Letter:
Spectrographic Calibration

Flood vs Beam vs On Axis

Injection of Calibration References

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Abstract

This letter reports preliminary results with spectrographic calibration of small telescope spectrographs. We have experienced thermal expansion and mechanical flexture. We are investigating using a converging beam with the same f/ratio and PSF as a star. This is proving hard to do. Recent discussions has brought us to consider the problem from several aspects. These results mainly center on the LOWSPEC family of spectrograph by Paul Gerlach.

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1 Overview

For about 18 months the cohort suffered Green saying to ignore the signal and focus on the noise. If noise is kept under acceptable control – the science result's signal can be shown to be objectively better.

One critical source of "noise" is calibration line shift, accuracy, usefulness in the recent Spectro-L thread.

The short question is between utilizing a gas lamp for reference calibration lines by flooding a slit (flood) or using a precisely formed converging beam (beam). The Question come down to the quality of lines made by the lamp, and how does the impact of a simple experiment of subtracting the first comp image from the last comp image – assuming one has followed a strategy along the lines of 1) comp-sci-sci-sci-comp or 2) comp-sci-comp-sci-comp-sci-comp. Flats have important questions of their own but are not germane to this question.

IRAFs answer to how to subtract images comp1.fits from comp2.fits: `imarith comp1 - comp2 diff.fits`. We've seen shifts of several pixels across one observation.

Answering the difference between flood vs beam,. first start with the "thin lens equation"[1]:

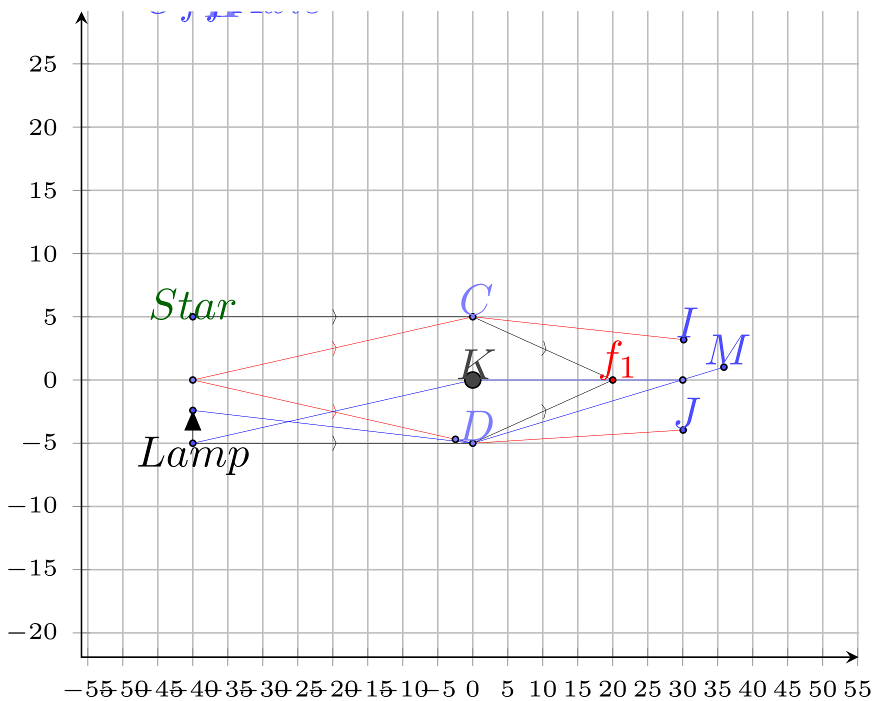

Figure 1-1: Lens Makers Formula with star and cal-lamp light. (Not happy with the rendering – Tikz needs upgrading.)

$$\frac{1}{f} = \frac{1}{s_1} + \frac{1}{s_2} \tag{1}$$

where f is the actual focal length of the lens/lens assembly for infinity ; s_1 is the distance from the lens to the target and s_2 is the distance from the lens to the virtual image.

[1]The "lens makers formula" deals with the radius of curvature for lens surfaces. Appendix B.

A few waypoints to notice: if s_1 is essentially at infinity, then $\frac{1}{s_1}$ goes to zero and the position s_2 is equal to the stated focal length. The next very interesting thing is that if a light is placed at s_2 (L–D not shown), the beam is essentially parallel – or at infinity and is said to be collimated.

In Fig. 1-1 there should be a lens indicated along C–K–D that did not render. In the spectrograph, the slit is at f_1. The arrow is an off-axis near-field bulb filiment, producing a ray Lamp $\rightarrow$ D $\rightarrow$ M, where the star's ray, along the same path, is from infinity $\rightarrow$ D $\rightarrow$ f_1. The two angles are not the same. Taking a bundle of lines along the filiment of the lamp produces a series of rays – each with a different angle. Variation in the position of the lamp can cause a mis-match of calibration locations. There is also a bias from the position of the bulb w.r.t. the slit.

If s_1 is close to the lens, then the rays are diverging into the lens and come to focus at s_2 some distance farther out than the focal length of the lens. The angle of the rays fall within the range subtended by the geometry of the circle or rays hitting the lens surface. A wider range, the closer the source to the lens.

A critical thing to remember, is that the target itself (size of the bulb – say the two electrodes) causes a mix of angles of rays in the bulb's beam. This adds up to more variance in incidence angles at the grating.

Flooding has diverging beams, acts like a "near-field" target and therefore the focus of the collimator is wrong w.r.t. a grating. By the grating equation, this generates a diverging beam at the grating – the incidence angle of rays at the 'right' side will be different than those from the 'left' side. This in essence effects the focus. Flooding off axis produces an asymmetry in the output of the collimator and will produce a "corresponding" shift in the lens. The asymmetry is introduced by changes due to thermal expansion and with flexure. Focusing with the comp lamp is invalid. Focusing with sky lines late in afternoon is much better.

For reference, the grating equation for a reflection grating:

$$\frac{m\lambda}{d} = sin(\alpha) + sin(\beta) \tag{2}$$

where m is the mode, λ in wavelength, α is the "angle if incidence" and β is the "angle of diffrection". The near-field lamp produces a wide range of α incidence angles that are not consistent with the far-field stellar image. The addition operator needs to be subtraction for transmission gratings.

Summary 1: Co-linear rays from the collimator to the grating improves the overall placement, line shape, and line width (focus) of the resulting spectra. Repeatable variations will produce a systematic wavelength identification. Non-repeatable variations due to variations in temperature and flexure introduce random wavelength positions.

1.1 Mitigation Strategies

Use a diffusing screen. This converts more coherent (not very coherent to begin with straight from the bulb) into a "Lambertian" source. The Lambertian source is usually depicted with a single point and speaks to the intensity at different angles projected away from that point. Integrating over all points boils down to a large mix of rays at different angles.

Summary 2: One can argue the narrow width of the slit mitigates the use of a flooding lamp, but measurements shows a small shift – one that can amount to 10s to 1000s of km s-1 in the spectra.

Summary 3: With energy $E = h\nu$ relates to wavelength ($lambda$) as $\nu = c/\lambda$, a shift in wavelength improperly converted to the targets frame of reference amounts to a misstatement of Energy. This is not accounted for through the line ratio analysis process.

Summary 4: It is obvious that radial velocity statements mis-stated as the $\Delta\lambda$ is non-linear and a shift due to mis-identification will have a material impact on radial velocity statements.

Mitigation by solving a spectrum using sky-lines or using the absorption features in the target itself (within the targets frame of reference) will help with line ratios. Solving with both sky-lines and with the target gives the shift needed to state the radial velocity.

1.2 Beam Case

Great idea, difficult to implement. The general idea is a diffusion method (scattering screen, microlenses, integrating sphere), a collimator, a matching f/ratio lens for the star's image and a way to match the injection angles. Its the injection matching that is proving mechanically difficult.

2 Conclusion

The use of comp lamps may be done away with if sufficient information in the form of sky-lines (light pollution and tellurics). Nodding the telescope and employing a sufficient exposure time can solve the flood vs beam question. In may cases, small telescope spectroscopy is well suited to detect and report gross changes of state with a target, and to help qualify novae. Novae respond well to low SNR and to very low R values. We have ignored many issues in this discussion that bear thought.

A Science Objectives

The quintessential aspects of spectral reduction boils down to the energy physics represented by effective feature width or the centroid of a target's features for radial velocity study. Small telescope spectrographs are in the R$\sim$ 600,1000,10000 range, generically for the Alpy, Lisa and LHires/echelle products from Shelyak. The prominent features include Hα or nova lines. R is essentially $\Delta\lambda/\lambda$, and for Hα of say 6000Å then the Alpy should have a 10Å resolution.

$$R = \frac{\lambda}{\Delta\lambda} \tag{3}$$

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta\nu}{\nu} = \frac{v}{c} \tag{4}$$

$$v = \frac{c}{R} \tag{5}$$

Here, a gross simplification using Hα as 6000Å ,

The spectrograph consists of essentially three parts: 1) the telescope, 2) the slit and 3) the spectrograph's optics.

R	v (km s-1)
600	500
1000	300
10000	29

Table 1: Gross Velocity in terms of Resolution R

The slit samples the "focal plane" from the telescope, a virtual image, at point of focus. The focus in the point of convergence for a bundle of rays from a science target (star, chunk of nebula, sky etc). The ray bundle is described well enough by the f/ratio of the main telescope. Oversimplifying, it is a consistent converging bundle of rays.

Other aspects that are often ignored include coma (off-axis aspect of where the slit position falls w.r.t. the telescope's curved focal plane) and other attendant astigmatisms. The so called focal "plane" is actually curved – unless flattened by additional optics. See (Schaeberle, 1898) for mind numbing details. A flat plane is common with Ritchey-Critérion telescopes and to a high degree with the CDK telescopes. Refractors, prone to field curvature will have Petzval correctors, or may use other flatteners. Newtonians may use a "Paracor" ™or other optics. Longer focal lengths suffer less but carry larger spot sizes for stars.

Also note the date of Schaeberle's publication. Schaeberle's concerns center on the fact that most casual thought centers on the principle ray along the optical axis.

The shape of this focal plane, and the field's energy contribution to each point on the focal plane surface is way to complicated to delve into here. The simplifying assumption is that the slit is tiny w.r.t. the surface; the desired image is tightly defined by the f/ratio's converging beam and aberrations can be ignored within an appropriate over-simplifying assumption. Assumption about 'out of focus' rays often miss the fact that the rays do not have the same f/ratio as the desired science image and that those contributions (mainly sky in the general case here) are axi-symmetric. They fail to become collimated, and present focus and shift issues for use with spectral calibration.

The injection of the cal and flat lamps do not necessarily satisfy these conditions. The main problem appears to be the issue of rays from the cal lamp are off-axis, non axi-symmetric, do not collimate in the same fashion as the science image and therefore present a range of angles of incidence at the grating. This in turn presents a range (both focus and shift) in the lines at the camera's sensor. We have measured this effect with simple experiments with the LOWSPEC spectrograph.

Our main issue with the LOWSPEC is flexure and thermal expansion. To minimize these issues we are currently re-conducting the experiment in a more temperature controlled setting using stiff aluminum bread-boards to host the LOWSPEC 3D printed optics.

Most SCTs are a train-wreck of design trade-offs. Richard Berry did a white paper that shows the best optical performance is only about 125mm behind the telescope. This distance is quite short. This means inserting guiders is a bit of bother.

A key problem of mismatching the f/ratio of the incoming beam w.r.t. to a spectrograph's collimating lens/mirror is the slit is now out of focus, and producing a range of angles of incidence to the grating. The focus mismatch has the effect of skewing these angles w.r.t. the position of the slit and optical axis.

The answer, for LOWSPEC, is to provide a prescription for the collimating lens and to accommodate the lens. The distance from the collimator to the grating is flexible – the distance to the slit is not.

B The lens makers' formula (for completeness)

$$P_{\texttt{lens}} = \frac{n_{\texttt{lens}} - n_0}{n_o}\left(\frac{1}{R_1} - \frac{1}{R_2}\right) \tag{6a}$$

$$\Phi\lambda = \exp\left(\frac{2\pi i}{\lambda}\frac{r^2}{2f}\right) \qquad \texttt{phase} \tag{6b}$$

where $P_{\texttt{lens}}$ is the "Power" in diopters, n is the index of refraction, R_1 is the radius of the "front" of the lens and R_2 is the radius of the "back" of the lens. Equation (6b) wrecks merry-hob in terms of chromatic aberration – another name for different wavelengths of light coming to focus at different points, or with different angles of incidence.

C Magnitude Drop with Beam Splitter

There is a commercial spectrograph that uses a beam splitter. Assuming a 90% transmission a 10% loss amounts to 0.114.

$$\Delta\,\texttt{mag} = -2.5\frac{\Delta I}{1} \tag{7}$$

$$0.114\,\texttt{mag} = -2.5 \times log_{10}(.90) \tag{8}$$

Along the beamsplitter's 10% axis, injecting a conforming beam gives more control over the exposure time and better photon statistics.

D Mirror Makers Formula

There is a sign switch due to reflection washing around in this one.

The lens makers formula's analog for mirrors (Nave, 2000):

$$\frac{1}{s_1} + \frac{1}{f} = \frac{1}{s_2} \tag{9}$$

where f is the focal length of the mirror, s_1 is the distance to the 'target' and s_2 is where the image is formed. Remember it reverses direction along the optical axis.

References

Nave, C. R. (2000). Doing it by the numbers: Javascript calculations in web-based instructional material. *APT Summer Meeting, Guelph, Ontario*. http://hyperphysics.phy-astr.gsu.edu/hbase/geoopt/mireq.html.

Schaeberle, J. M. (1898). General theory of the aberration in the focal plane of a parabolic reflector. *The Astronomical Journal*, 19:17–21. https://ui.adsabs.harvard.edu/abs/1898AJ.....19...17S.