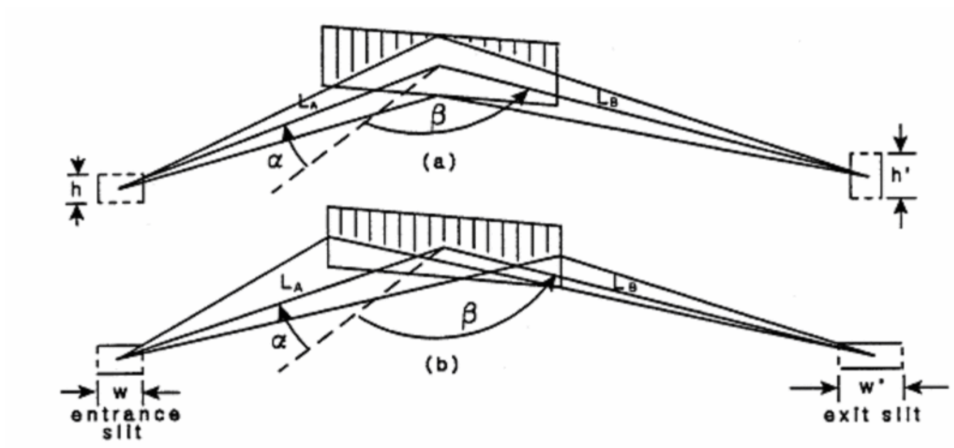

Figure 3: Anamorphic demagnification (Learner & Thevenon, 1988).

2 Imaged Slit Width on the Camera

The plate scale of the DeVeny spectral channel CCD is quoted as being $0.34''$/pixel. (When was that last measured, and how?) Using this scale, a $1''$ slit would appear to be 2.94 pixels wide at the detector for specular reflection ($m = 0$, $|\alpha| = |\beta|$). Because of the anamorphic demagnification discussed above, the optimum slit image width would be $2.94 \times r$ pixels for arbitrary $\theta_{\mathrm{grangle}}$.

Spectral lines from our four arc lamps have intrinsic linewidths $\lesssim$ 0.5 Å (Konjević et al., 2002). Since the dispersions of our gratings range from $\sim 0.5 - 4$ Å/pixel (in 1^{st}

order), this translates to an observed intrinsic linewidth of $\sim 0.1 - 1$ pixels, depending on the grating. When this intrinsic linewidth is convolved with the slit width (and the mathematics of this are eluding me at the moment), it causes a slight broadening of the apparent slit on the detector. For the lower-dispersion gratings (say, DV1 - DV8), this is minor enough to ignore (I think). In any event, when we focus the collimator, we fit a gaussian to the observed line and compute the FWHM. At best focus, this should be fairly close to the observed, demagnified slit size in pixels.

So, for example, with the DV2 grating (300 g/mm) set for a central wavelength of 5200 Å, we get a grating angle of 22.54°, and a demagnified slit width of 2.68 pixels for a 1″slit. Given a finite intrinsic linewidth, the actual observed line would be a tad wider.

3 Astigmatism and Focusing

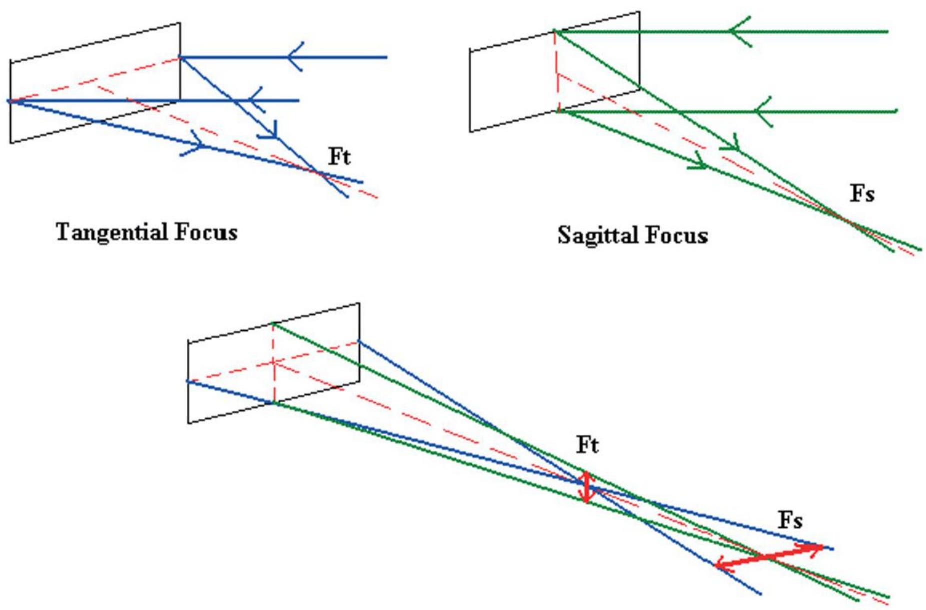

Figure 4: Astigmatism. https://static.horiba.com/fileadmin/Horiba/Technology/Measurement_Techniques/Spectroscopy/Monochromator_Spectrographs/Monochromators_Spectrographs/fig7_15_Effects_of_Astigmatism.jpg)

The upshot of the astigmatism caused by the anamorphic demagnification is that the spectral and spatial planes do not come to focus at the same place. In the illustration of Figure 4, our spectral dimension would be the blue “Tangential Focus”, and the spatial dimension would be the green “Sagittal Focus”. In such situations, it is common to find the "least bad" focus as a compromise between getting sharp tangential focus (with smeared out sagittal information) and sharp sagittal focus (with smeared out tangential information). We lose a little of both to balance out.

Q: For spectral work, it seems there would be some situations where one would want sharp spectral focus at the expense of spatial resolution (brighter stars, for instance), some situations where spatial focus is more important than spectral resolution (galaxies maybe?, or faint solar system objects), and situations where the compromise is best (fainter objects, for which we would like to not smear out the photons too much spatially, but spectral resolution is important). Is this a proper interpretation?

Next are two things that have really puzzled me:

1. In a figure from the 2015 DeVeny manual, the projected line widths appear to grow with the higher-resolution gratings despite the grating needing to be tilted at a steeper angle (and therefore having a stringer demagnification). See Figure 5.

2. When computing the collimator focus, the `dfocus` routine assumes a nominal focus FWHM equal to the projected slit width, as discussed in §2. As discussed there, this should be the "best focus" width, yet the focus curves for each line reach a minimum value lower than this. See Figure 6.

3.1 Projected Line Widths

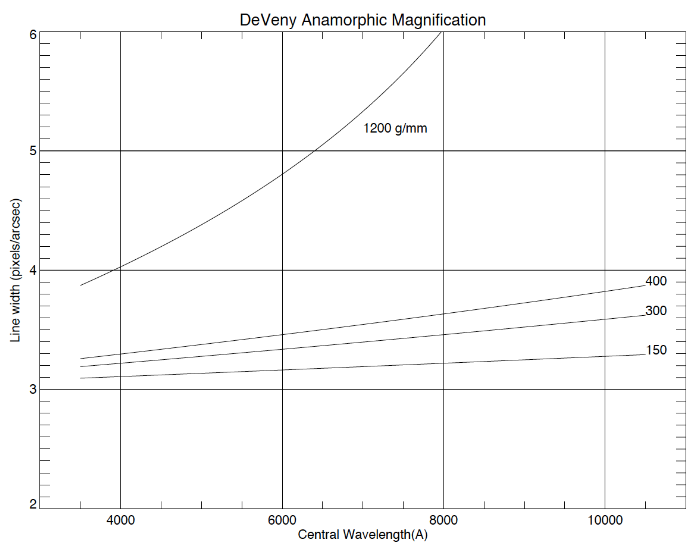

Figure 5: Projected line width vs. grating and central wavelength setting. (Figure from the 2015-Jun DeVeny Manual.)

When delving into the collimator focus question (*i.e.*, "Why do we not set the collimator focus at the minimum of the focus curve?") to begin with, Tom sent the 2015-Jun version of the DeVeny manual, which contained information about the astigmatism that subsequently disappeared from later versions (including the 2018-Jul version from which I prepared the v1.6-beta manual).

Included in that version is Figure 5, which plots projected linewidth as a function of central wavelength pointing for four different gratings (DV1, DV2, DV4, and DV9). What, exactly, is this figure demonstrating, especially with the title "Anamorphic Magnification"? Is this plot currently relevant, or somehow a relic of a previous configuration? As one moves to the higher-resolution gratings, the intrinsic linewidth (pixels/Å) becomes a larger percentage of the projected slit width (pixels/″), but it should not come to dominate the fitted FWHM of the arc lines.

3.2 Focus Minima

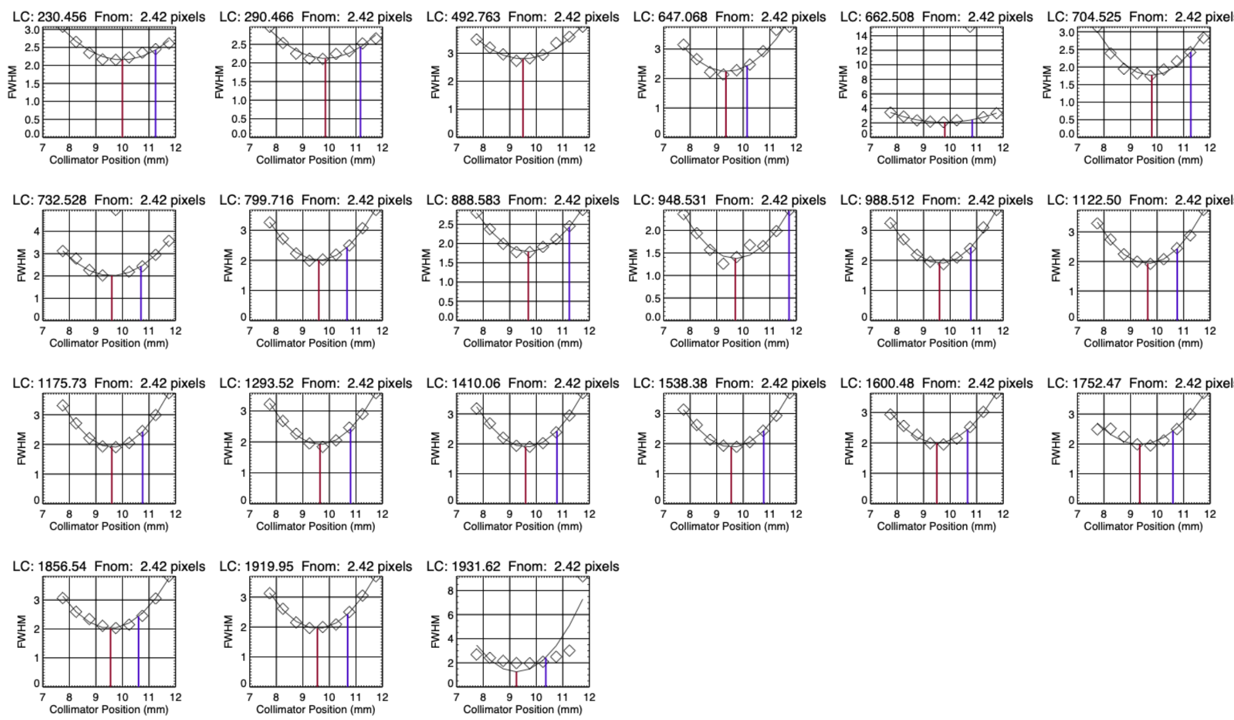

Figure 6: `dfocus` line fitting for the DV4 grating, with $\theta_{\rm grangle} = 27.89°$, and λ_C = 8000 Å. Slit demagnification, computed with the `deveny_grangle` routine yields a slit demagnification of 2.43 pixels/″, and the slit width was set to 1.0″. Data were taken 2020-12-30UT.

The initial answer to our question of "Why do we not set the collimator focus at the minimum of the focus curve?" is answered in terms of astigmatism, and compromising between the spectral and spatial foci. However, the `dfocus` routine selects as the "nominal linewidth" what should be the in-focus width of the slit, and the measured linewidths actually get smaller. Figure 6 is one page from the hardcopy postscript output of `dfocus` on the night of 2020-12-30UT. The grating was DV4, with $\theta_{\text{grangle}} = 27.89°$ ($\lambda_C = 8000$ Å, and slit width $1.0''$. Use of Equation 1 and the 2.94 pixels/$''$ plate scale yields a demagnified slit width of $2.43''$.

Q: Many of the lines have narrowest FWHM $\sim 2.0''$ (red lines). How is this possible?

To help understand how `dfocus` does its work, I ended up porting the IDL code over to python. It runs, but at the moment yields slightly different results from the IDL version – I suspect this is due to the Gaussian fitting portion, but I have yet to investigate. At present, I will focus on what the code does and the IDL outputs (like Fig. 6). In the subroutine `dfitlines`, a Gaussian is fit to the identified spectral line (from an earlier step) in each image from the focus sequence. The value returned is FWHM $= 2.355 \times \sigma$, which is the correct value for converting a Gaussian width to FWHM. Admittedly, I have not had the code produce a graph for each line for each step in the focus sequence, but how can a fitted Gaussian be narrower than the optimum focus for the slit?

At the spectral focus (labeled Tangental Focus in Figure 4) point, this is where the rays in the tangent plane come to a focus and form the image of the slit. As the rays diverge on either side of this point, the spectral direction should expand and spread out again.

4 Next Steps

So, there are several open questions at this point.

- If the nominal linewidth, used in `dfocus` to compute the purple "optimal focus" setting, is not the spectral focus width of the slit image on the CCD, what is it?
- Are the use cases outlined in §3 the reason to not set the collimator at the minimum of the focus curve? It would be instructive to take engineering data of a Be star as the collimator focus value is changed. This would provide information on both the spatial (point source) and spectral (emission line source) foci as we move through the two focus points.
- Are there other missing steps in my reasoning in this document for the physics of this process?

References

Konjević, N., Lesage, A., Fuhr, J. R., & Wiese, W. L. 2002, Journal of Physical and Chemical Reference Data, 31, 819

Learner, J., & Thevenon, A. 1988, Jobin-Yvon Optical Systems/Instrumentss SA, 48, 1198

Schweizer, F. 1979, Publications of the Astronomical Society of the Pacific, 91, 149