**MAESTRO Pre-design and Format**

To: MAESTRO circulation

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Nov. 3, 2000

This describes the optical pre-design of MAESTRO. Equations and notation are taken from Schroeder's Astronomical Optics (Chapters 13-15).

I'm still not completely happy with the format.

## 1. Assumptions.

- Blue optimized, to be used down to 3200 $\AA$. We can tolerate degradation of throughput and image quality in the UV within reason. The format will be designed however to include the spectrum to 3200 $\AA$.

- Spectrograph will be located at

  the MMT: $D_{MMT}$ = 6.505 m, f/9 secondary

  or the LBT: $D_{LBT}$ = 8.408m, f/15 secondary

- The detector will be a 4096x4096 CCD with 15$\mu m$ pixels. So the detector is 61.4 × 61.4 mm

- The cross-disperser is a single prism made out of UBK7, with a 50 degree apex angle.

- A quasi-Littrow design is adopted at Cass, similar to that of the LCO Dupont echelle sepctrograph, Jim McCarthy's echelle at McDonald, or Shectman's echelle for Magellan. The main differences with these previous spectrographs are (1) the choice of detector, (2) the choice not to have two channels, and (3) the desire to work shortward of 4000 $\AA$.

- Camera/collimator optics are limited to 200 mm diameter, so it is straight-forward to (1) get blanks, particularly calcium fluoride, (2) get someone to figure the optics and (3) get someone to coat the optics. I hope Roland's design doesn't have any difficult aspheres.
- The echelle grating will be made by Richardson Labs, who have a proven track record of producing high quality, high efficiency echelle gratings. Other vendors are cheaper (e.g. Hectochelle is not using Richardson gratings) but my experience is that you get what you pay for.
- I've explored formats for echelle gratings which have the blaze angle and groves/mm of existing Richardson Lab stock gratings.

## 2. Spectral Resolution.

The spectral resolution for a one arcsecond slit is given by R$\phi$, where

$$R\phi(arcsec) = 2d_1 \, \frac{sin\delta \;\; cos\theta}{D \;\; cos\alpha}$$

here

R = spectral resolution = $\lambda$ / $\Delta\lambda$

$\delta$ = the blaze angle of the echelle grating

$\theta$ =the angle of the incident beam onto the grating with respect to the blaze ($\theta = 0$ for Littrow)

$\alpha = \delta + \theta$

D = the diameter of the telescope

$d_1$ = the size of the collimated beam at the echelle grating.

So given our beam size of 200 mm and the MMT or LBT telescope primary, and assuming a Littrow configuration, the spectral resolution depends on the blaze angle only.

For the MMT,

R$\phi$(arcsec) = 12,683 tan$\delta$

and for the LBT,

R$\phi$(arcsec) = 9812 tan$\delta$

We'd like R=30,000 (10 km/sec) at the MMT with a 1 arcsec slit, so $\delta$=67 degrees. With this grating at the LBT, the 1 arcsec resolution is 13 km/sec, with a 0.7 arcsec slit 9 km/sec. The maximum resolution with 2 pixel sampling is 3 km/sec, which would require a 0.3 arcsec slit at the MMT or a 0.25 arcsec slit at the LBT.

## 3. Projected Slit Width, Required Optical Image Quality.

The projected slit width at the detector, $\omega'$ in microns is

$$\omega'(\mu m) \;\; = 5 \;\; r \;\; \phi(arcsec) \;\; D(m) \;\; F_2$$

where

r = the anamorphic demagnification

$F_2$ = the camera focal ratio.

In order to get a reasonable plate scale given our 15 $\mu$ m pixels, we take an f-ratio of $F_2$ = 3. In other words, a lens will be needed to take the f/9 or f/15 telescope beam and make it f/3. We assume r=1.0.

Then the scale is **0.154 arcsec/pixel at the MMT and 0.119 arcsec/pixel at the LBT**. In order to get a plate scale better matched to our detector, we'd need a *faster* camera, which would be hard to fabricate.

The median seeing at the old MMT was 0.8 arcsec FWHM. The seeing monitor measured the seeing in the optical, at a fairly red wavelength, I would guess effectively about 7000Å. Most of the seeing measurements were better than 1 arcsec, and they never measured seeing better that 0.4 arcsec. At the blue end of MAESTRO, we expect the image quality delivered at the slit to be somewhat worse than the seeing measured with the seeing monitor.

The median seeing of 0.8 arcsec FWHM corresponds to a gaussian with

$\sigma = 0.8\ arcsec\ /\ 2.354\ =\ 0.34$ arcsec.

Most of the light is within $\pm 2\ \sigma$, or 1.36 arcsec. The range of the seeing, 0.4 - 1.0 arcsec FWHM, corresponds to $\sigma$ = 0.17 - 0.425 arcsec, and $\pm 2\sigma$=0.7-1.7 arcsec, which 4.7-11 pixels at the MMT.

Thus the spectrum will be oversampled with 15 $\mu$ pixels. The median seeing FWZM of 1.36 arcsec corresponds to 9 pixels at the MMT, and so we'd always bin the CCD down to get 2-3 pixels per resolution element. If we have optics which can deliver images that are good enough to allow the observer to have 2.5 pixel sampling with the 15$\mu$m pixels and no binning (i.e. have the maximum spectral resolution), then the full $\pm 2\sigma$ gaussian corresponds to 0.385 arcsec or a FWHM of 0.227 arcsec. Only crazed observers would narrow the slit down far enough to get the maximum spectral resolution.

**In other words, Roland's initial design, if I understand it correctly, would be seeing limited all of the time**. The maximum spectral resolution is listed in Table 1 for the different choice of gratings.

## 4. Length of the Orders.

The groove spacing of the echelle grating determines the length of each order's free spectral range, $L$. See Schroeder's Fig. 13.12.

$$L(mm) \quad = \quad f_2 \ \ \Delta\beta \quad = f_2 \frac{\lambda_o}{\sigma\ cos(\delta - \theta)}$$

where

$f_2 = F_2 \times 200mm = 600mm$,

$\sigma =$ the distance between grooves

$\lambda_o =$the central wavelength of the order.

$\delta =$ blaze angle of the echelle grating.

## 5. Spacing between Orders.

Let $A_x$ be the angular dispersion of the cross-disperser, in arcsec/length,then

$\Delta y \ = 2 \ f_2 \ A_x \ \Delta\lambda$

where

$\Delta y$ =the distance between orders in length units

$f_2 = 600$ mm

$\Delta\lambda =$ the free spectral range

and the factor of 2 comes from the fact that we use the prism in double pass.

For a prism,

$A_x = \frac{d\beta}{dx} = \frac{t}{a} \ \frac{dn}{d\lambda}$

where

t = base length of prism

a = height of the prism

$dn/d\lambda = 0.066 \ \mu m^{-1}$ at $\lambda$=5000 $\AA$ for UBK7

and $dn/d\lambda \propto \lambda^{-1}$.

For a 50 degree apex angle, t/a=0.933.

## 6. Echelle Formats

I computed the cross-dispersed formats for a blaze angle $\delta$=67 degrees, varying the grove spacing in order to try to get as much of the spectrum on the 4kx4k CCD while having an acceptable slit length. For 67 grooves/mm you get continuous spectral coverage to 6000 $\AA$ with a 6 arcsec slit, and partial coverage out to 1 micron. It would be better to have a more rectangular CCD – I'm discussing this with Mike.